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Coordinate Calibration and Automatic Punch Design of Flexible Printed Circuit

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Abstract

This project is aimed to study and manufacture a novel auto-checking and punch system of FPC, which is based on computer vision, image processing and automatic control technique. The system realizes the auto-punching process by a serial of workflow, including catching material, taking photos, punching, dropping material and home moving. Coordinate calibration is the core of automatic punch system which accurately calculates the motor pluses by pre-calibrating system hardware coefficient and error, properly selecting reference coordinate system, real-time calculating location of reference point and twice image skew correction based on radon transform. Experiments show it satisfies the required precision standard of system.

Keywords: *Flexible Printed Circuit, Automatic Punch, Radon Transform, Twice Skew Correction, Coordinate Calibration*

1. Introduction

As a flexible printed circuit made of flexible insulation base material, flexible printed circuit[1,2] has some advantages which are superior to hard printed circuit board. As it is easy to bend, wind and fold and it can be arbitrarily arranged in accordance with the requirements for spatial distribution. Besides, it can be removed and stretched in three-dimensional space at will for integration for component assembly and conductor jointing. As the flexible printed circuit is ductile, it is easy to bend, wind or have other defects in the processing process due to factors such as static electricity and air pressure etc. As a result, flexible printed circuit is hard to process and many processes must be done manually as the automation level in the industry is low. With the development of technology, recently automation production has been gradually applied in some of the processes[3-6], such as welding and electroplating etc. A good many processes, however, must be done manually.

As one of the crucial processes in flexible printed circuit production, punching is adopted in correction alignment in later stage. The punching process for the current flexible printed circuit can only be done manually by experienced workers for artificial alignment and punching one by one. There might be dozens of holes to be punched. Therefore the work efficiency is low. There exist serious defects: the first one is low efficiency; the second one is high labor cost.

As the price of labor power is constantly rising, the traditional mode of production will lead to rising cost. Therefore, it is urgent to develop a new automation technology to replace the existing manual operation. Currently, there is only little research on flexible printed circuit automatic punching machine and only few enterprises put forward some specific solutions and introduce computer vision to correct the punching intervals. Nevertheless, this system is simple and the relative position can be corrected by a photo shot to recognize the reference point, considering the relative error rather than of the materials. As a result, the location deviation is great so that punching efficiency is reduced.

The main contribution of this paper lies in that a solution to the flexible printed circuit system is proposed based on the platform of machinery and hardware. Manual punching process is simulated for automatic punching for the flexible circuit; source of error in the flexible circuit punching flow is analyzed in detail to further analyze the effective correction method, which involves reasonable selection for the coordinate system, correction derivation and final error evaluation. The correction mode of linear photo is proposed to effectively acquire the conversion relationship between the material coordinate system and the reference coordinate system through effective identification for the reference points and second order correction for the angle of inclination.

As for coordinate correction problem, this project focuses on the following crucial problems: 1) system parameters and source of error evaluation; 2) reference coordination selection;3) pulse calculation;4) error evaluation; 5) Real-time reference point calculation and evaluation for angle of inclination.

2. Punching machine system design

Viewed from machinery and hardware, the system mainly includes stamping punch, industrial camera, material gripper, X axis motor and Y axis motor (stepping motor or servomotor), motion control card, console (computer) and work platform etc.

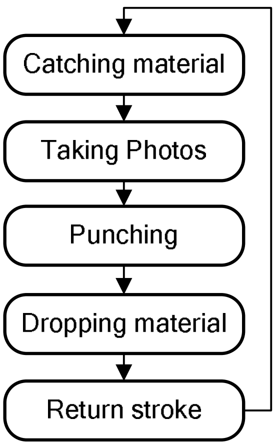


Fig. 1 working process for automatic punching

In order to achieve automatic punching, the system simulates the principle for manual punching (aligning-punching), the following working process (Fig.1) is designed in accordance with feature of coordinate correction for machine vision:

2.1 Catching material

Mechanical finger is used to catch flexible material. Mechanical motion of material on the whole platform is controlled till material dropping is finished.

2.2 Taking photos

As the material to be punched might not be neatly piles or the machinery finger makes the material not neat enough, with some microdeformation. Furthermore, the positions for grabbing material might vary for each time. Because the deviation between materials coordinates system and camera coordinate system shall be worked out. And the deviations mainly include reference point position deviation and overall angle deviation.

