A Visual Inspection System for Accurate Positioning of Railway Fastener

Jianwei LIU†, Hongli LIU†, Xuefeng NI†, Nonmembers, Ziji MA†††, Member, Chao WANG†††, Nonmember, and Xun SHAO†††, Member

SUMMARY Automatic disassembly of railway fasteners is of great significance for improving the efficiency of replacing rails. The accurate positioning of fastener is the key factor to realize automatic disassembling. However, most of the existing literature mainly focuses on fastener region positioning and the literature on accurate positioning of fasteners is scarce. Therefore, this paper constructed a visual inspection system for accurate positioning of fastener (VISP). At first, VISP acquires railway image by image acquisition subsystem, and then the subimage of fastener can be obtained by coarse-to-fine method. Subsequently, the accurate positioning of fasteners can be completed by three steps, including contrast enhancement, binarization and spike region extraction. The validity and robustness of the VISP were verified by vast experiments. The results show that VISP has competitive performance for accurate positioning of fasteners. The single positioning time is about 260ms, and the average positioning accuracy is above 90%. Thus, it is with theoretical interest and potential industrial application.

key words: fastener, accurate positioning, region extraction, visual inspection, binarization

1. Introduction

Faster is an important component of railway, it needs periodically maintenance and replacement. However, fastener disassembly mainly depends on trained railway workers to finish now, which is slow, laborious, and potentially dangerous. As shown in Fig. 1(a). With the extension of railway network, fastener disassembly faces more challenges than before. Therefore, it is urgent to develop automatic fastener disassembly car.

An automatic disassembly car is composed of disassembly module and positioning module. As shown in Fig. 1(b). Once the precise of fastener is obtained, disassembly can be completed automatically. Therefore, obtaining the accurate positioning of fastener is the key to finish automatic disassembling. Meanwhile, it is also the main research content of this paper. In recent years, visual inspection technology [1]–[3] has attracted more attention from industries and researchers because it can provide reliable inspection and the cost is low. Therefore, we adopt vision method to complete accurate positioning of fastener.

In the past decade, researchers have proposed some fastener positioning methods. Yang et al. [4] utilized direction field and template matching to realize fastener positioning. Li et al. [5] locate fastener region by the Hough transform. In literature [6], Feng et al. locate the fastener region based on the geometric relationship between sleeper, rail and fastener. In literature [7], Babenko describes a fastener positioning method based on a convolutional filter bank. Similarly, Gibert et al. [8] obtain the fastener position by deep multitask learning. The methods mentioned above can locate the fastener, but they can only obtain the fastener region. For accurately obtaining precise position of fastener, these methods will fail. In literature [9], Peng et al. proposed a multi-feature hierarchical location algorithm to realize fastener accurate positioning. The method realizes fastener accurate positioning by locating the position of the circular gasket and the hexagon nut. However, in the actual railway, the characteristic stability of circular gasket and hexagon nut is poor and which leads to the low accuracy of fastener accurate positioning. Guo et al. designed a robot for automatic installation of rail fasteners [10]. It relies on distance measuring sensor to complete fastener coarse positioning and image processing method to realize accurate positioning. However, the proposed accurate positioning method is mainly aimed at the ideal environment of the laboratory and the robustness is poor.

In summary, the major problems in previous works are as follows:

1) Most of the existing literature mainly focuses on fastener region positioning and the literature on accurate positioning of fastener is scarce.

2) The only existing literature on accurate positioning of fastener has two critical shortcomings. The one is the
stability and robustness of the selected feature for fastener accurate positioning is poor. The other is experiments are performed in an ideal laboratory environment.

3) The only existing literature carried out experiments on a small railway fastener samples, which cannot effectively verify the performance of the positioning system.

To handle the shortcomings in the above literature, by referring to the visual inspection system mentioned in literature [11], [12], a visual inspection system for accurate positioning of fastener (VISP) is built in this paper. It has good positioning accuracy and robustness. The contributions of our works are as follows:

1) The binarization method combining global threshold and Niblack method (named GT-Niblack) is proposed for image binarization. Pseudo noise can be effectively removed and the spike region can be better separated by this method, which is benefit for the accurate extraction of spike region.

2) The weight allocation method is proposed for spike region extraction. Compared with the traditional circular Hough transform detection method, this method has better robustness to noise.

