High Precision Measurement of Tools

An Integrated Approach Based on HALCON

Gerhard Blahusch, Wolfgang Eckstein, Carsten Steger, Stefan Lanser
MVTec Software GmbH
Orleansstr. 34, D-81667 München, Germany
{blahusch|eckstein|stegerc|lanser}@mvtec.com

A methodology for proving the accuracy of a system for high precision measurement of cutting tools is described. The tools are backlit by infrared illumination. Images are acquired by telecentric lenses and standard cameras and framegrabbers. The outer boundary of the tools is extracted by subpixel edge detection and is then approximated by lines and circular arcs. All processing is done on standard hardware in real time. To guarantee high precision measurements, all components of the system have to be evaluated. The key components are image acquisition, including illumination, lenses, filter, camera and framegrabber, and all operators used by the system, e.g., filtering, subpixel edge detection, and an appropriate polygon approximation. Since radial distortions of the images are quite large, even though telecentric lenses are used, camera calibration is essential for the accuracy of the system, since it allows the elimination of these distortions. The influence of each of the above components is discussed, and the behaviour of the complete system is analyzed. With this analysis it can be proved that the system has an overall accuracy of 1/10th of a pixel and a precision of 1/25th of a pixel for real data.

1 Introduction

The background of this article is the measurement of drilling tools, both for fabrication and use. This measurement has to be done with a high accuracy due to low tolerances in modern production which is about two microns. This accuracy has to be provided not only in the center of the image but in the complete field of view.
To solve this problem all components starting from the illumination up to the feature extraction have to be carefully selected and optimally matched. The use of only one wrong component would result in a significantly lower quality. Thus all components of the system are analyzed and their influence on the accuracy is considered. Herein we will see that based on HALCON, a state of the art image processing environment, an efficient and fast measurement tool can be implemented.

2 Hardware Setup

2.1 Overview

A schematic view of the setup is shown in Figure 1.

The system consists of a LED (L), which backlights the cutting tool (T). On the opposite side, a CCD-camera (C) acquires the silhouette of the sample. The camera is connected to a framegrabber (F). The image processing (I) is performed on the computer, measuring angles, circles, lines, intersections, etc.

2.2 Illumination

For the lightning of the tool a near infrared LED is used. In the near infrared the influence of the surrounding light is smaller and the whole system

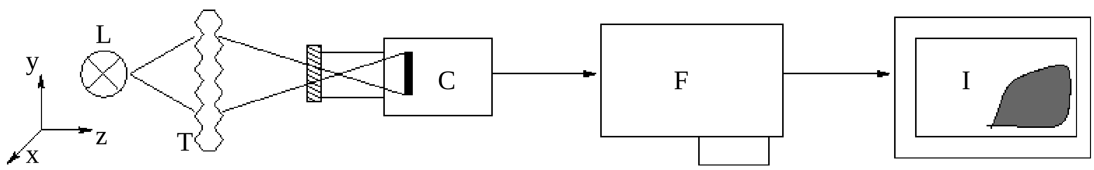

Figure 1: Schematic view of the arrangement (L: LED, T: cutting tool, C: camera, F: framegrabber, I: image processing

can work without an enclosing shielding. Adequate optics placed before the LED allow a homogenous illumination of the whole field of view – a necessary condition for a constant overall precision. The intensity of the LED is tuned for an optimum saturation of the dynamic range of camera and framegrabber. This guarantees a high contrast between tool regions and background regions in the image.

2.3 Camera and Optics

A progressive scan camera is used to capture the images. Progressive scan cameras acquire an image in one pass, in contrast to cameras based on the interlace technique with a horizontal displacement between even and odd lines. The camera has a resolution of 640x480 pixel and generates a NTSC-signal with 8 bit depth. A short exposure time gives a sharp image during movements.

To reduce the effects of perspective distortion a telecentric lens system is mounted on the camera. In a telecentric lens the aperture is positioned directly at its focal point. Hence, only parallel rays are able to pass through this aperture and therefore as the reflecting object seems to be infinitely remote, there can be no perspective distortion. Furthermore, the magnification is independent of the distance to the lens.

2.4 Framegrabber

The camera is connected to a PCI-framegrabber that allows a pixel-synchronous grabbing of images. Standard analog framegrabbers use a clock chip running typically four to ten times the pixel resolution. They start digitizing a line on the first upward edge of the clock after the falling edge of the horizontal synchronization signal (HSync) has occurred. Thus, for each line there is a random offset by which the line is shifted with respect to the true HSync, resulting in a random shift by up to one fourth to one tenth of a pixel [1]. To gain a higher resolution than one tenth of a pixel, the framegrabber is synchronized with the pixel clock of the camera.