2.3 Punching

Number of pulses on points to be punched can be worked out in accordance with the results of photos and the coordinate deviation between points to be punched and the reference points, mechanical constants such as K value efficient of the motor etc. Then control X motor and Y motor to the specific pulse positions. Start up the command of punching machine to finish punching.

2.4 Dropping material

Move the material to the dropping point and drop the material.

2.5 Return stroke

The motor returns to the material drooping point for the next cycle.

3. System hardware design diagram

In accordance with the principle and flow for automatic punching, the following system structure scheme is design as shown in Fig.2. Windows console is adopted as the system console which includes the main hardware equipments. And they are classified into image collection, warning, motor control, mechanical finger and stamping punch in accordance with functional modes. Controlling motors include motors required for controlling horizontal X direction and Y direction. The mechanical finger includes control switches for the cylinder and vacuum valve. The stamping punching machine works in a semi-automatic trigger mode. The communication between the main modules is controlled by motion control card, including command sending and feedback query.

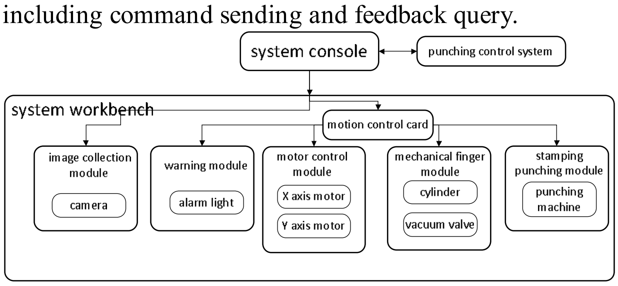


Fig. 2 System structure diagram

4. Coordinate calibration

4.1 Error analysis

There are many hardware equipments in the whole system. Errors, therefore, are inevitably introduced, including the error of the mechanical equipments themselves and material deviation.

Viewed from the mechanical equipments, main errors introduced include the following:

1) The X axis and Y axis of the motor might not be completely perpendicular, which will cause angular error;

2) The motor motion might step out. For example, sudden stop or torsional moment exceeds the rated moment.

3) Driven by flexible devices such as belt, the K value of the motor might slightly fluctuate.

In view of material, displacement easily occurs to reference point position as the materials (flexible printed circuit) is not neatly piled and the angle of material is not completely parallel to the coordinate axis. During the movement, it is easy to bent or wind.

Besides, the angle and position of camera will also cause errors. For example, there exists some difference between the coordinate axis of the camera and that of the motor. There might also be some elevation angle or depression angle in direction of Z axis of the vertical workbench. Meanwhile, weather the workbench is flat and neat or not will also influence the motion trail of materials.

Due to the above mentioned limitations, there might be some deviation in punching calculation. The allowable deviation for pneumatic punching machine is small and only small range punching correction is allowed. Therefore, relevant parameters must be calculated to reasonably make up the system hardware errors.
As errors are inevitable during the machining process, punching control for the punching machine will bring errors, which will cause punching failures. The calibration for mechanical devices is of vital importance. The calibration is mainly for camera angle, material placement angle and X axis finger angle. Besides, errors caused by mechanical system shall also be considered. Whether the selection for reference coordinate system is reasonable or not will directly influence the difficulty in calibrating main parameters. The calibration process for automatic punching will be illustrated in detail in the following on aspect of selection for coordinate system, parameters correction, pulse calculation and allowable error etc.

4.2 Selection for coordinate system

During the whole process for circuit punching, there are three coordinate systems, material coordinate system, camera coordinate system and workbench coordinate system. As what is shown in Fig.3, the camera and punching machine are fixed in the workbench; the flexible board is placed on the material table. Among the three coordinate systems, the material coordinates system cannot be used as the reference coordinate system as materials will move together with the mechanical finger; while the camera and workbench coordinates can be used as reference coordinates as they are relatively fixed.

Considering the relative deviation among mechanical equipments, it is hard to make X axis and Y axis of the motor absolutely vertical. Therefore, it is reasonable to adopt the camera coordinate system as the reference coordinate system. With the shooting center as the origin of coordinates, the width direction of the image is X axis and the height direction of the image is Y axis. Of course, other virtual reference coordinate system can also be selected for the whole system, but it will make the coordinate transformation in this system more complicated.

With the position of camera as the reference system, the coordinate origin of X axis motor and Y axis motor does not coincide with the camera origin. And they are not completely parallel to X axis and Y axis. As for the punching machine, though it is not within the view distance, it is in a specific position in the camera coordinate system. Though the materials keep moving, the deviation angle remains the same.

