A NOVEL METHOD FOR 3D MEASUREMENT OF RFID MULTI-TAG NETWORK USING A MACHINE VISION SYSTEM

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Abstract

The three-dimensional (3D) coordinate measurement of radio frequency identification (RFID) multi-tag networks is one of the important issues in the field of RFID, which affects the reading performance of RFID multi-tag networks. In this paper, a novel method for 3D coordinate measurement of RFID multi-tag networks is proposed. A dual-CCD system (vertical and horizontal cameras) is used to obtain images of RFID multi-tag networks from different angles. The iterative threshold segmentation and the morphological filtering method are used to process the images. The template matching method is respectively used to determine the two-dimensional (2D) coordinate and the vertical coordinate of each tag. After that, the 3D coordinate of each tag is obtained. Finally, a back-propagation (BP) neural network is used to model the nonlinear relationship between the RFID multi-tag network and the corresponding reading distance. The BP neural network can predict the reading distances of unknown tag groups and find out the optimal distribution structure of the tag groups corresponding to the maximum reading distance. In the future work, the corresponding in-depth research on the neural network to adjust the distribution of tags will be done.

Keywords: 3D measurement, RFID multi-tag network, dual-CCD system, neural network, machine vision.
high-speed real-time technique for measuring 3D coordinates, based on fringe projection with consideration of the camera lens distortion [6]. Chen proposed a novel non-contact, full-field, 3D, multi-camera digital image correlation (DIC) measurement system [7]. Su presented an economic real-time system for tracking a fast moving object using adjacent inexpensive multiple web cameras [8]. Comparing with the use of a single camera for the 3D coordinate measurement, the time consumed using two cameras to achieve the target 3D coordinate measurement is less and the operation is simple. Besides that, comparing with using three and multiple cameras, using two cameras has been able to meet the 3D coordinate measurement requirements, and the measurement cost is low. So, two CCD cameras (vertical and horizontal ones) are used to measure the 3D coordinates of RFID tags.

RFID technology is a wireless communication technology, which has been widely used in many fields [9]. An important advantage of RFID technology is the simultaneous recognition of multiple targets. However, in order to achieve simultaneous recognition of multiple targets, it is necessary to face the problem of how to improve the performance of tag reading. Nowadays, the commonly used approach to improve the tag reading ability is to use an anti-collision algorithm to solve the data conflicts caused by multiple tags existing in the same radio frequency (RF) channel at the same time, such as ALOHA algorithm and the binary tree algorithm [10–12]. Although these algorithms solve the collision problem in the communication protocol layer, they could not deal with the impact of actual external interference on the air communication.

Some scholars have researched the optimization of RFID tag distribution. In the reference [13], Ni L.M. presented LANDMARC: a location sensing prototype system that uses RFID technology for locating objects inside buildings. The major advantage of LANDMARC is that it improves the overall accuracy of locating objects by utilizing the concept of reference tags. However, because of irregularity of the tags’ arrangement, the locating performance of LANDMARC has been affected. Zhao Y. proposed the VIRE approach to locate objects inside buildings in which the tags were set as a regular polygon [14]. A 2D localization system based on the phase-of-arrival evaluation of passive ultrahigh frequency (UHF) RFID transponders was presented and several tags were arranged to create a uniform linear array in order to handle the ambiguity caused by the phase evaluation [15]. Nevertheless, the tag signals interfered with each other due to the corresponding distribution. In [16], Yu calculated the extremum of azimuth matrix and obtained the optimal geometric distribution of tags in the Fisher matrix of evaluation. The work optimized the tags’ distribution to improve the reading performance of RFID system in theory. However, the research reported in [16] was only analysed in theory, not in a practical application. Based on the above research, the paper applies an image processing method to improve the acquisition efficiency of the 3D coordinates of RFID tags, which could provide the data support for the subsequent BP neural network analysis to optimize the tag distribution and improve the reading performance of RFID system in a practical application. Firstly, the horizontal and vertical cameras are used to obtain the images of RFID tags from different angles. Then, on the basis of image processing, the 3D coordinates of the tags are determined with a template matching method. Finally, a BP neural network is used to model the nonlinear relationship between the RFID multi-tag network and the corresponding reading distance. The BP neural network can predict the reading distances of unknown tag groups and find out the optimal distribution structure of the tag groups corresponding to the maximum reading distance. Compared with the corresponding system, the proposed system has three advantages. Firstly, the proposed system can prevent the electromagnetic interference in a dynamic environment, which could easily affect the direct measurement results obtained by antennas. Secondly, the image processing results can be combined with the subsequent BP neural network analysis to obtain the relationship between the node network of multi-tags and the reading performance of RFID system. Thirdly, the use
of two cameras improves the acquisition efficiency of the 3D coordinates of RFID tags, which provides the data support for the subsequent optimization of tag distribution. However, as the proposed system is still in the laboratory research stage, the system contains multiple modules and algorithms. Therefore, the system is complicated in the process of RFID tag 3D measurement. The real-time performance needs to be improved. The research on the real-time and system integration will follow in the future.

