UNCALIBRATED STEREO VISION FOR PCB DRILLING

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Abstract

Machine vision systems are often used in conjunction with industrial robots to automate manufacturing operations. However, such automation is limited by the need for accurate calibration of both the robot and the vision system. This paper will discuss how the mathematics of projective geometry may be used in conjunction with a model of the workpiece to avoid the need for camera calibration. This in turn eases the integration of machine vision with certain industrial processes. Particular consideration is given to the application of this technique to printed circuit board (PCB) drilling.

1 Background

1.1 Robotic manufacturing

Robots are currently used in many industrial applications since they provide numerous advantages over simpler forms of mechanisation and human labour. These include higher productivity, reduced down-time and increased quality and consistency [5]. Since robotic systems are programmable they can accommodate changing requirements in the production line. However, in practice such changes often require considerable reprogramming effort and consequently incur a significant set-up time. In addition, it is vital that the robot is accurately calibrated before use if it is to operate robustly [2].

If the exact position of the parts being processed varies, this is likely to prevent the robot from achieving its goal. A computer vision system can be used in conjunction with the robot to circumvent this problem. Images of the part concerned are interpreted by a computer which uses certain visual features to calculate the exact position of the part within the image. It is then necessary to calculate the location of the part with respect to the robot, which involves generating a mapping from image coordinates to world coordinates. This mapping is defined by a process of camera calibration, in which the exact position and characteristics of the camera are determined and stored. Often, a single camera provides sufficient visual feedback, although two or more cameras may be required for accurate three dimensional positioning.

1.2 Printed circuit boards

Electronic products have been constructed using printed circuit boards (PCBs) for several decades, and this is unlikely to change in the foreseeable future. The PCB provides a convenient mechanism for physically securing electronic components whilst connecting them electrically in the required configuration [3].

When the design of an electronic circuit has been finalised, a computer aided design (CAD) package is used to help the designer lay out the components and interconnecting tracks on the surface of the PCB. Most modern boards consist of several layers of tracks, separated with thin, non-conducting laminates and interconnected at strategic points with via holes, which pass right through the board. The CAD package can be used to generate the artwork needed to lay down the tracks for each layer of the PCB. Two different methods are commonly used to attach components to the board. The first method involves inserting the wire leads of the various components through holes drilled in the PCB, and soldering the underside of the board to secure them. The second, more modern approach is to

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solder especially designed components to the surface of the PCB. Via holes are usually required in both cases.

1.3 Automatic PCB manufacture

PCB drilling and component insertion and placement are often carried out automatically using specialised machinery. Such machines are frequently able to use the CAD layout data generated in the design phase to control their operation. By alleviating the need to program the drill explicitly, the set-up time for each new PCB is greatly reduced. However, since the machines must position the drill precisely, accurate registration with the position of the PCB is critical.

The work described in this paper was motivated by difficulties encountered with low volume PCB drilling machines. Using a machine of this type (see Figure 1, for example) can impose several restrictive constraints on the PCB manufacturing process, in order to achieve the board registration required. For this reason manual PCB drilling is still considered preferable in many cases [7].

Figure 1: Typical low volume PCB drilling machine.

2 Uncalibrated stereo

2.1 Projective geometry

Projective geometry provides a mathematical framework which models the effects of *perspective transformation* of geometric shapes. A perspective transform between two planes is shown in Figure 2. Using the central projection model, points in the world plane $\mathcal{W}$ are transformed to the image plane $\mathcal{I}$. For example point $\boldsymbol{P}$ at (X, Y) is mapped onto point $\boldsymbol{p}$ at (x, y). This mapping is defined by

$$\begin{pmatrix} kx \\ ky \\ k \end{pmatrix} = \begin{pmatrix} t_{11} & t_{12} & t_{13} \\ t_{21} & t_{22} & t_{23} \\ t_{31} & t_{32} & t_{33} \end{pmatrix} \begin{pmatrix} X \\ Y \\ 1 \end{pmatrix}, \tag{1}$$