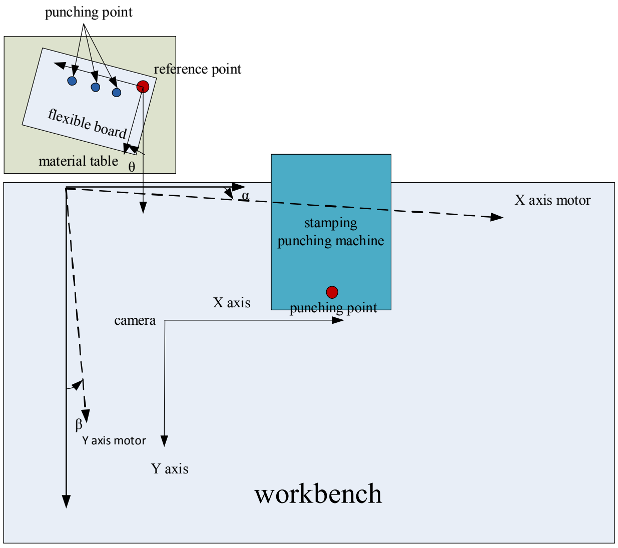


Fig.3 Schematic diagram for the workbench of the punching machine

4.3 Parameters correction

Various parameters in the system will directly influence the accuracy of coordinate correction calculation, such as motor deviation, position of punching point and material deviation. In order to acquire the reasonable position, key parameters must be pre-corrected.

Angle parameter α:
It is motor X axis correction and the angle of image X axis. Method of correction: put the correction point of the material in the camera vision and then move the X axis. Check the positions variation track for the images in the two collections and the angle of X axis of camera.

Angle parameter β:
Acquire the angle of Y axis in reference coordinate system. Method of correction: put the correction point of the material in the camera vision and then move the Y axis. Check the positions variation track for the images in the two collections and the angle of Y axis of camera.

Coordinate scale factor:

The scale factor of image field and spatial domain k_1**:** Camera coordinate is measured by pixel dimension while the equipment of material is measured by actual distance such as standard unit mm. Unit conversion is required in the calculation process. Method of correction: place a ruler in the photos and observe the distance of the ruler and pixel scale($k_1 = N/M$, where, N is the length of the tape (unit：mm)，M is the length of pixel (unit：pixels)).

The scale factor of pulses and spatial domain k_2:
Conversion relationship between motor pulse and actual distance. Method for correction: one is calculation through shaft radius and rotational speed; considering the possible error of mechanical evaluation, the positions of reference points in the image can be collected. When the motor rotates, calculate the distance error between the two points and then divide it by the number of pulses. ($k_2 = P/N$, where, N is the motion distance (unit：mm)，P is the number of motion pulses (unit：pluses)).

Coordinate of punching point:
In order to work out the appropriate punching position, the position of punching point $P_z(x_z,y_z)$ based on camera coordinate system shall be calculated. The method of correction: move the motor and move the punching point to the field of view of the camera to obtain the relative coordinate position $P_0(x_0,y_0)$ (unit: pixel), after the pulse(t_x,t_y) X axis motor and Y axis motor move the points to be punched to the center of the stamping punching machine. The distance between the punching position and image center can be worked out in accordance with formula (1).

$$\begin{bmatrix} x_z \\ y_z \end{bmatrix} = \begin{bmatrix} \cos\alpha & \sin\beta \\ \sin\alpha & \cos\beta \end{bmatrix} \begin{bmatrix} t_x \\ t_y \end{bmatrix} / k_2 + \begin{bmatrix} x_0 \\ y_0 \end{bmatrix} / k_1 \quad (1)$$

4.4 Pulse calculation

Suppose a current point to be punched and it is in the image coordinate system P0(x0,y0), then the punching pulse shall meet the requirement for formula (1). And the number of pulses required is:

$$\begin{bmatrix} t_x \\ t_y \end{bmatrix} = \begin{bmatrix} \cos\alpha & \sin\beta \\ \sin\alpha & \cos\beta \end{bmatrix}^{-1} \left(\begin{bmatrix} x_z \\ y_z \end{bmatrix} - \begin{bmatrix} x_0 \\ y_0 \end{bmatrix} / k_1 \right) \times k_2 \quad (2)$$