3) A railway image dataset is constructed, which includes fasteners in different conditions and is benefit for validating the performance of VISP effectively.

The rest of this paper is organized as follows: Sect. 2 describes the overview of VISP. The fastener region extraction is given in Sect. 3. Section 4 describes the image contrast enhancement and binarization. Section 5 describes the spike region extraction and fastener accurate positioning. Experiments and analysis are given in Sect. 6 in detail. Finally, our work is summarized in Sect. 7.

2. System Overview

VISP is made up of two parts: image acquisition subsystem (IAS) and image processing subsystem (IPS). The former is used for capturing railway images, and the latter is designed to locate the accurate position of fastener. As shown in Fig. 2.

IAS includes several components. Dalsa LA-GM line-scan camera is the core component, which has 2048 pixels resolution and maximum line rate can be reached 52000 lines/s. The two line light sources as illumination setup and used for reducing the influence of natural light. Moreover, the encoder is mounted on the wheel, which is used to trigger the camera to acquire the railway image.

After the railway images are captured by IAS, it is transmitted to the IPS through the Gigabit Network line. And then the IPS performs a series of processing on the railway image to complete fastener accurate positioning.

Since the precise position of fastener is same as the spike center, the accurate positioning of fastener can be realized by locating the spike center. Thus, in the following sections, our target is to extract the spike region and get its center position. Meanwhile, all fasteners including spike can be positioned by the VISP.

3. Fastener Region Extraction

Except the fastener region, the railway image captured by IAS also includes sleepers, rails and other irrelevant regions. These regions not only have a great impact on accurate positioning of fastener, but also increase the image processing loads. Therefore, the fastener region extraction is a necessary procedure for accurate positioning of fastener.

In this paper, we extract fastener region by coarse-to-fine method. At first, the coarse position of fastener can be determined by the position of sleeper and track. Then, the precise position can be obtained by template matching.

3.1 Coarse Positioning

In the obtained railway image, track is over-exposure due to the high reflection rate of the track head. So the brightness of the track region is obviously greater than other regions. According to the feature, we set a high threshold to binarize railway image and the maximum connected region in the processed image is the track region.

The sleeper positioning method consists of three steps.

1) Divide image into two parts using the located track.
2) Cut out a 100-pixel-wide subimage from each of the two parts.
(3) Binarize the two subimages and conduct “and” operate. The maximum connected region in the processed image can be recognized as sleeper.

3.2 Fine Positioning

In this paper, template matching is used for fine positioning and this process includes the following two steps.

(1) Calculating the orientation field of the template image and the coarse positioning image according to the formula (1).

\[
\theta = \frac{1}{2} \tan^{-1}\left(\frac{2 \sum I_x I_y}{\sum I_x^2 - \sum I_y^2}\right) + \frac{\pi}{2}
\]

where \( \theta \) is the direction estimation. \( I_x \) and \( I_y \) are the horizontal and vertical gradients of the pixel in the image. Generally, \( I_x \) and \( I_y \) can be calculated by Sobel gradient.

(2) Sliding the template image on the coarse positioning image and calculating the orientation field correlation according to the formula (2). The position with greatest correlation is the accurate position of fastener.

\[
R = \frac{\sum_{m,n} A_{m,n} B_{m,n}}{(\sum_{m,n} A_{m,n}^2)(\sum_{m,n} B_{m,n}^2)^{\frac{1}{2}}}
\]

where \( A_{m,n} \) and \( B_{m,n} \) are the orientation field of the pixel point \((m, n)\) in template image and coarse positioning image.

4. Contrast Enhancement and Binarization

4.1 Image Contrast Enhancement

Due to the change of ambient light, the railway images captured by IAS will appear uneven illumination. It will cause image contrast to become poor, and finally the positioning accuracy will become worse. Inspired by related technology of face recognition [13], in this paper, in order to eliminate the influence of uneven illumination and improve positioning accuracy of fastener, homomorphic filter (HF) is adopted to eliminate uneven illumination and enhance the contrast of fastener images.

