PRECISE TOOL MEASUREMENT USING DIGITAL PHOTOGRAMMETRY

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Abstract:
Tool measurement with an accuracy of a few microns is an important, but also time consuming and expensive element in industry. Up to now the geometry of the cutting edges of tools is checked by mechanical devices. This paper presents a new approach using computer vision techniques. Basic components of the system are two CCD-cameras which allow to get the three-dimensional position of the inserts of the tools. In order to reach the required accuracy a precise reseau grid is used as a control point field for the orientation of the cameras. Because of the small angular aperture of the CCD-cameras beam splitters have been attached in front of the cameras so that the images of the control point field and of the cutting edges can be evaluated one after the other. Investigations with end measures have shown that an accuracy of 3 μm for the position of cutting edges can be reached.

Key Words: Accuracy, Industrial, Machine Vision, 3-D

1. Introduction

With the increase of untended automated manufacturing systems, there is also a tendency to automated measuring systems, which do not only check the product quality of workpieces, but perform also the inspection of tools. This is very important for economical manufacturing, because it helps to avoid reworking and rejecting. Due to the progress in computer-technology and the development of optical sensors opto-electronical measuring systems are developed, which reduce the influence of operators and which contribute to accelerate the measurements [Pfeifer et al.,1982].

This paper presents a new method to check the geometry of drilling and milling tools, which are used for stock-removal production in computer controlled manufacturing systems. Fig.1 shows an example of a drilling tool with several triangle shaped cutting edges.

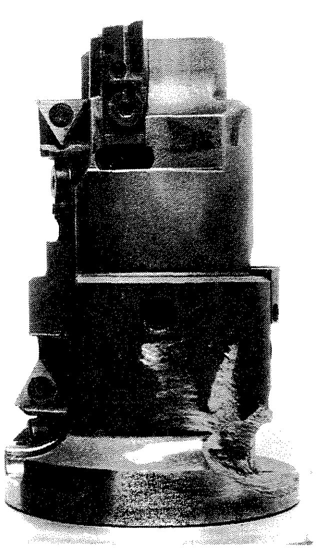

Fig.1: drilling tool with several inserts

The essential parts of the tools are the cutting edges and before a tool is used for production the position of the cutting edges must be controlled to guarantee the quality of the manufactured workpieces. Up to now this is done by profile projectors or coordinate measuring machines.

The new method described here makes use of computer vision techniques to evaluate the data of a pair of two CCD-cameras, which are pointed convergently on a tool. Thus they allow to get three-dimensional information about the cutting edges of the tools.

A precise reseau grid is used as a control point field for the orientation of the cameras. A special approach for the orientation of the cameras has been developed, because of the small size of the available CCD-arrays, which makes it impossible to get control points and the unknown object in one image. Otherwise the image scale would be two small to reach the required accuracy of a few microns. With a scale of about 1 : 2.5 a triangle shaped insert can be projected on one image. At this scale the pixel size in the object space is about 20 microns, so that with an edge detection accuracy of 0.1 pixel an accuracy of 2 microns is possible. As no control points can be seen in the images at this scale, beam-splitters have been attached in front of the objectives so that parts of the reseau grid can be seen too, depending on whether the reseau or the tool is illuminated. Therefore a calibration of the beam-splitters is also required.

2. Hardware Configuration

The main part of the system consists of a fixed pair of standard CCD-cameras with macro-lenses and beam-splitters. They can be shifted parallel to two reseau-grids which are placed on each side of the tool which is to be measured. The cameras are connected to a 386-PC with an image processing board inside which does above all the A/D conversion and stores the digital image data.

The reseau grids with a size of 400 $\times$ 80 mm^2 have a mesh width of 2 mm. Each single cross is placed with an relative accuracy of 1 μm and an absolute accuracy of 2.5 μm over a length of 400 mm. According to the manufacturer the flatness of the glass varies only for 5 μm over 80 mm.

The tool is placed on a rotating table so that by turning the cutting edges can be put in a position parallel to the reseau grids and the cameras. Otherwise some edges could be hidden by the tool. As measurements with an accuracy of a few microns in the object space are influenced by a variation in temperature a device for the measuring of the temperature with six single sensors was also installed. Fig.2 shows the laboratory layout (without the PC).