Where,

$$\begin{bmatrix} \cos\alpha & \sin\beta \\ \sin\alpha & \cos\beta \end{bmatrix}^{-1} = \begin{bmatrix} \cos\beta & -\sin\beta \\ -\sin\alpha & \cos\alpha \end{bmatrix} / (\cos\alpha\cos\beta - \sin\alpha\sin\beta)$$

Namely:

$$\begin{bmatrix} \cos\alpha & \sin\beta \\ \sin\alpha & \cos\beta \end{bmatrix}^{-1} = \begin{bmatrix} \cos\beta & -\sin\beta \\ -\sin\alpha & \cos\alpha \end{bmatrix} / (\cos(\alpha+\beta))$$

There might be deviation between the relative position of material and image coordinate system. How to determine the coordinate system in the image is the key factor to guarantee punching. As there are a series of punching points in the material, linear photo correction method is adopted.

$$P_h = k_1 \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} + \begin{bmatrix} x_r \\ y_r \end{bmatrix} \tag{3}$$

Select the specific points and reference point in material (taking material table in Fig.3 for example, the origin in the material coordinate system is the reference point). Suppose the position in image coordinate system when taking photos is $P_r(x_r,y_r)$. There is certain distance between the points to be punched and reference points as well as the position. Suppose the relative coordinate (material coordinate system)to be $(\Delta x, \Delta y)$, the position of the punching point in the image coordinate P_h can be calculated by formula (3), where θ is the inclination angle of the image.

Combining formulas (2) and (3), number of pulses required for punching point motion and the punching machine can be worked out.

$$\begin{bmatrix} t_x \\ t_y \end{bmatrix} = \begin{bmatrix} \cos\alpha & \sin\beta \\ \sin\alpha & \cos\beta \end{bmatrix}^{-1} \left(\begin{bmatrix} x_z \\ y_z \end{bmatrix} - \left(k_1 \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} \nabla x \\ \nabla y \end{bmatrix} + P_r \right) / k_1 \right) \times k_2 \tag{4}$$

It can be simplified as follows:

$$\begin{bmatrix} t_x \\ t_y \end{bmatrix} = \begin{bmatrix} \cos\alpha & \sin\beta \\ \sin\alpha & \cos\beta \end{bmatrix}^{-1} \left(\begin{bmatrix} x_z \\ y_z \end{bmatrix} - \left(\begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} + \begin{bmatrix} x_r \\ y_r \end{bmatrix} / k_1 \right) \right) \times k_2 \tag{5}$$

In formula (5), the main parameters α and β are the inclination angles of the motor and shall be pre-corrected and obtained; Position of punching point (x_z,y_z) shall also pre-obtained; $(\Delta x, \Delta y)$ is the template parameter, which is relevant with the shape of flexible board; K_1 and K_2 are scale parameters and shall be pre-corrected; while position of reference point (x_r,y_r) and the inclination angle of the image parameter θ shall be obtained at real-time.

4.5 Error evaluation

In real situation, source of error will be more complicated. Some pre-corrected parameters might slightly change in mechanical motion. In order to simplify system error evaluation, it is supposed that the system mechanical parameters are pre-corrected and fixed. The possible errors consist of the position of reference point and image inclination angle. The number of actual pulse is (t'_x, t'_y):

$$\begin{bmatrix} t'_x \\ t'_y \end{bmatrix} = \begin{bmatrix} \cos\alpha & \sin\beta \\ \sin\alpha & \cos\beta \end{bmatrix}^{-1} \left(\begin{bmatrix} x_z \\ y_z \end{bmatrix} - \left(\begin{bmatrix} \cos\theta' & -\sin\theta' \\ \sin\theta' & \cos\theta' \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} + \begin{bmatrix} x'_r \\ y'_r \end{bmatrix} / k_1 \right) \right) \times k_2 \tag{6}$$

Pulse error Er：

$$\text{Er} = \begin{bmatrix} t'_x \\ t'_y \end{bmatrix} - \begin{bmatrix} t_x \\ t_y \end{bmatrix} \tag{7}$$

Institute formulas (5) and (6), then

$$\text{Er} = \begin{bmatrix} \cos\alpha & \sin\beta \\ \sin\alpha & \cos\beta \end{bmatrix}^{-1} \left(\left(\left(\begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} - \begin{bmatrix} \cos\theta' & -\sin\theta' \\ \sin\theta' & \cos\theta' \end{bmatrix} \right) \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} + \left(\begin{bmatrix} x_r \\ y_r \end{bmatrix} - \begin{bmatrix} x'_r \\ y'_r \end{bmatrix} \right) / k_1 \right) \right) \times k_2 \tag{8}$$