2. Design of measurement system

2.1. Design of illumination system

In order to better select a light source, we compare the main characteristics of several common light sources in Table 1. In view of the content of Table 1, we find that the LED light source performs better, featuring high design freedom, high wavelength selection, fast response, long service life and so on. So, the illumination system is designed using LED as the light source.

Table 1. Comparison of several common light sources.

<table>
<thead>
<tr>
<th>Serial no</th>
<th>Compare items</th>
<th>Energy-saving fluorescent light</th>
<th>High pressure sodium light</th>
<th>Metal halide light</th>
<th>LED light</th>
<th>Electrodeless light</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>lifetime/h</td>
<td>About 12000 h</td>
<td>About 20000 h</td>
<td>About 10000 h</td>
<td>About 50000 h</td>
<td>About 60000 h</td>
</tr>
<tr>
<td>2</td>
<td>The whole light effect /(lm/w)</td>
<td>90~100</td>
<td>100~120</td>
<td>85~100</td>
<td>100~110</td>
<td>90~100</td>
</tr>
<tr>
<td>3</td>
<td>Light failure /%</td>
<td>5%</td>
<td>10%</td>
<td>25%</td>
<td>3%</td>
<td>5%</td>
</tr>
<tr>
<td>4</td>
<td>Color rendering</td>
<td>&gt;80</td>
<td>20~25</td>
<td>60~65</td>
<td>&gt;80</td>
<td>&gt;80</td>
</tr>
<tr>
<td>5</td>
<td>Start the stabilization time</td>
<td>1~3 s</td>
<td>4~8 min</td>
<td>10~15 min</td>
<td>Instantaneous</td>
<td>Instantaneous</td>
</tr>
<tr>
<td>6</td>
<td>Restart time /min</td>
<td>Instantaneous</td>
<td>10~15</td>
<td>10~15</td>
<td>Instantaneous</td>
<td>Instantaneous</td>
</tr>
<tr>
<td>7</td>
<td>Color temperature (k)</td>
<td>3000~6000 (Optional)</td>
<td>About 2000</td>
<td>3000~4000 (Optional)</td>
<td>3500~7000 (Optional)</td>
<td>2700~6500 (Optional)</td>
</tr>
<tr>
<td>8</td>
<td>Strobe</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
</tbody>
</table>

The illumination system uses a broad spectrum of white light LEDs as a luminous material. The light source is a combination of two-LED array strip. When the LED array is installed on the mechanical platform of an electro-optical system, the LED array on each side is independently illuminated. The details of illumination system are as follows: type: T5E10, power: 12 W, beam angle: 120°, luminous flux: 1080 lm, colour temperature: 6000 K. The angle and power can be adjusted according to the target. The illumination system is shown in Fig. 1 and Fig. 2.
2.2. Design of measurement system

2.2.1. Construction of measurement platform

A schematic diagram of the dual-CCD semi-physical measurement platform is shown in Fig. 3, and its photo – in Fig. 4. The measurement platform consists of a reader, a reader antenna, an RFID tag, an RFID tag bracket, a control computer, a servomotor, a vertical camera, a horizontal camera, an illumination system, a guide rail and a turntable. The bottom of the RFID tag bracket is labelled. The RFID reader is connected to the reader antenna and the control computer. The vertical and horizontal cameras are connected to the control computer.

