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To cite this article: Kejing Li et al 2019 J. Phys.: Conf. Ser. 1237 022006

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A Correction Algorithm of QR Code on Cylindrical Surface

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Abstract. When capturing a QR code on a cylinder, there may be geometric distortions due to the angle of the camera and the cylindrical deformation, which makes the QR code difficult to recognize. To solve this problem, a correction algorithm for QR codes is proposed in this paper. First, the boundary of the QR code on the cylinder is extracted by a morphological algorithm and geometry calculations. Then, the feature points on the image are accurately located. Next, the standard size of the QR code is determined by using the cross-ratio method in descriptive geometry. Finally, the image is corrected by perspective projection. It is proven that the algorithm can correct the distortion of the cylinder image effectively, and it has the ability to properly identify cylindrical QR codes.

1. Introduction
The QR code, also known as a quick-response matrix code, is a kind of two-dimensional code.

A large amount of information can be stored in a QR code, which has the advantages of readability, high confidentiality, and strong anti-counterfeiting properties. The QR code uses 13-bit compression to represent Chinese characters, which is much more efficient than other two-dimensional codes. Therefore, QR codes have been used widely in transport packaging, product traceability, food security, and other applications.

With the popularization of two-dimensional code technology, it has become a research hotspot to locate and recognize QR codes effectively. There are many applications where the QR code is used, and when the code is in a complicated background, it is necessary to locate and extract useful information about the QR code. Especially when the QR code is on a non-planar surface, such as a curved surface, the captured QR code displays distortion. To achieve accurate recognition, the QR code needs to be corrected for distortion. In order to solve this problem, many methods have been proposed to locate and identify QR code images with deformation and on complex backgrounds. In [1], a black auxiliary rectangle is added to the outside of the QR code to locate and correct the QR code on the planar surface. This method can determine the position of the QR code, though its application may be limited greatly due to adding the auxiliary rectangle to the outside of QR code. Furthermore, it may fail to recognize a QR code in a complicated background. Reference [2] detects the external contour of the QR code using an algorithm that combines corner detection and convex hull. The outline of the QR code image is detected by judging whether a point is within the current convex hull. This method requires many calculations, and the precision of the algorithm is lower than other solutions. In [3], the contour of the QR code with cylindrical deformation is further calculated by determining the relevant parameters of the cylindrical equation.

This paper solves the problem of locating and correcting QR codes on a cylindrical surface. The algorithm locates six feature points of the QR code and obtain the transformation matrix of the
perspective projection. This algorithm can not only correct the general image distortion, but also correct QR codes with cylindrical distortion.

The arrangement of this paper is as follows. Section 2 introduces the locating algorithm for the QR code. In Section 3, a correction algorithm is proposed to eliminate the distortion. In Section 4, experiments are conducted to illustrate the performance of the algorithm.

2. Location of QR code

2.1. Boundary extraction

The QR code consists of a series of small black and white squares, with some small holes and gaps inside the image. The first step is to perform the morphological transformation of the image before extracting the boundary of the QR code image.

Dilation is used to fill small holes and narrow gulfs in objects. The morphological transformation dilation \( \oplus \) combines two sets using vector addition [4]. The dilation \( X \oplus B \) is the point set of all possible vector additions of pairs of elements, one from each of the sets \( X \) and \( B \).

\[
X \oplus B = \{ p \in \mathbb{R}^2, p = x + b, x \in X \text{ and } b \in B \}
\] (1)

Dilation is a transformation that increases the object size. If the original size needs to be preserved, then dilation is combined with erosion. Erosion \( \Theta \) combines two sets using vector subtraction of set elements and is the dual operator of dilation.

\[
X \Theta B = \{ p \in \mathbb{R}^2, p + b \in X, \forall b \in B \}
\] (2)

Figure 1 shows an image of a QR code projected on a cylinder, the closed operation of the image, and the result of boundary extraction, respectively, in (a), (b), and (c).