HF is a method that simultaneously compresses the brightness range of image and enhances the contrast in the frequency domain. The process of image enhancement by HF is shown in Fig. 6. Specially, in this procedure, \( H(u, v) \) is constructed with the Gauss high pass filter \( H_{high}(u, v) \).

\[
H(u, v) = (H_H - H_L)H_{high}(u, v) + H_L
\]

where \( H_L < 1, H_H > 1, H_{high}(u, v) = 1 - e^{-D(u,v)/D_0^2} \). \( D(u,v) \) is the distance between the origin and the center of Fourier transformation, \( D_0 \) is the cutoff distance, and \( C \) is used to control the sharpness of slope between \( H_L \) and \( H_H \).

The images before and after enhancement are shown in Fig. 7 (a) and (b). It is clear that the latter becomes bright and contrast is enhanced, which will be benefit for the following binarization and the spike region extraction.

4.2 Image Binarization

According to the Fig. 3, binarization is an important step for accurate positioning of fastener. The binarization result has an important influence on whether the spike region can be accurately extracted. Finally, it will affect the accurate positioning of fastener. The commonly used binarization methods mainly include three types: global threshold method (such as OTSU [14]), local threshold method [15] (such as multi-threshold gradient intensity) and dynamic threshold method (such as Niblack [16], Bernsen [17]). Due to the background of fastener image is complicated, the binarization method with global threshold or local threshold is not suit for fastener images. Therefore, in this paper, we adopt dynamic threshold method to realize fastener image binarization.

Specially, here, Niblack method is adopted for fastener image binarization. However, this method is prone to pseudo-noise (that is, when the template region is background, some background may be recognized as the target
The process is described as follows:

Calculating the average gray value of all pixels to serve as the global threshold, and use it to weight the threshold obtained by Niblack method. Thus, we get the new binarization threshold. The formula is described as follows:

\[ TN(x, y) = d \cdot Ti + (1 - d) \cdot T(x, y) \]  

(4)

where \( Ti \) is global threshold, \( T(x, y) \) is the threshold corresponding to pixel \((x, y)\). \( d \) is the correction value between 0 and 1.

When the template region is background, the threshold calculated by Niblack method is less than global threshold. So the new threshold will be increased and avoids the problem of pseudo-noise.

5. Spike Region Extraction and Fastener Positioning

5.1 Spike Region Extraction

The smallest bounding rectangles containing the connected regions are shown in Fig. 9 (b). The horizontal and vertical directions represent the height and width of the connected regions, respectively. In ideal cases, spike region in the obtained fastener image should be a standard circle. We can extract spike region according to the formulas (5). The first and second formulas obtained according to the circle characteristics [18]. The third formula obtained according to the geometry relationship between spike region and the whole image, that is, the ratio of smallest rectangle containing spike region to whole image is a fixed value. In this paper, the size of fastener sub-image is \( 360 \times 200 \) and the diameter of spike region is about 92 pixels, thus, the ratio is 0.035. Meanwhile, the ideal value is invariant as long as the camera height and the image size remain unchanged.

\[
\begin{align*}
Y_1 &= \frac{L_{\text{width}}}{L_{\text{height}}} = 1 \\
Y_2 &= 4\pi \cdot \frac{S_{\text{area}}}{(P_{\text{area}})^2} = 1 \\
Y_3 &= \frac{L_{\text{width}} \cdot L_{\text{height}}}{(I_{\text{width}} \cdot I_{\text{height}})} = 0.035
\end{align*}
\]  

(5)

where \( L_{\text{width}} \) represents the width of the smallest rectangle and \( L_{\text{height}} \) represents the height, \( S_{\text{area}} \) represents the area of the connected region, \( P_{\text{area}} \) represents the perimeter of the connected region, \( I_{\text{width}} \) represents the width of the image and \( I_{\text{height}} \) represents the width.

However, in actual case, the spike region in the obtained fastener image cannot satisfy the ideal extraction formulas mentioned above. It will produce offset between the calculated values by above formulas and the ideal values (where the ideal values are 1, 1, and 0.035). Now we modified the above formulas to get the following formulas. Based on these formulas, we propose a weight allocation method to extract spike region.

\[
\begin{align*}
Y_1' &= \text{abs} \left( \frac{L_{\text{width}}}{L_{\text{height}}} - 1 \right) \\
Y_2' &= \text{abs} \left( 4\pi \cdot \frac{S_{\text{area}}}{(P_{\text{area}})^2} - 1 \right) \\
Y_3' &= \text{abs} \left( \frac{L_{\text{width}} \cdot L_{\text{height}}}{(I_{\text{width}} \cdot I_{\text{height}})} - 0.035 \right)
\end{align*}
\]  