![Schematic diagram of the dual-CCD semi-physical measurement platform.](image)

The semi-physical test platform consists of an image acquisition system and a tag reading distance dynamic testing system. The theoretical range of operational distance is 0~10 m.

![Photo of the semi-physical platform for 3D measurement of RFID tags.](image)
However, after performing the measurement experiments indoors, the range of operating distance has been limited to 0–4 m. An RFID tag uses UHF RFID tags – H47. The size of CCD camera is 1288 × 964 pixels. The size of pixel is $3.75 \times 3.75 \, \mu \text{m}$. The CCD’s frame rate is 30 FPS. The readers use an Impinj Speedway Revolution R420 reader. The reader antenna uses a Laird A9028 far field antenna. The maximum RF output power of the reader antenna is 30 dBm.

2.2.2. Measurement process

The whole test platform is used for 3D coordinate measurement of RFID tags. The test flow is shown in Fig. 5. A number of brackets with RFID tags are placed on the turntable. The dynamic tag reading distance testing system is started to obtain the reading distance of tag distribution. The control computer controls the vertical and horizontal cameras to collect images of the turntable and tags. The obtained images are stored in the control computer. Then, the template matching method is used to obtain the 2D coordinate and vertical coordinate of each tag. Eventually, the 3D coordinate of each tag is obtained.

![Flowchart of RFID tag 3D measurement](image)

Fig. 5. A flowchart of RFID tag 3D measurement.

3. 3D coordinate measurement of RFID tags

3.1. Image matching

In order to measure 3D coordinates of RFID tags, an image matching method is needed. The template matching method is used to match the tag images with the template. Firstly, we select an image ($M \times N$ pixels) as the matching template. Secondly, in the target image, a matching point is determined, which is called the target point. With the target point as the centre, $M \times N$ pixel grey-scale arrays can be obtained from the $K \times L$ ($K > M$, $L > N$) pixel search area of the target image. All $M \times N$ pixel grey-scale arrays are sequentially taken out from the search area. The correlation coefficients of the grey-scale arrays and the template are calculated one by one.
When the correlation coefficient reaches a certain threshold (0.7), the search window area is determined as the matching region. When the correlation coefficient of the grey-scale array and the temple is bigger than 0.7, the matching is successful. Otherwise, the matching fails. A diagram of the template matching principle is shown in Fig. 6. Through the template matching, a matching region can be found in the image.

![Fig. 6. A diagram of the template matching principle.](image)

### 3.2. 2D coordinate measurement of RFID tag

In order to obtain 2D coordinates of RFID tags, the iterative threshold segmentation and the morphological filtering method are used to process the image. The iterative threshold segmentation is used to obtain the binary image of the turntable. The morphological filtering method is used to corrode and inflate the binary image to obtain the fill image of the turntable. The structural element used for corrosion and expansion is a disk with a radius of 11. The origin of the turntable is calculated, which is shown in Fig. 7 a–d. Then, a polar coordinate system is established with the direction of the horizontal camera as the polar axis in Fig. 7d.

![Fig. 7. The centre point location of the turntable and establishment of a polar coordinate system. A binary image of the iterative threshold segmentation (a); the result of the morphological filtering method (b); The centre point location of the turntable (c); schematic diagram of the polar coordinate system (d).](image)
The RFID tags are placed on the turntable. The mark point is pasted at the bottom of each tag. One of the mark points is selected as the mark point template. Each tag’s mark point is matched with the template. The matching results are shown in Fig. 8. Through the template matching, each tag’s position is recognized. The distance between each tag’s mark point and the centre of the turntable is denoted as $r$. The $i_{th}$ tag’s distance is recorded as $r_i$.

![Fig. 8. Matching results of bottom mark points of 7 tags.](image)

### 3.2.1. Horizontal camera controlling

Firstly, we use the control computer to adjust the horizontal camera so that it is positioned at the centre of the guide rail. It is adjusted so that it can clearly focus on the $i_{th}$ tag. It collects the image of the $i_{th}$ tag. The distance $d_i$ between the $i_{th}$ tag and the horizontal camera is calculated with (1):

$$d_i = L_1 - r_i,$$

where $L_1$ is the distance from the horizontal camera to the centre of the turntable. $r_i$ is the distance from the $i_{th}$ tag’s mark point to the centre of the turntable.