or more compactly by

$$\boldsymbol{p} = \boldsymbol{T}\boldsymbol{P}. \tag{2}$$

$\boldsymbol{T}$ is the transformation matrix, and $\boldsymbol{p}$ and $\boldsymbol{P}$ are the image and world points respectively, expressed in *homogeneous coordinates* [4]. For perspective transformation, $\boldsymbol{T}$ has six essential parameters (three for rotation and three for translation) [9]. In the general case $\boldsymbol{T}$ has nine parameters (the nine elements, $t_{11} \ldots t_{33}$). In fact, only eight of these are independent because it is the ratio of homogeneous coordinates which is significant, and there are just eight ratios among the nine elements of $\boldsymbol{T}$. This more general mapping, known as a *projective transformation*, is suitable for a wider range of situations — for example it can be used to model a sequence of perspective plane transformations.

2.2 Calculating the transform

To summarise, the projective transform can be used to model the mapping between two (or more) images of a part, provided that the part is planar. If $\boldsymbol{T}$ is known, then it is straightforward to map corresponding points between different images, or indeed between each image and a CAD model of the

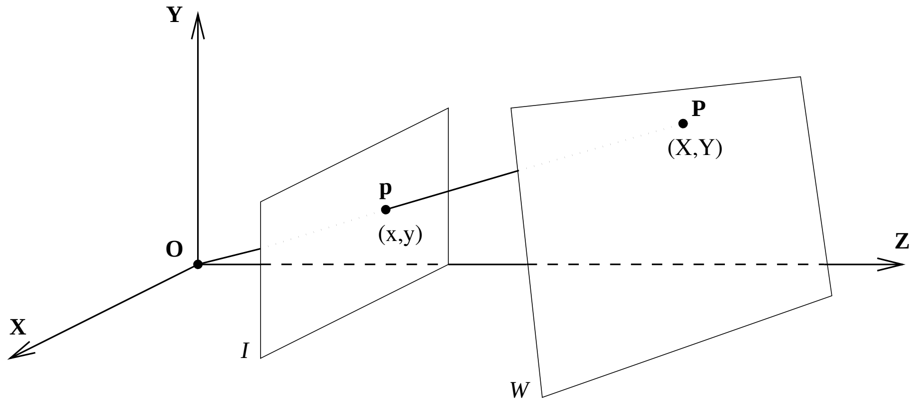

Figure 2: A perspective transform between two planes (world plane $\mathcal{W}$ and image plane $\mathcal{I}$).

part. There are many industrial applications where the workpiece is flat and thus the planar constraint is not limiting — PCB manufacture is a good example.

$\boldsymbol{T}$ may be computed by solving Equation 2 using four known points in general position (i.e. no three collinear). Each point has two degrees of freedom and therefore generates two equations. In detail, from Equation 1 we have

$$\begin{aligned} x &= \frac{kx}{k} = \frac{t_{11}X + t_{12}Y + t_{13}}{t_{31}X + t_{32}Y + t_{33}} \\ y &= \frac{ky}{k} = \frac{t_{21}X + t_{22}Y + t_{23}}{t_{31}X + t_{32}Y + t_{33}} \end{aligned} \quad (3)$$

and in turn

$$\begin{aligned} x\,(t_{31}X + t_{32}Y + t_{33}) &= t_{11}X + t_{12}Y + t_{13} \\ y\,(t_{31}X + t_{32}Y + t_{33}) &= t_{21}X + t_{22}Y + t_{23}. \end{aligned} \quad (4)$$

The system of linear equations obtained by applying Equation 4 to four known points generates a matrix equation for the elements of $\boldsymbol{T}$ as a vector. This can be solved by standard linear methods [8, 9].

3 Automatic PCB drilling

3.1 Application of projective geometry

As outlined in Section 1.3, this work was motivated by the restrictions encountered whilst using a low volume PCB drilling machine. To remove the need to position the PCB precisely in the machine, a two-camera visual feedback system has been added. The cameras are used to view the PCB and the drill bit and the images generated are processed to detect their respective positions. For each image, four pads are used to determine the elements of the perspective transform matrix, $\boldsymbol{T}$. This is done by solving Equation 4 for $\boldsymbol{T}$, using the (x, y) position of each pad as seen in the image and the actual (X, Y) position as defined in the CAD layout data.