(6)

For each connected region, we get the values of \( Y_1', Y_2', Y_3' \) by formula (6) and sort \( Y_1', Y_2', Y_3' \) in ascending order. Then allocating the maximum weight (where the maximum weight is the number of connected regions) to connected region corresponding to the least \( Y_1' \) and the weights of connected regions corresponding to other \( Y_1' \) values are decreasing progressively. The process of \( Y_2' \) and \( Y_3' \) are same as \( Y_1' \). Finally for each connected region, its sum of weights can be obtained and the maximum value corresponding to the connected region is target region. The formula is as follows.

\[
i^* = \text{Arg} \sup_{i=1,2,3-N} \left[ k_i \cdot Y_{i1} + k_i \cdot Y_{i2} + k_i \cdot Y_{i3} \right]
\]  

(7)

Where \( k_i \cdot Y_{i1}, k_i \cdot Y_{i2}, k_i \cdot Y_{i3} \) represent the weight, \( i = 1, 2, 3, N \) represents the connected region, \( i^* \) represents the index of the target region.

The result of spike region extraction by weight allocation method is shown in Fig. 9 (c). It can be clearly seen that all the irrelevant regions except for spike region have been removed.

5.2 Fastener Accurate Positioning

The spike region and its smallest outer rectangle can be obtained by Sect. 5-A. And then the attribute values of the smallest outer rectangle also can be obtained, including the pixel coordinate value lying upper left corner and
width of the two sides. They can be represented by array \([x_{\text{width}}, y_{\text{height}}, l_{\text{width}}, l_{\text{height}}]\). In that way, the spike center can be expressed as follows:

\[
\begin{align*}
X_{\text{width}} &= x_{\text{width}} + l_{\text{width}}/2 \\
Y_{\text{height}} &= x_{\text{height}} + l_{\text{height}}/2
\end{align*}
\]  

(8)

where \(x_{\text{width}}\) represents the coordinate value of the pixel which lies in upper left corner along the width direction, \(y_{\text{height}}\) represents the coordinate value of the pixel along the height direction, \(l_{\text{width}}\) represents the length of side along the width direction, \(l_{\text{height}}\) represents the length of side along the height direction.

Based on Sect. 2, the precise position of fastener is same as the spike center, so the accurate position of fastener is obtained. Thus, the fastener accurate positioning is completed. The result of positioning is shown in Fig. 10.

6. Experiments and Analysis

In this Section, we conducted a large number of experiments to show the performance of VISP. Firstly, we construct the experimental dataset and give the evaluation index of the positioning performance. Then a large number of experiments are conducted, including verification and comparative experiments. Finally, the real-time performance of VISP is analyzed.

6.1 Experimental Data

Since there is no public dataset for accurate positioning of fasteners at present, we collect railway images from real railway line (Changsha-Shimen section) and design a dataset used for the experiments in this paper. The dataset includes 2000 railway images and 4000 fastener subimages. Moreover, the dataset includes fasteners of different conditions (normal, stains and sundries). Thus, our dataset is rich and diverse. The size of all the railway images is 1600×1200 and fastener subimage is 360×200.

6.2 Evaluation Index

For the actual fastener, it is hard to know the ground-truth center. Therefore, we use manually labeled centers as standard. Here, the absolute error (AE) is used for evaluating whether fastener positioning is accurate [19]. It is defined as

\[
AE = |x_{\text{groundtruth}} - x_d|
\]

(9)

where \(x_d\) is the detected fastener center and \(x_{\text{groundtruth}}\) is the labeled center.

In practical engineering application, the positioning error required by the disassembly car is within 3mm. Thus, 3mm error is used as the criterion for judging whether the positioning is accurate. According to the proportional relationship of object imaging \(\frac{w}{d} = \frac{\delta}{3}\) (Here, \(d\) is the physical size of spike diameter, the value is 24mm. \(w\) is pixel width of the spike diameter, the value is 70 pixels in this paper. \(\delta\) is positioning error), we know that 3mm error corresponds to 8.75 pixels. Therefore, in the following experiment, fastener positioning is considered to be accurate as long as \(AE \leq 8\) pixels.

After determining the evaluation index of the accurate positioning of the fastener, the accuracy \(P\) is used to evaluate the fastener positioning performance. It is defined as follows:

\[
P = \frac{T}{N}
\]

(10)

where \(N\) is the total number of images, \(T\) is the number of images which are accurate positioning.

