Measurement of the Cable-End's Three-Dimensional Position and Orientation based on Stereo Vision

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The automatic handling of flexible belt objects is crucial for high speed and high precision of operation process. The measurement of belt object's position and orientation is important for the implementation of automatic manipulation. In this paper, the method to measure the flexible cable-end's position and orientation based on stereo vision is proposed. First, the method to calculate the cable-end's three-dimensional (3D) position based on image processing is explained. Next, the cable-end's orientation calculation method is described by referring the unit vectors attached to cable-end. Finally, the experiments were carried out to show the precision and accuracy of the proposed method. The results verified that the cable-end's position and orientation are measured precisely using the proposed method.

***Key Words*:** Image processing, stereo vision, flexible cable

1. Introduction

Recently, the application of industrial robots in many industries gives advantages in low cost product and high speed operation [1], [2]. Moreover, the usage of automatic industrial robots also gives advantage in high precision of operation which produces good quality products. However, the deformable objects such as cloth, flexible cables, papers and others are hard to be handled by robots due to its inconstant shape body. As a result, the deformable objects are often handled manually. Recently, research on deformable objects such as flexible belt objects [2], flexible wire [3], etc. actively performed toward their manipulation.

Manual handling of deformable objects gives disadvantages in low speed and low accuracy of production as well as high cost of production. In order to solve the problem, the automatic handling of deformable objects is required. Consequently, the final goal of this research is to develop the automatic manipulation of flexible cable in 3D space. To achieve the goal, the method to measure the flexible cable-end's position and orientation in 3D is proposed in this paper. The size of the cable is 150mm×15mm×0.1mm. A robot hand is used to handle the cable, while the stereo camera is employed to capture the images of the cable. The application of stereo camera gives benefits in measuring the cable-end's position in 3D accurately [4].

In the previous research [1], the simulation and measurement of flexible cable by using high speed camera was carried out. Unfortunately, the research conducted was in 2D, while the flexible cable actually deforms its shape in 3D. Therefore, the measurement of flexible cable in 3D is highly essential to improve the accuracy of measurement and increase the handling dimensions of flexible cable.

The rest of this paper is organized as follows. Section II explains the method of measurement of cable-end's position and orientation in 3D. The experiments and results to show the precision and accuracy of the proposed method are explained in section III. Finally, the conclusion and future work are given in section IV.

2. Measurement of Cable-end's Position and Orientation in 3D

2.1 Camera calibration and stereo image rectification process

Camera calibration is the process to calculate the internal and external parameters. In this research, internal parameters included camera focal length for *x* and *y*-axes, original point of normalized image coordinate system and lens distortion parameters. On the other hand, the external parameters are rotation matrix and parallel translation from camera coordinate system to robot base coordinate system.

In order to perform the stereo camera calibration, the calibration board provided by 3D Media Company as shown in Fig. 1 is used. Firstly, the board is assembled to robot hand. Then, the hand is moved to 30 different points and for every point, the images of calibration board is captured. Besides, the position and orientation of robot's flange surface are recorded. Finally, the camera parameters are calculated by using image processing. Moreover, the 3D Media Company's programming library which is called TVL (3D Media Vision Library), is installed in the programming environment.

Fig. 1 Calibration board

The stereo image rectification process is where the radial and tangential lens distortion is removed. Furthermore, the rectification process also includes the adjustment of angles and distances between images, giving the output of the process is row-aligned and rectified images as shown in Fig. 2 below. The original point of the coordinate system *O* is at the center of left image projection. Furthermore, the focal lengths for both cameras are the same, and the lens has no distortion. Besides, epipolar lines for both left and right images are horizontal. The corresponding points for left image (u_l, v_l) and right image (u_r, v_r) have the same value of vertical axis $v_l = v_r$. The rectification process was carried out by using the calculated results of internal parameters in image processing.

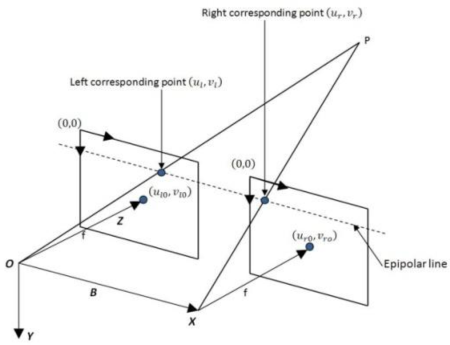


Fig. 2 Rectified stereo camera coordinate system

2.2 Calculation of cable-end's position in 2D

After image rectification process, the cable-end's detection in 2D is carried out for both left and right images. In this section, the method applied in image processing to calculate the cable-end's position in 2D is discussed. We applied OpenCV library to implement the calculation process. The input image of the cable is shown in Fig. 3.