Having calculated the transformation from each image to world space, the position of the drill bit can be calculated. The first stage is to project a line through the axis of the drill bit in each image. These lines indicate the path of the drill bit which will be seen in each image as it is moved towards the PCB. It is impossible to determine from a single image where on the PCB the drill will make contact. However, the two projected lines can be integrated by mapping them into world coordinates, using the appropriate inverse planar projective transform, $\boldsymbol{T}^{-1}$. Since each mapping is only valid for points in the plane of the PCB, the transformed lines will only be valid at the point where the drill bit actually touches the PCB. Therefore the intersection of the transformed lines is the point where both are accurate mappings, which in turn represents the point where the drill bit will contact the PCB.

When a hole is to be drilled, the machine initially only has to move to the approximate pad location. The vision system can then be used to calculate any error, and the end effector can make a small movement to compensate before the hole is drilled. It is helpful if the cameras are located roughly perpendicular to each other (to reduce the effect of error in image processing on the calculation of the drill location). Absolutely no explicit camera calibration is required, and the cameras can be moved freely at any time.

3.2 Other issues

The algorithm outlined in the last Section does raise issues other then the projective geometry presented here. The robust detection of the pads on the PCB in a noisy industrial environment is a challenging problem. However, in conjunction with this work, a suitable three-stage process has been developed to locate visual features in an image reliably [6]. Similarly, calculating the correspondences between pads detected in an image and those listed in the CAD file is not trivial. This problem has been researched in [1]; for the relatively small number of pads which are typically present in the image of part of a PCB, computation is straightforward.

3.3 Preliminary results

The scheme proposed in this paper has been applied to the drilling machine of Section 1.3 to determine drill positioning error, with respect to a through hole PCB.

Figure 3 shows part of a PCB which was used for preliminary tests, including the two example calculations presented here. The pad to be drilled is indicated in Figure 3, along with the three additional pads which were used to define the transformation matrix $\boldsymbol{T}$. Figures 4(a) and 4(b) show the stereo views of the drill bit and PCB, and Figure 4(c) shows the result of mapping the projected path of the drill bit into world coordinates. The intersection of these projections indicates that the bit is incorrectly positioned, and will miss the target pad. When the drill bit has been moved to compensate for this error (Figures 4(d) and 4(e)), this is reflected in the projection (see Figure 4(f)) and drilling may proceed.

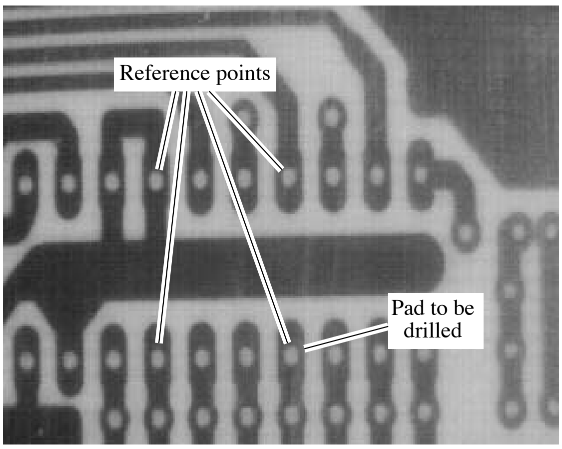

Figure 3: The PCB used for testing.

4 Conclusions

This paper has presented a novel application of projective geometry to robotic manufacture. The projective transformations between the CAD data for a part and images of the same part can be simply calculated. The position of the robot end effector with respect to the part can then be calculated, without any need to calibrate the vision system. This approach has been applied to low volume PCB drilling, and preliminary results indicate its effectiveness. Potential problems, such as modelling non-linear lens effects have not appeared in practice.