6.3 Validity Test

6.3.1 Test for Fastener Region Extraction

For this test, the ground truth is the bounding box of fastener in railway image. We set IoU to 0.8 and the extraction accuracy is used as the evaluating indicator of fastener region extraction method. We randomly choose 1000 railway images from the dataset to test the effect of fastener extraction. The accuracy can reach above 96%. The results are shown in Fig. 11.

Based on the Fig. 11 and the accuracy value, it can be concluded that the effect of fastener region extraction method is well. For the most of fasteners in different environments, they can be extracted by the method (coarse-to-fine method) in this paper.
6.3.2 Test for Accurate Positioning of Fastener

In this experiment, we test the accurate positioning performance of VISP. The test contains fasteners of different conditions (normal, stained and sundries). Each type has 800 images. All the test samples are from Sect. 6-A. The positioning results are shown in Fig. 12 and the results of positioning accuracy are summarized in Table 1.

As can be seen from Fig. 12 and Table 1, VISP has good performance for accurate positioning of fastener. For normal fasteners, the positioning accuracy can be achieved 99%. And for the other fasteners, the lowest accuracy is 84%. For the positioning failure fasteners, the reason is that there may be some stains or obstructions in the spike region, which result in the extracted spike region is incomplete. Finally, this causes the positioning center to deviate significantly from the labeled center so that fastener positioning failed.

Table 1 Positioning accuracy in complicated environment.

| Type      | Normal | Stains | Sundries |
|-----------|--------|--------|----------|
| P         | 0.99   | 0.84   | 0.91     |

6.4 Comparison with Other Related Works

Image binarization and spike region extraction are the core parts of VISP and the corresponding methods for each part are the main contributions in this paper. Therefore, in this section, we compare these methods with other related well-established approaches firstly. Then, the positioning method of this paper is compared with other positioning method in the literature to further highlight the performance of our proposed method.

6.4.1 Comparison of Binarization Methods

In order to further verify the effectiveness of the proposed binarization method, we compare our method (GT-Niblack) with other traditional binarization methods, including Kittler [20], Bernsen, Sauvola [21] and Bradley [22] methods. The test fastener samples are randomly selected from the dataset in Sect. 6-A. The number is 2000. The comparative results assessed by the positioning accuracy are shown in Table 2.

Table 2 Comparison of positioning accuracy for four binarization methods.

| Method   | Kittler | Bernsen | Bradley | Sauvola | GT-Niblack |
|----------|---------|---------|---------|---------|------------|
| P        | 0.16    | 0.37    | 0.46    | 0.88    | 0.9        |

Fig. 13 Comparative results of binarization. (a) Original image. (b) The results of binarization. (c) Positioning results with different binarization methods. From left to right is Kittler, Bernsen, Bradley, Sauvola and GT-Niblack.

Obviously, from the Table, we can see that our binarization method (GT-Niblack) outperforms other methods. In detail, our method is slightly better than Sauvola method. But for the Kittler, Bernsen, and Bradley methods, our method has obvious advantage. For this result can be explained from two aspects, the one is global threshold method has good segmentation effect for images with clear foreground and background. However, the background of the fastener image is cannot meet this condition. The other is local threshold methods will produce pseudo noise during image segmentation, which will have impact on spike region extraction. Finally, it will affect accurate positioning of fastener.

Figure 13 shows some visualized results, we can also see that the method of this paper performs better.

6.4.2 Comparison of Spike Region Extraction Methods

Spike region extraction is to detect the round spike. And Hough Transform (HT) [23] is just a typical method to detect circle. Therefore, in this experiment, we compare our method (weight allocation method) with HT use the same samples collected on Sect. 6-D-2). Meanwhile, the detection parameters of HT are set as follows: radius step is 2, angle step is 0.5, and detection radius is 20~30 pixels. The results assessed by the positioning accuracy are summarized in Table 3.