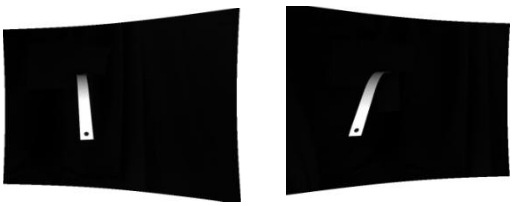
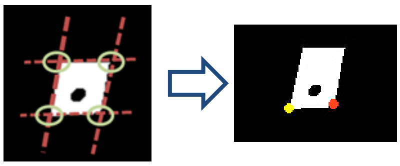


Fig. 3 Left and right input cable images

Firstly, the detection range is set on the image. Then, the maximal area extraction process is carried out in the detection range to remove the noise and display only the cable's shape on the image. In details, the connected pixels on the image are labeled as one region and the number of pixels in each region is measured. Only the shape of region with the largest number of pixels is displayed on the image.

The next step is to measure the mark's center point. In order to achieve the goal, the contour finding process is done. Contour finding process is a process to find the edge pixels that separate different segments in an image. Furthermore, we applied the mode which is called CV_RETR_TREE for contour finding process in OpenCV library. It can retrieve both the outer shape of the cable's contours and the contour of the mark's shape. Basing on the mark's contour, the center point of the mark can be found by moment calculation formula. After that, based on mark's center point, 30×30[pixel] of detection range is set.

The image processing is continued by measuring the position of cable-end in the detection range. In this process, the Hough transform method is applied to find the lines at the cable–end. In Fig. 4 (a), the red-dashed lines represent the detected lines on the image. Next, the intersection points as shown by the green circles, are found from the detected lines. Finally, the lowest 2 points were selected as cable-end's points. The result is shown in Fig. 4 (b).



(a) (b)

Fig. 4 Measurement of cable-end

2.3 Measurement of cable-end's position and orientation in 3D

After acquiring the mark's center point and cable-end's position in 2D, the position is converted to 3D in image processing by employing 3D Media Company library (TVL) in the programming environment. Based on rectified stereo camera coordinate system shown in Fig. 2, the depth value *Z* can be derived as Eq. (1)

$$Z = \frac{Bf}{d}\ , \qquad (1)$$

where, disparity *d* is defined by the difference of the corresponding points' horizontal position $d = u_l - u_r$. Baseline *B* is the distance in (mm) between the centers of projection. Next, the position of the cable-end's position in

3D can be derived as below:

$$\left(\frac{u_l - u_0}{d}B,\ \frac{v_l - v_0}{d}B,\ Z\right) \tag{2}$$

Let $O - xyz$ be a robot base coordinate system and $C - \xi\eta\zeta$ be another coordinate system attached to cable-end. A, B and C is the unit vectors along ξ, η and ζ respectively. The A, B and C vectors can be described by the base coordinate system as

$$A = \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix},\ B = \begin{bmatrix} b_x \\ b_y \\ b_z \end{bmatrix},\ C = \begin{bmatrix} c_x \\ c_y \\ c_z \end{bmatrix}. \tag{3}$$

The rotation matrix R which presenting the cable-end's orientation can be determined by specifying these three vectors as shown in Eq. 4. Fig. 5 shows the cable-end's coordinate system.

$$R = [A \quad B \quad C] \tag{4}$$

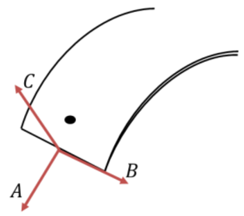


Fig. 5 *A*, *B* and *C* unit vectors on the cable-end

Given the unit vector $u = [u_x \quad u_y \quad u_z]^T$ be the axis of rotation and α refers to angle of rotation for u. Moreover, the quaternion parameters q_0, q_1, q_2 and q_3 can be derived from rotation matrix R as

$$q_0 = \pm\frac{1}{2}\sqrt{a_x + b_y + c_z + 1} \tag{5}$$

and

$$\begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix} = \frac{1}{4q_0}\begin{bmatrix} b_z - c_y \\ c_x - a_z \\ a_y - b_x \end{bmatrix}. \tag{6}$$

In addition, rotation axis u and rotation angle α can be computed as shown in Eq. 7 and 8.

$$\alpha = sin^{-1}\left(\sqrt{q_1^2 + q_2^2 + q_3^2}\right) \times 2 \tag{7}$$

$$\begin{bmatrix} u_x \\ u_y \\ u_z \end{bmatrix} = \frac{1}{\sin\left(\frac{\alpha}{2}\right)}\begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix} \tag{8}$$

3. Experimental Validation

3.1 Translation movement experiment

The objective of the experiment is to verify the accuracy of the proposed method by calculating the translation distance of the cable. In this experiment, the static condition of the cable is moved by robot hand in translation movement to different point of locations.