Where, motor angle deviations α and β are small, close to 0. Therefore, the error is approximately as follows:

$$\text{Er} \approx \left(\left(\left(\begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} - \begin{bmatrix} \cos\theta' & -\sin\theta' \\ \sin\theta' & \cos\theta' \end{bmatrix} \right) \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} + \begin{bmatrix} \Delta x'_r \\ \Delta y'_r \end{bmatrix} / k_1 \right) \right) \times k_2 \tag{9}$$

Considering that the variation range for inclination angle θ is small, no more than 5° and the calculation error for the reference point is no more than one pixel, it can be concluded from formula (9) that the main influencing factors of errors are image inclination angle. And the error will doubles when the relative displace between punching points increases. It is found in experimental detection that if the angular error is about one degree, the error in punching coordinate will be one or two millimetres, which is beyond the permissible range. Therefore, inclination detection is extremely important during the photographing and calculating process. As a result, it shall be approach to the real value as for as possible.

Image recognition for flexible board is introduced in the following part. And how to work out the calculation for the position of reference point and image inclination by linear photo is also researched in the following.

5. Image recognition

For the flexible printed circuit, the main purpose of the image recognition is to recognize the object of reference point and calculate the inclination angle of the image. Fig. 4 is the collected diagram on site of the flexible printed circuit, of which the reference point generally is a circle, located in the rectangular box, and the entire image is evidently slant.

5.1 Reference point recognition

At present, there are many calculated ways to detect circle, Hough transformation, as a common way, put forward by Paul Hough in 1962[7], could transform the rather difficult global detection problem in the image into easier solved partial peak detection problem in the parameter space. The applications of the space conic curves based on Hough transformation are very widespread, also always an active academic research field[8,9], and some calculated ways even employ accelerated hardware platforms, such as CUDA or OpenCL.

As for this text, the author takes two points into account; one is the efficiency of the calculated way, which must be simultaneous; the other requests the calculated way should have higher Robustness to avoid bigger effects caused by ambient light changes on the calculation results. This system employs gray image-based gradient feature to recognize the center of a circle and reduces the effects of actual ambient light changes. The calculated way is generally within 200 ms, and more accurate. The red circle in Fig. 4 reflects the detection results.

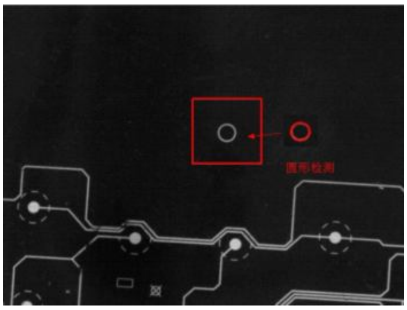


Fig. 4 Circle detection

4.2 The calculation of inclination angle

There are many ways to calculate the inclination angle, involving Hough transformation[10], Radon transformation[11,12], nearest neighbour method[13,14], least square method[15] and Fourier transformation[16]. For Radon transformation is rather in common use and its calculated way is more adaptable, widely used in license plate correction, OCR document recognition and industrial area. However, one important factor effecting the Radon transformation is the complexity of the calculating time. Detecting on a large scale with higher accuracy may prolong the system and deplete internal storage, which is very disadvantageous to the system requiring the simultaneous detection and punching design.

Considering the higher accuracy of stamping punch, this text employs the Radon transformation. As to the flexible printed circuit in the text, the author imitates the graded Radon transformation and adopts the strategy of correction twice to correct the inclination angle.

1) Use the low accurate Radon transformation within the possible range ($-\theta_t$, θ_t) of the inclination angle to obtain the estimated θ1 of the inclination angle.

2) Transform accurately within the △θ of the length, with θ_1 as a center to obtain the accurate inclination angle.