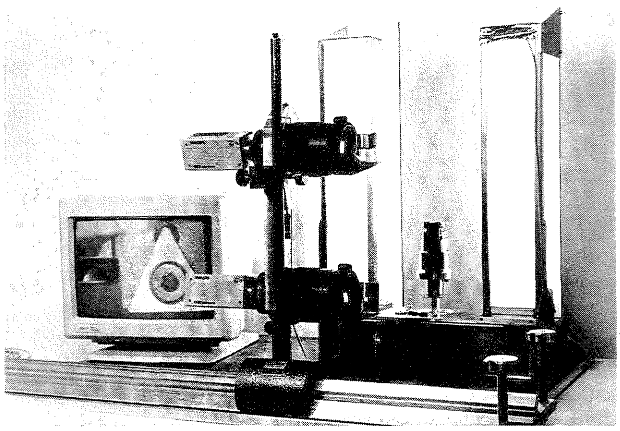

Fig.2: photograph of the laboratory layout

The arrangement of the beam-splitters and the course of the light rays is explained in Fig.5 and Fig.6.

3. Orientation of the Cameras

The layout shown in Fig.2 was mainly chosen because of the very small angular aperture of the CCD-cameras. The combination of a 1/2"-CCD-array with a principal distance of 120 mm gives an angular aperture of only 4 gons. Under these conditions the orientation parameters are highly correlated and the orientation is unstable. So the original idea of placing the cameras between the tool and the reseau grid as shown in Fig.3 had to be rejected.

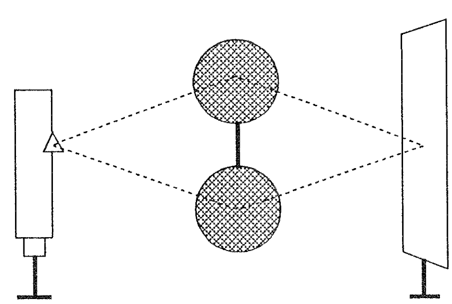

Fig.3 : rejected layout

The position of the cameras can only be computed with an accuracy of a few millimeters which does not matter, if the unknown object points lie in the object space surrounded by control points. But if there is an extrapolation like in Fig. 3 the accuracy of the projection centres is essential and the computation of the object point coordinates difficult.

Therefore several different configurations were tested. Two of them are presented with theoretical and empirical results.

In order to render the orientation parameters more stable, the angular aperture of the cameras was artificially widened by adding another beam splitter to each camera pointing to another reseau grid. Fig. 4 and Fig. 5 show these layouts, in one case the tool opposite to the reseau grids and in the other case the tool between them. Fig. 5 corresponds to the finally chosen layout of Fig. 2.