Further work on the drilling system is required to verify that the ideas in this paper can be applied to create a robust, practical machine. Since camera positions are not critical, it may be beneficial

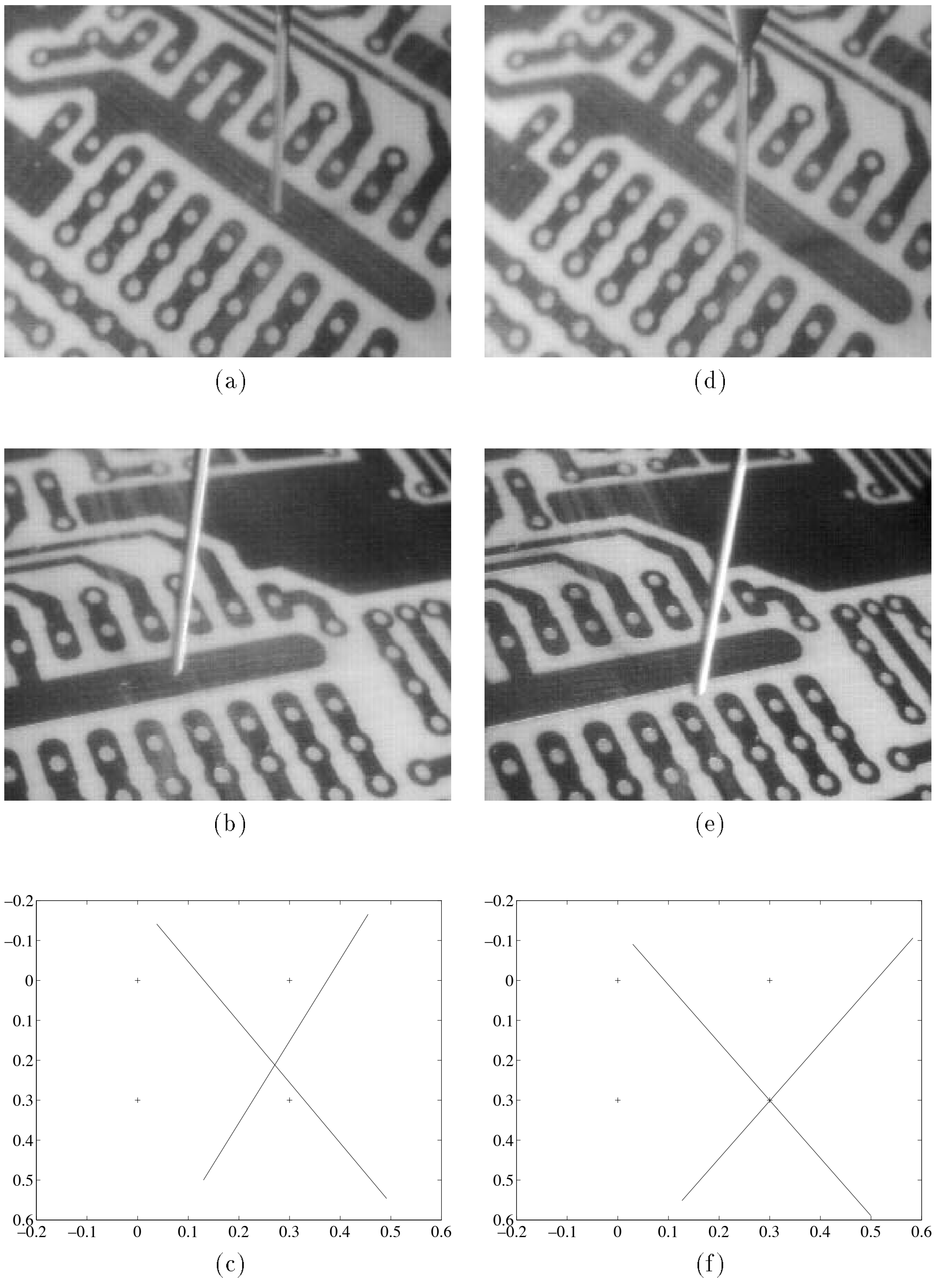

Figure 4: (a) & (b) Stereo views of misaligned drill and (c) the calculated drill position in real space, which highlights the positioning error. (d) & (e) Stereo views of the corrected drill position and (f) the transformation to real space shows that accurate positioning has been achieved. All units are inches.

to mount the cameras on the end effector of the robot. This would reduce the field of view and hence produce correspondingly higher resolution images. It may be possible to extend the work to facilitate other PCB manufacturing operations such as component insertion and placement. Indeed, the technique may be applicable to a more diverse range of industrial applications where CAD models are used to define flat parts, for example drilling, riveting and peg-in-hole assembly operations.

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