![QR Code Image](image1.png)

Figure 1 Boundary extraction

2.2. Feature-point extraction

Cylindrical distortion exists along the surface of the cylinder when an image is mapped on it. Moreover, because of the angle of camera, the captured QR image may be distorted severely, which may cause difficulties in recognition and decoding. Therefore, an appropriate algorithm should be found to obtain a recognizable QR image. To do this, the feature points of the QR code need to be located first.

Based on the boundary of the QR image obtained in Section 2.1, the feature points are detected. The Harris corner-detection algorithm is used to locate the feature points of boundary image of the QR code. Let \( T_i(x_i, y_i) \) \( (i = 1, 2, ..., m) \) indicate the coordinates of feature points; then, the distance between the feature points can be calculated by formula (3).

\[
L = \sum_{i=1}^{m} \sum_{j=1}^{m} \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}
\] (3)

The distances calculated by formula (3) are sorted from largest to smallest and the first two distances are used, for which the two pairs of points correspond the four corners (Q1, Q3, Q4, Q6), as shown in Figure 2.
Next, a straight line that passes through the midpoints of Q1, Q3 and Q2, Q4 are added and the Harris corner-detection algorithm is applied to detect the new image with straight lines and determine points Q2 and Q5 by the following formula, as shown in Figure 3.

\[
L \left\{ (x_i - x_{Q_i})^2 + (y_i - y_{Q_i})^2 \right\} = L \left\{ (x_i - x_{Q_s})^2 + (y_i - y_{Q_s})^2 \right\}
\]  

(4)

2.3. Determining the size of the QR code with cross ratio

The cross ratio is an invariant defined in descriptive geometry. The cross ratio of four points, A, B, C, and D, on a straight line is defined as follows:

\[
(ABCD) = \frac{AC \cdot BD}{AD \cdot BC}.
\]  

(5)

where AC denotes the distance from point A to point C. The cross ratio of points A', B', C', and D' is defined as (A'B'C'D') in exactly the same way. Figure 4 illustrates the QR code with deformation and cylindrical distortion. According to the theory of descriptive geometry, the cross ratio of four collinear points is invariant under projection transformation.

\[
(ABCD) = (A'B'C'D')
\]  

(6)

The method can first determine the coordinates of four points (A', B', C', and D') on the cylindrically distorted QR image. Assume that the corresponding points on the standard QR code are A, B, C, and D. According to the description of the invariant feature of the cross ratio in descriptive geometry [5], the cross ratio of the corresponding points is equal, and is defined as \( \lambda \). According to the standard QR code, the distances of AB and CD are always 7 modules long. Assume that the distance of BC is \( x \) modules long, so there are \( AB = BD = 7 + x \) and \( AD = 14 + x \). Thus, the formulation is:

\[
x = 7 \times \left( \sqrt{\frac{\lambda}{\lambda - 1}} - 1 \right).
\]  

(7)
There are a total of forty sizes of QR codes, where the smallest version is 1, which corresponds to a size of $21 \times 21$ modules. Each time the version number increases by 1, each side of the QR code increases by 4 modules. The version number of the QR code can be determined according to the following formula and further estimate the size of the QR code.

\begin{equation}
    v = \text{round} \left( \frac{x-3}{4} \right) \tag{8}
\end{equation}
\begin{equation}
    s = 17 + 4 \cdot v \tag{9}
\end{equation}

3. Correction algorithm of QR code

In this section, it introduces the algorithm to correct cylindrical deformation and tilting deformation. In this paper, the transformation matrix of perspective projection is obtained via the matching feature-point pairs. By applying the matrix to the QR code image, the image correction is completed.

The coordinates of $Q_i$ represent the features points of distorted image, as $(u_i, v_i)$. The coordinates of $P_i$ are the points on the image plane, as $(X, Y, Z)$. According to perspective projection, there is \cite{6}

\begin{equation}
    k \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}, \tag{10}
\end{equation}

where $(X, Y, Z)$ represent the position in the global Euclidean coordinate system, $k$ denotes a scale factor, and $m_{11}$ to $m_{34}$ are the components of the projection matrix, denoted as $M$.