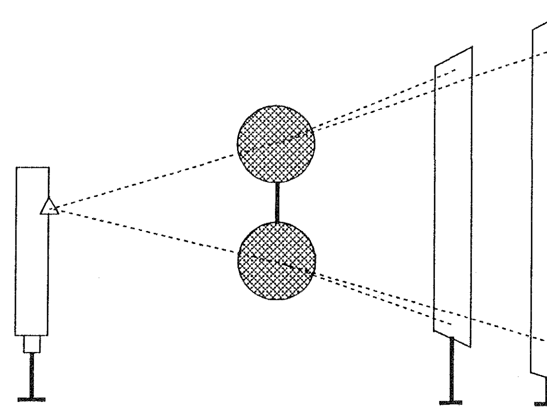

Fig.4 : layout 1

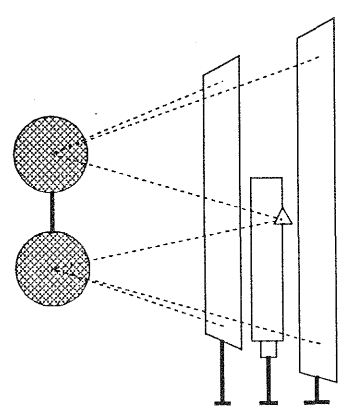

Fig.5 : layout 2

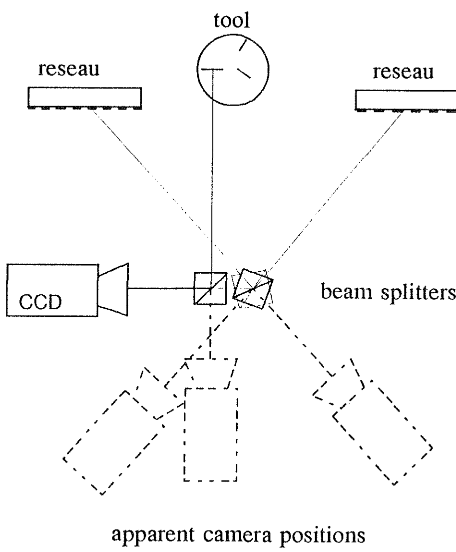

Fig.6: Arrangement of the beam splitters

Fig.6 shows the way the beam splitters were arranged in front of the lenses to obtain a constant distance to the tool so that the object remains in the range of focus while the cameras are shifted parallel to the reseau grids. It is necessary to shift the cameras because the cutting edges of the tools lie in different distances to the rotation axis and at different heights. By turning the tool the edges can always be put in a plane parallel to the reseau grids so that no movement in depth is necessary. Whether the cutting edges or parts of the reseau grids are projected onto the CCD-arrays is determined by the illumination of the desired spot.

With the use of three beam splitters per camera it seems as if there are six cameras. Because all components are fixed together the exterior orientation of one image is enough to determine the orientation of the whole optical system. As the images have a very narrow angular aperture there is no influence of lens distortion detectable. The parameters of the inner orientation are highly correlated with the exterior orientation, so it is sufficient to have only rough values. The mathematical model for reseau crosses in the first image is described by the well known collinearity equations:

$$\underline{x}_{i1}=f(\varphi_1,\omega_1,\kappa_1,X_{01},Y_{01},Z_{01}) \tag{3.1}$$

$\underline{x}_{i1}$: image coordinates of the independent first image

$\varphi_1 - Z_{01}$: parameters of the exterior orientation

The geometric relation for the other five dependent images are determined by the orientation parameters of the first image and the parameters of the relative orientation between the first and each of the other five images j.

$$\underline{x}_{ij}=f(\varphi_1,\omega_1,\kappa_1,X_{01},Y_{01},Z_{01},d\varphi_j,d\omega_j,d\kappa_j,b_{xj},b_{yj},b_{zj}) \tag{3.2}$$

$\underline{x}_{ij}$: image coordinates of the dependent images

$d\varphi_j - b_{zj}$: parameters of the relative orientation

As there are several images with a constant relation to each other it is not enough to compute 5 parameters for the relative orientation. 6 Parameters are necessary to obtain a homogeneous scale for the whole imaging system.

Simulations have shown that the standard deviations of the exterior orientation parameters for layout 1 and 2 are almost identical, that means that the unknown object points do not contribute to stabilize the computation of these parameters. Table 1 summarizes the standard deviations, assuming an accuracy of 1 μm for image coordinates and an angle of 80 gon between the bundles of rays in horizontal direction.

φ_1 [mgon]	ω_1 [mgon]	κ_1 [mgon]	X_{01} [μm]	Y_{01} [μm]	Z_{01} [μm]
8.5	3.9	3.3	1.9	0.8	0.5

Tab. 1: theoretical standard deviations of the exterior orientation parameters (layout 1 and 2)

The X-axis lies in horizontal direction , the Y-axis in vertical direction and the Z-axis perpendicular to X and Y. As expected the determination of φ_1 and X_{01} is more difficult compared to the other parameters. But it is of no use to widen the opening angle to a farther degree because of the limited range of focus.