3.1.1 Experimental method

1. The cable is set to board. Then, the board is assembled to robot hand.
2. Firstly, the robot hand is moved to point 1. Next, according to robot base coordinate system, the cable is moved 100 mm in *x*-axis and the point is defined as point 2. The frame image of the moving cable from point 1 to point 2 is captured by stereo camera.
3. After that, according to robot base coordinate system, the cable is moved 100 mm in *z*-axis from point 2 and the terminal point is defined as point 3. The frame image of the moving cable from point 2 to point 3 is captured by stereo camera.
4. Next, according to robot base coordinate system, the cable is moved 100 mm in *y*-axis from point 2 and the point is defined as point 4. The frame image of the moving cable from point 2 to point 4 is captured by stereo camera.
5. The cable-end's position in each frame image is calculated as explained in section 2. Then, the translation distance between the initial frame image and the last frame image for each movement is computed.
6. Step 2 to 5 is repeated for 3 times and the average value is taken.

3.2 Rotation movement experiment

The objective of the experiment is to calculate the orientation of the cable-end by implementing the proposed method. In this experiment, the static condition of the cable is rotated by robot hand from the first position of cable-end coordinate system. Then, the rotation axis and rotation angle for each rotation movement is computed.

3.2.1 Experimental method

1. The cable is set to board. Then, the board is assembled to robot hand. Firstly, the cable is moved to the first position of cable-end coordinate system, which is defined as point 2. Next, from point 2, the cable is rotated around ζ-axis for 45 degrees in counter clockwise direction and the terminal point is defined as point 5. The frame image of the moving cable from point 2 to point 5 is captured by stereo camera.
2. Afterward, from point 2, the cable is rotated around ξ-axis for 45 degrees in clockwise direction and the terminal point is defined as point 6. The frame image of the moving cable from point 2 to point 6 is captured by

stereo camera.

3. Next, from point 2, the cable is rotated around η-axis for 45 degrees in clockwise direction and the terminal point is defined as point 7. The frame image of the moving cable from point 2 to point 7 is captured by stereo camera.
4. The cable-end's position in each frame image is calculated. Then, the cable-end's orientation is computed based on first position of cable-end's coordinate system. The rotation axis and angle between initial frame image and last frame image are determined.
5. Step 2 to 4 is repeated for 3 times and the average value is taken.

3.3 Results and analysis

The experiment results of translation movement experiment are given in Table 1. The result shows the average value of translation distance for mark's center point and cable-end points. Furthermore, the rotation movement experiment result is presented in Table 2 where term CCW stands for counter clockwise.

Table 1 Translation movement experiment result

	Average translation distance result [mm]			Error [mm]		
	X	***Y***	***Z***	***X***	***Y***	***Z***
+100mm in *x*-axis	100.01	0.19	0.14	0.01	0.19	0.14
+100mm in *z*-axis	0.04	0.34	99.98	0.04	0.34	0.02
+100mm in *y*-axis	0.05	100.46	0.05	0.05	0.46	0.05

Table 2 Rotation movement experiment result

	Error			
	Rotation angle	Rotation axis		
	α (degree)	u_ξ	u_η	u_ζ
Rotation around ζ-axis 45° CCW	1.060	0.013	0.007	0.000
Rotation around ξ-axis 45° CCW	0.669	0.002	0.053	0.039
Rotation around η-axis 45° CCW	0.916	0.031	0.002	0.047

Based on the results from Table 1, the errors in *x*, *y* and *z*-axis for every translation movement are very small which is below 0.5 mm. These results proved that the translation values are calculated precisely by using the proposed method. However, from each frame image for all movements, the average cable-end's recognition success rate is unlimited which is 90.2%. The reason is that there are conditions when more than 4 lines are detected causing the incorrect cable-end's positions were detected. As the conclusion, the accuracy of the measurement is high but the recognition success rate is limited.

Based on the results from Table 2, the rotation angle errors occurred in all rotation movement are small. This indicates that the rotation angles are calculated accurately by using the method. Moreover, the rotation axis errors for all movements are small which is below 0.1. This proves that the cable is rotated properly around ξ, η and ζ-axes.

4. Conclusions and Future Works

In this paper, we proposed a method of measurement of cable-end's position and orientation in 3D. The stereo camera calibration is essential to obtain camera parameters that will be used in rectification process and 3D position calculation. After rectification process, the cable-end's position is measured. Then, the cable-end's orientation is determined based on unit vectors attached to cable-end. In order to examine the precision of the cable-end's position measurement, the translation movement experiment was carried out. The results proved that the translation distance was calculated precisely and therefore the cable-end's position was measured accurately. However, the average cable-end's recognition success rate was a little limited. Next, the rotation movement experiment was conducted to examine the precision of cable-end's orientation measurement. The results verified the orientation was computed precisely as the errors of rotation axis and angle were small.

In the future the measurement of cable-end's position and orientation in real-time will be performed. Moreover, the flexible cable's automatic handling will be implemented.

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