Based on the Table 3, it is concluded that weight allocation method is superior to the HT. HT relies on contour for object detection, and the contour is susceptible to noise. Es-
Table 3: Comparison of positioning accuracy for spike region extraction methods.

| Method          | P    | HT   | Weight allocation |
|-----------------|------|------|-------------------|
|                 | 0.76 | 0.9  |                   |

Table 4: Comparative results of our method and the method in literature.

| Method                  | Fastener type | Normal | Stains | Sundries |
|-------------------------|---------------|--------|--------|----------|
| Our method              | 0.99          | 0.84   | 0.91   |          |
| Method in literature [9]| 0.98          | 0.62   | 0.9    |          |

especially for the fastener image, the contour of spike is easily submerged in noise. Therefore, it is difficult to extract spike region by HT to complete fastener positioning. However, weight allocation method uses modified circular characteristic to extract spike region and it does not rely on spike contour. Therefore, weight allocation method is robust to noise and the detection accuracy is higher than HT. As a whole, the positioning accuracy is about 90% with weight allocation method, and it is lower than 80% with Hough Transform. Hence, the weight allocation method proposed in this paper is better.

6.4.3 Comparison with the Method in the Literature

In order to further highlight the performance of proposed positioning method in this paper, we compare our method with the method in the literature [9]. The experimental samples are same as the samples collected in Sect. 6-A. Table 4 shows the comparison results. For the normal and sundries fasteners, our method is slightly better than the method in the literature. But for the stains fasteners, our method has obvious advantage. The reason is that the features of circular gasket and hexagon nut of stained fasteners are basically disappeared, but the feature of spike still stable. Thus, our method has better effect to realize fastener positioning by locating spike.

6.5 Real-Time Analysis of VISP

We tested the real-time performance of the VISP. The experiment was carried on a laptop with an Intel(R) Core(TM) i5 CPU (3.2 GHz) and 4GB memory. The program was implemented with Visual C++ and OpenCV.

In practical engineering application, the disassembly car needs to be completed fastener positioning within 2s. However, in this paper, the VISP can complete accurate positioning of fastener within about 260ms, which is far less than the requirement of 2s. Thus, the VISP can meet the requirement of real-time.

7. Conclusion

In this paper, a visual inspection system is constructed for accurate positioning of railway fastener (VISP). It comprises of image acquisition subsystem (IAS) and image processing subsystem (IPS). To realize accurate positioning of fastener, we first present a coarse-to-fine method to extract the fastener sub-image. Then, the fastener image is processed by contrast enhancement, binarization and spike region extraction. Finally, the accurate position of fastener can be obtained according to the located center of spike region. Specially, GT-Niblack method is proposed for image binarization and the method can remove pseudo noise. Weight allocation method is proposed for spike region extraction and the method is robust to complicated environments. The experimental results demonstrate that VISP performs well for accurate positioning of fastener and the average positioning accuracy can be achieved 90%. Thus, it is with potential industrial application.

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Jianwei Liu is with the College of Electrical and Information Engineering, Hunan University, Changsha, China. He is a Ph.D. student with Hunan University. His research interests include machine vision, railway fastener inspection and signal processing.

Hongli Liu received the B.Sc. degree in electrical engineering and the Ph.D. degree in control theory and engineering from Hunan University, Changsha, China, in 1985 and 2000, respectively. He is currently a Professor with the College of Electrical and Information Engineering, Hunan University. His current research interests include intelligent information processing and transmission technology.

Xuefeng Ni is with the College of Electrical and Information Engineering, Hunan University, Changsha, China. He is a Ph.D. student with Hunan University. His research interests include machine vision, railway defect inspection and signal processing.

Ziji Ma received the B.Sc. degree in electronic information engineering from Hunan Normal University, Changsha, China, in 2001, and the Ph.D. degree in information science from the Nara Institute of Science and Technology, Nara, Japan, in 2012. He is currently an Associate Professor with the College of Electrical and Information Engineering, Hunan University. His research interests include machine vision, signal processing, and V2V communication. He is a member of IEICE.

Chao Wang received the B.Sc. degree in electronic information engineering from Hunan Normal University, Changsha, China, in 2008. He is currently an Assistant Professor with the University of South China, Hengyang, China. His research interests include machine vision, railway inspection and signal processing.

Xun Shao received the Ph.D. degree from Osaka University, Japan, in 2013. He was a Researcher with the National Institute of Information and Communications Technology, Japan, from 2013 to 2017. He is currently an Assistant Professor with the School of Regional Innovation and Social Design Engineering, Kitami Institute of Technology, Japan. His research interests include computer networks and distributed systems. He is a member of IEICE.