The differences between layout 1 and 2 lie in the correlation of the unknowns. Because of the extrapolation in layout 1 the correlation between φ_1 and X_i amounts to 0.77 and the correlation between ω_1 and Y_i to 0.42. These values are much higher than in layout 2, where the correlation between φ_1 and X_i and between ω_1 and Y_i amounts only to 0.09. The different correlations cause the different standard deviations for unknown object coordinates as shown in Table 2.

	x[μm]	y[μm]	z[μm]
layout 1	3.3	2.3	6.5
layout 2	2.0	2.0	6.3

Tab. 2: theoretical standard deviations for unknown object points

In order to control the theoretical values empirical investigation were made and have given the results shown in Tab. 3. They were derived by repeated measurements of reseau crosses as unknown object points. Both tests were made under similar conditions.

	x[μm]	y[μm]	z[μm]
layout 1	13	4	9
layout 2	3	3	9

Tab. 3: empirical standard deviations for unknown object points

The empirical value for the X-coordinate of object points is higher than expected. The reasons for this are the deviations from ideal measuring conditions, which influence mainly the X-direction. A not totally compensated variation in temperature or vibrations could be such deviations. Furthermore a less precise reseau grid was used for these measurements. Additional tests of layout 2 with high precision reseau grids haven given an accuracy of 2 μm in Y-direction and accordingly to the base-to-height ratio 6 μm in Z-direction.

Layout 2 proves to be the more stable one, therefore it was chosen as final configuration. In cases where only a reduced accuracy is required layout 1 might also be suitable.

3. Calibration of the Optical System

The procedure described above assumes, that the position of the components of the imaging system remain stable and that the relative orientation of each single bundle of rays is known.

Furthermore the control points of both reseau grids must be known in one coordinate system, so that the position of one reseau grid in relation to the other must also be determined.

This can be achieved by replacing the unknown object (i.e. the tool) by a third precise reseau grid. Then the camera system is shifted systematically over this additional reseau grid and at different places the reseau crosses of all 6 images, which can be taken at a single position are measured. Then all the observations can be put into an adjustment with following unknowns:

$\varphi_i, \omega_i, \kappa_i, X_{0i}, Y_{0i}, Z_{0i}$: parameter of the exterior orientation for each independent image i

$d\varphi_j, d\omega_j, d\kappa_j, b_{xj}, b_{yj}, b_{zj}$: parameter of the relative orientation for each dependent image j= 1,5

$\varphi_1, \omega_1, \kappa_1, X_1, Y_1, Z_1$: transformation parameters for the first two reseau grids

$\varphi_2, \omega_2, \kappa_2, X_2, Y_2, Z_2$: transformation parameters for the third reseau grid onto the first reseau grid

As the unknowns are highly correlated it is often enough to adjust only the rotation angles of the transformation 1 and 2 and to keep the translation parameters which must be known in advance with an accuracy of about 1 mm, which can be easily measured manually.

The determination of the first transformation parameters become superfluous, if the position of the reseau grids is not influenced by vibrations. As there is up to now only a laboratory setup the calibration of these parameters is sometimes necessary too.

The parameters of the transformation of the third reseau grid onto the first reseau grid can also be eliminated if there is an appropriate three-dimensional calibration field available. The problem is that for each new configuration a new calibration field is necessary and reseau grids with certain dimensions are not made in series and have terms of delivery of up to one year.

For one of the configurations which were tested in the course of the investigations a calibration field was made of ultra flat glass with reseau crosses that were projected onto the glass with photographic means. The crosses were measured with an analytical plotter and after four glass plates had been fixed together, the calibration was made with photogrammetric methods. This procedure is very time consuming. Comparisons of the calibration of the optical system with and without calibration object have shown, that there is no difference for the measuring of unknown object coordinates, so the calibration with single reseau grids is prefered.

The procedure of the calibration can be easily done automatically, if there is a shifting device for the cameras and if the light can be switched on and off automatically.

4. Measuring of Cutting Edges

One of the most frequently used forms for cutting edges are triangle shaped inserts which can be replaced when all three sides are damaged or worn out.

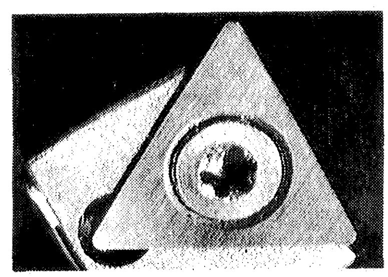

Fig. 7: triangle shaped insert of a cutting tool

Fig.7 shows such an insert the way it is seen by the CCD-cameras. The cutting edges are clearly visible and can be easily measured automatically with digital image processing techniques. To minimize the time used for the image processing the procedure is parted into two steps. At first the location and the orientation of the triangle is determined to get the approximate position of the edges, then the precise edge detection with linear edge operators is performed.