Afterwards, we calculate the object distance $l_i$, which is required by the horizontal camera for the $i_{th}$ RFID tag:

$$l_i = \frac{fl'}{l' - f},$$

where $l'$ is the distance between the lens and the CCD sensor inside the horizontal camera, $f$ is the focal length of the horizontal camera.

Finally, the distance $\Delta L_i$ needed to be adjusted for the horizontal camera is calculated with (3):

$$\Delta L_i = d_i - l_i.$$ 

If $\Delta L_i$ is larger than zero, the horizontal camera approaches the tag. Otherwise, the horizontal camera moves away from the tag.

### 3.2.2. 2D coordinate measurement of RFID tag

The control computer adjusts the servomotor to drive the turntable to rotate. The horizontal camera is adjusted so that it can clearly focus on the $i_{th}$ tag. The angle at which the $i_{th}$ tag turns is the polar angle $\theta_i$. The $\theta_i$ and the above $r_i$ are the $i_{th}$ RFID tag’s 2D coordinate parameters. The 2D coordinate of the $i_{th}$ RFID tag is further calculated as $(r_i \cos \theta_i, r_i \sin \theta_i)$. The above steps in Subsection 3.2 should be repeated to calculate each tag’s horizontal 2D coordinate.
3.3. Vertical coordinate measurement of RFID tag

After obtaining the 2D coordinates of RFID tags, one of the tags is selected as the template. The distance from the centre of the template to the turntable is calculated as the vertical coordinate of the template. The control computer controls the servomotor to drive the turntable to rotate. The horizontal camera is adjusted so that it can clearly focus on the template. The image of the template is collected in the control computer. The image cropping method is used to process the template image. The horizontal camera is adjusted to obtain clearly each tag’s image. The obtained images are sequentially taken out to match with the template image. The matching results of the first tag group are shown in Fig. 9.

![Fig. 9. The results of matching seven tags in the vertical direction. Tag 1 (a); Tag 2 (b); Tag 3 (c); Tag 4 (d); Tag 5 (e); Tag 6 (f); Tag 7 (g).](image)

After successful matching, the numbers of pixels between the centres of measured tags and the template are calculated. Because the size of each pixel in the CCD is known and the distance between the image plane and the horizontal camera is fixed, the size of each pixel in the image can be determined by the triangle similarity relation. According to the difference in the number of pixels in the vertical direction between a measured tag and the template, the relative
distance between the measured tag and the template in the vertical direction can be determined. A schematic diagram of the similarity relation is shown in Fig. 10:

![Fig. 10. A sketch map of the similarity relation.](image)

The relation of coordinates is given by the following equation:

$$H_i = h \pm c_i \times a,$$

where $H_i$ is the vertical coordinate of the $i_{th}$ tag, $h$ is the vertical coordinate of the template, $a$ is the length of the image pixel, $c_i$ is the number of pixels between the centre point of the $i_{th}$ RFID tag and the centre point of the template. When the centre point of the $i_{th}$ RFID tag is below the centre of the template, the (4) takes the “−” sign. When the centre point of the $i_{th}$ RFID tag is above the centre of the template, the (4) takes the “+” sign.

4. RFID multi-tag neural network

In order to obtain the optimal tag distribution network corresponding to the maximum reading distance, the mass distribution network and the corresponding reading distances must be tested. In order to quickly identify and optimize the network distribution structure of the tags in a practical application, it is necessary to establish a nonlinear relation model between the tag network distribution structure and the reading distance, i.e. a nonlinear relation model between the 3D coordinates of the tag groups and the corresponding reading distances. Considering the time consumption of different methods presented in Table 2, the paper just uses a simple BP neural network to model the nonlinear relationship between the 3D coordinates of the tag groups and the corresponding reading distances. The time consumed by the BP neural network analysis in this paper is only 10.31 s. The neural network is trained with 100 sets of data, and the trained network is used to predict the reading distances of 28 tag groups. The prediction error of BP neural network is defined as (5):

$$E = \frac{d_p - d_r}{d_r} \times 100\%.$$  (5)

The values of BP neural network prediction error are shown in Table 2 and Fig. 11.