Equation (10) can be simplified as

\begin{equation}
    \begin{bmatrix} x_1 & y_1 & z_1 & 1 & 0 & 0 & 0 & 0 & -x_1u_1 & -y_1u_1 & -z_1u_1 \\ ... & ... & ... & ... & ... & ... & ... & ... & ... & ... & ... \\ ... & ... & ... & ... & ... & ... & ... & ... & ... & ... & ... \\ ... & ... & ... & ... & ... & ... & ... & ... & ... & ... & ... \\ ... & ... & ... & ... & ... & ... & ... & ... & ... & ... & ... \\ x_6 & y_6 & z_6 & 1 & 0 & 0 & 0 & 0 & -x_6u_6 & -y_6u_6 & -z_6u_6 \\ 0 & 0 & 0 & 0 & x_1 & y_1 & z_1 & 1 & -x_1v_1 & -y_1v_1 & -z_1v_1 \\ ... & ... & ... & ... & ... & ... & ... & ... & ... & ... & ... \\ ... & ... & ... & ... & ... & ... & ... & ... & ... & ... & ... \\ ... & ... & ... & ... & ... & ... & ... & ... & ... & ... & ... \\ 0 & 0 & 0 & 0 & x_5 & y_5 & z_5 & 1 & -x_5v_5 & -y_5v_5 & -z_5v_5 \end{bmatrix} \begin{bmatrix} m_{11} \\ m_{12} \\ m_{13} \\ m_{14} \\ m_{21} \\ m_{22} \\ m_{23} \\ m_{24} \\ m_{31} \\ m_{32} \\ m_{33} \\ m_{34} \end{bmatrix} = \begin{bmatrix} u_1 \\ ... \\ ... \\ ... \\ u_6 \\ v_1 \\ ... \\ ... \\ v_5 \end{bmatrix}. \tag{11}
\end{equation}

The coordinates of the six feature points and the size of standard QR image have been calculated. The process of perspective projection is shown in Figure 5.
In equation (12), \( D \) is the diameter of the cylinder, \( m \) is the difference in distance along the direction of depth on the cylindrical surface, and \( W \) is the width of the cylinder image.

\[
m = D/2 - \sqrt{(D/2)^2 - (W/2)^2}
\]  

(12)

The coordinate of the cylindrical QR code with respect to the Z direction represents the depth information, then Q1, Q3, Q4, and Q6 are on the same plane. If the distance along the Z direction is \( c \), the distance of Q2 and Q5 along the Z direction is \( c-m \). There are some correspondences.

\[
\begin{align*}
Q1\rightarrow P1 & : (X1,Y1,c)\rightarrow(0,0) \\
Q3\rightarrow P3 & : (X1,Y1,c)\rightarrow(0,s) \\
Q5\rightarrow P5 & : (X1,Y1,c-m)\rightarrow(s,s/2) \\
Q2\rightarrow P2 & : (X2,Y2,c-m)\rightarrow(0,s/2) \\
Q4\rightarrow P4 & : (X1,Y1,c)\rightarrow(s,s) \\
Q6\rightarrow P6 & : (X1,Y1,c)\rightarrow(s,0)
\end{align*}
\]  

(13)

4. Experimental results

The algorithm proposed in this paper can correct the cylindrical distortion and tilting deformation of the QR code, which can meet the requirements of recognition accuracy. Table 1 is the correction result for the QR code of cylindrical distortion of different degrees, where \( D \) is the diameter of the cylinder and \( W \) is the width of the standard QR code on the cylinder.

| Num | Distorted QR codes | Recognizable | Correction | Recognizable |
|-----|-------------------|--------------|------------|--------------|
| 1   | D=1.6*width       | No           | ![Corrected QR](#) | Yes          |
| 2   | D=1.8*width       | No           | ![Corrected QR](#) | Yes          |
| 3   | D=1.84*width      | No           | ![Corrected QR](#) | Yes          |
| 4   | D=1.88*width      | No           | ![Corrected QR](#) | Yes          |
5. Conclusion
A method to correct the distortion of the QR code image with cylindrical and tilting deformations is proposed. The algorithm realizes the correction for multiple distortions. The experimental results show that our method has a high recognition accuracy for QR codes with cylindrical distortion.

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