The task to find approximate values for the desired edges in a reasonable time is not as simple as it seems [Wang et al., 1991]. In the image there are several additional edges and a line structure and circles inside the triangle. So this task was also parted into single steps. At first the image with a size of 768 $\times$ 512 pixels is squished to a quarter of its original size. This reduces the data considerably and eliminates most of the image noise. Then single edge pixels are extracted and in a next step all those edge pixels that do not lie on a straight line are eliminated. From these straight lines triangles are reconstructed and the smallest equilateral one is selected.

The part of the approximate search may later be replaced by using the information of a CAD-system where the construction data of the tools are stored.

The rounded corners of the inserts cut the worked metal too, therefore it is also necessary to measure these corners. The assignment of edge pixels in the upper and the lower image can be done with the help of epipolar lines. As the accuracy for single points is not sufficient the edge points of the corners have to be adjusted by a circle, whose radius can be taken out of the construction drawings.

The positions of the inserts are determined in the coordinate system defined by the reseau grids. They have to be transformed into the tool coordinate system which is defined by the rotation axis. As the tools are rotating during the manufacturing process the angular position of the edges is not as important as their distance to the rotation axis. The determination of the rotation axis of the tools has been postponed because this is a standard task and it requires a high precision clamping device for the tool on the rotation table which was not available. It can be easily performed by measuring a single rotating point at different heights. The centres of these circles lie on the rotation axis.

5. Reached Accuracy

In the field of industrial measuring technique it is a commonly accepted way to check the quality of measuring devices with end measures which are high precision steal blocks. They have two opposite sides with lapped measuring surfaces. The width of the end measures is manufactured with an accuracy of less than a tenth of a micron.

With optical means it is impossible to measure surfaces of polished steal without any structure or targets. The edges of the end measures are not sharp enough to represent the surfaces. Therefore two attachments were taken from a measuring microscope and put at the end measure as shown in Fig. 8.

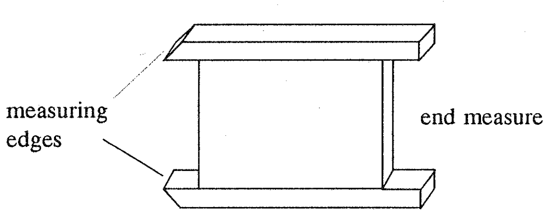

Fig. 8: test object

The wedge-shaped attachments have also a lapped measuring surface which ends in a very sharp edge. The distance between the two edges corresponds to the nominal value of the end measures.

Two end measures of 30 mm and of 100 mm length were measured repeatedly at different location within the object space. As this procedure means measuring a straight line in images with known orientations, the test object could not be measured in a horizontal position. In this case the measuring edges lie vertical, that is parallel to the base of the cameras, and the epipolar lines are almost parallel to the edges, too. As there are no distinct points there is an ambiguity which can only be solved if there is further information available, for example the intersection of two edges. With triangle shaped inserts this is always the case.

Table 4 shows the results of the repeated measurements.

	30 mm in vertical position	30 mm tilted at 50 gons	100 mm in vertical position
accuracy of a distance	4.4	4.2	3.7
accuracy of a single edge	3.1	3.0	2.6

Tab. 4: results for end measures [μm]

Those values were evaluated out of the differences between the measured distances and the nominal value that means they give the absolute accuracy.

This accuracy could only be reached because the sharpness of the edges allows a precise edge detection in the images. Under these conditions the illumination which is normally a critical point for the image processing was easy to handle. For round edges the direction of the light rays and the position of the cameras might influence the results. This point demands further investigations.

6. Conclusions

The investigations described above show that it is possible to apply photogrammetric methods in the industrial measuring technique. Metal edges of cutting tools can be measured with an accuracy of 3 μm if the edges are well defined.

The automation of the system has still be completed, that means the automatic positioning of the cameras and the automation of the illumination. It should also be possible to measure differently shaped cutting edges.

As a future step the integration of the system in the manufacturing process could also be taken into consideration.

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