<table>
<thead>
<tr>
<th>Methods</th>
<th>Average time consuming (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BP neural network</td>
<td>10.31</td>
</tr>
<tr>
<td>GA-BP neural network</td>
<td>216.59</td>
</tr>
<tr>
<td>PSO-BP neural network</td>
<td>229.67</td>
</tr>
</tbody>
</table>
It can be seen from the above results that the BP neural network can basically predict the reading distances of the tag groups. The maximum reading distance is 1.8751, and its corresponding optimal tag network distribution structure is shown in Fig. 12.

![Fig. 11. Error values of BP neural network prediction.](image1)

![Fig. 12. The optimal structure of RFID tag network.](image2)

It can be seen from Table 3, Fig. 11 and Fig. 12 that the BP neural network can effectively predict the reading distances of tag groups and find out the optimal distribution structure of tag groups corresponding to the maximum reading distance.

### Table 3. BP neural network prediction results of the reading distances in RFID systems.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>$x_1/m$</th>
<th>$y_1/m$</th>
<th>$z_1/m$</th>
<th>...</th>
<th>$x_7/m$</th>
<th>$y_7/m$</th>
<th>$z_7/m$</th>
<th>$d_r/m$</th>
<th>$d_p/m$</th>
<th>$E$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.2101</td>
<td>−0.0188</td>
<td>0.3019</td>
<td>...</td>
<td>0.2192</td>
<td>−0.2254</td>
<td>0.3801</td>
<td>2.00</td>
<td>1.8751</td>
<td>−3.35</td>
</tr>
<tr>
<td>2</td>
<td>0.1248</td>
<td>0.0367</td>
<td>0.3075</td>
<td>...</td>
<td>0.1072</td>
<td>−0.1944</td>
<td>0.3032</td>
<td>1.94</td>
<td>1.1688</td>
<td>−11.45</td>
</tr>
<tr>
<td>3</td>
<td>0.1653</td>
<td>0.1319</td>
<td>0.2555</td>
<td>...</td>
<td>0.0682</td>
<td>−0.1079</td>
<td>0.3070</td>
<td>1.32</td>
<td>1.1406</td>
<td>3.69</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>26</td>
<td>0.1682</td>
<td>0.0137</td>
<td>0.3161</td>
<td>...</td>
<td>0.0644</td>
<td>−0.1748</td>
<td>0.3102</td>
<td>1.11</td>
<td>1.0913</td>
<td>−17.95</td>
</tr>
<tr>
<td>27</td>
<td>0.0374</td>
<td>0.1467</td>
<td>0.3495</td>
<td>...</td>
<td>0.1674</td>
<td>−0.0121</td>
<td>0.3158</td>
<td>1.36</td>
<td>1.3553</td>
<td>3.46</td>
</tr>
<tr>
<td>28</td>
<td>0.1454</td>
<td>0.0359</td>
<td>0.3497</td>
<td>...</td>
<td>0.0712</td>
<td>−0.1514</td>
<td>0.3147</td>
<td>1.68</td>
<td>1.8014</td>
<td>24.24</td>
</tr>
</tbody>
</table>

### 5. Conclusion

In this paper, a 3D coordinate measurement system of RFID multi-tag network based on a dual-CCD system is designed, and the 3D coordinates of RFID multi-tag networks are measured by the image method. After that, a BP neural network is used to model the nonlinear relationship between the 3D coordinates of RFID tags and corresponding reading distances. The BP neural network can predict the reading distances of unknown tag groups and find out the optimal distribution structure of the tag groups corresponding to the maximum reading distance. The proposed system can prevent the electromagnetic interference in a dynamic environment and improve the acquisition efficiency of the 3D coordinates of RFID tags, which provides the data support for the subsequent analysis. The proposed method can be used to optimize the distribution of RFID multi-tag networks in a practical engineering application, which could improve
the reading performance of RFID multi-tag networks. The research results are valuable for engineering applications. However, as the proposed system is still in the laboratory research stage, the further study is needed to improve the real-time performance of the system. Meanwhile, the corresponding in-depth research on the neural network to adjust the distribution of tags is required.

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References