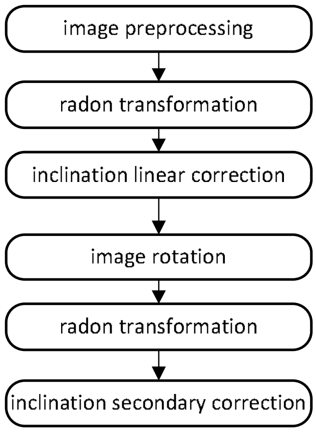
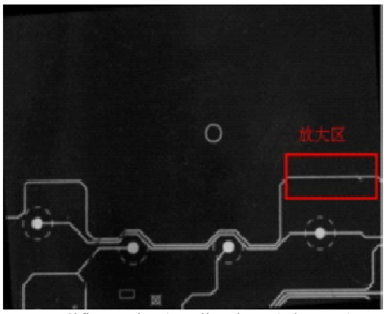
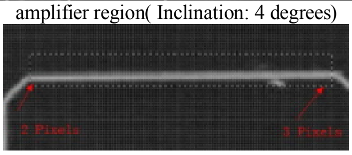


Fig. 5 Flow of inclination secondary correction

Fig. 5 reflects the process of secondary inclination correction. At first, collect photos for pre-treatment, involving image denoising and edge extraction. Then Radon transform for the first time, and considering the possible range of the inclination angle, calculate the projective number of the Radon, with 1° interval generally. Calculate the reasonable range of the inclination angle according to the distribution characteristic. The deviation may be about 1° at this moment. Radon transform again with 0.05° interval and within the range of 1° of the inclination angle, count the distribution characteristic of the projective number and calculate the most reasonable skew angle. The deviation may be about 0.05° at this moment, and the deviation length is within one or two pixels elements.

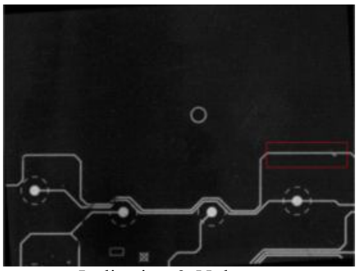


amplifier region(Inclination: 4 degrees)

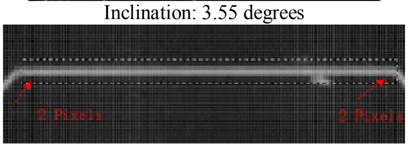


local region amplification (error 1-2 pixel)

Fig. 6 Inclination linear correction



Inclination: 3.55 degrees



local amplification (error 0-1 pixel)

Fig. 7 Inclination secondary correction

Fig. 6 reflects the linear correction of the image with 1° interval, and then the inclination angle may be about 4°. The right side is the partial enlarged photo of the red area, and the proper slant of the straight line can be seen. The right area is higher, and the deviation may be about one or two pixels. Fig. 7 reflects the second correction, the angle is adjusted to 3.55° or so, and the deviation is controlled within one pixel element.

Generally, the flexible printed circuit needs twice punching, punching 4-8 times for each time. Fig. 8 reflects the flexible printed circuit after punching, and the red area indicates correct punching having been done.

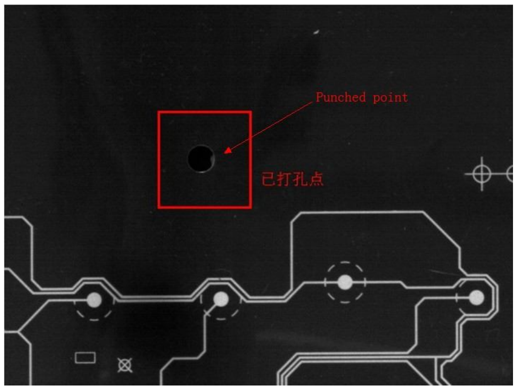


Fig. 8 FPC after punching

6. Conclusion

This project aims to research automatic technology for flexible circuit board manufacturing. Combining with computer vision, image process and automatic control technology, automatic punching system is developed for flexible circuit board. The system simulates the principle for manual punching and the automatic punching process is achieved by a series of flows such as catching material, taking photos, punching, dropping materials and return stroke etc.

As the core technology in automatic punching machine design, coordinate correction directly influence the punching accuracy. As for coordinate correction, the source of system errors and error evaluation are analyzed in detail in this paper; besides, concrete correction process such as selection for coordinate system, system parameter correction and pulse calculation are explained in detail.
Image recognition technology is adopted in image correction process. Accurate evaluation for reference point and inclination of materials are achieved by linear photographing technology, which accurately locates the position of punching point in the camera coordinate system and basically meets the requirement for permissible deviation of punching.

With the improvement in system hardware, currently, the efficiency of automatic punching is improved by optimizing the design for machinery hardware and further analyzing the punching operation; on the other hand, the influence of error and the correction algorithm are further researched and the punching error is further reduced to improve the stability and robustness of the system.

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