3 Image Processing

3.1 Camera Calibration

The optics of the system causes distortions of the images. The elimination of these distortions is essential for the accuracy of the system. It is achieved by the calibration of the camera. The calibration is the exact determination of the parameters that model the optical projection of 3D world points onto a pixel on the CCD-Sensor. The underlying camera model in HALCON is a pinhole camera with radial distortions, modeling pillow- or barrel-shaped distortions [2] [3] [4]. This results in a total set of 12 camera parameters. They are divided into internal and external camera parameters. The internal parameters describe the characteristics of the used system of lens and camera, including the radial distortion, and are necessary here. The external parameters describe the position and orientation of the camera in the world coordinate system.

The transformation of a point P_W from the world coordinate system into the camera coordinate system P_C is done by a rotation R and a translation T:

$$P_C = (x, y, z) = R * P_W + T \qquad (1)$$

With the “focal length” b the transformation from the camera coordinate system into the 2D image plane u results from a perspective projection:

$$u = (u_x, u_y) = \left(b\frac{x}{z}, b\frac{y}{z} \right) \qquad (2)$$

Radial distortions are approximated by

$$v = (v_x, v_y) = \left(\frac{2u_x}{1+\sqrt{1-4\kappa(u_x^2+u_y^2)}}, \frac{2u_y}{1+\sqrt{1-4\kappa(u_x^2+u_y^2)}} \right) \qquad (3)$$

with the radial distortion coefficient κ. Finally the transformation into the pixels p of the acquired image is carried out with:

$$p = (p_x, p_y) = \left(\frac{v_x}{S_x} + C_x , \frac{v_y}{S_y} + C_y \right) \qquad (4)$$

S_x and S_y are scale factors describing the distance between two neighboring cells on the CCD sensor and C_x and C_y are the coordinates of the image center point.

The determination of the internal camera parameters results from the analysis of a number of images of a calibration plate. The camera calibration in HALCON uses a planar calibration plate as shown

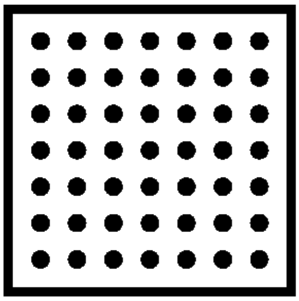

Figure 2: Pattern of the calibration table

in Figure 2. The pattern on the plate consists of 7x7 circles as calibration marks inside a surrounding rectangle. It is very important that the positions of the mark coordinates are known with a high accuracy. The precision must be better than 10^{-3} of the extend of the plate. For example, the plate for the system described in chapter 4 has a size of 6x6 mm for the outer rectangle and the position of the circles is determined with an accuracy better than 1µm. This calibration plate was manufactured by metal evaporation on a transparent carrier with techniques developed for microelectronics.

The procedure of the camera calibration is done in HALCON in two steps. First, several images (about 20 to 30) with a calibration plate at different positions in the image are acquired. In every image, the calibration plate and the positions of the marks are extracted. In the second step, the desired camera parameters are calculated from the set of data from the first step. This is done in a least squares technique with suitable chosen start parameters. The distortion of the images can then be eliminated using the camera parameters, especially the radial distortion coefficient.

In the case of a telecentric system some modifications in the camera model are necessary. Since the image size is independent of the coordinate z, equation (2) changes to the simple form $u_x = x$ and $u_y = y$. In this case, the scale factors S_x and S_y are the dimensions of a pixel in real world coordinates. This means that real distances can easily be measured in the image by the difference of pixel coordinates. For the calibration procedure, it is sufficient to acquire images of the calibration plate at different positions in the xy-plane. Variations in the z-coordinate do not gain further information.

To demonstrate the effect of the calibration, we have performed several experiments. One result is shown in Figure 3. An approximation of the curvature of a vertical line is measured across the field of view from the left to right side of the image. With an ideal system the curvature is independent of the position and equally zero. The upper curve shows the results before the calibration, the lower curve after the calibration. Before the calibration, the curvature increases to the borders of the image. Afterwards, the radial distortion is clearly reduced.

The calibration of the system is usually done once at the installation or after major changes in the hardware setup. The next steps describes the extraction of the properties of the tools from the image.

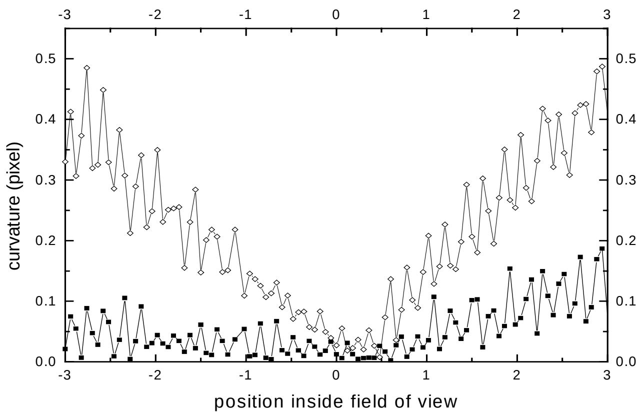

Figure 3: Curvature of a vertical line before (upper curve) and after (lower curve) calibration

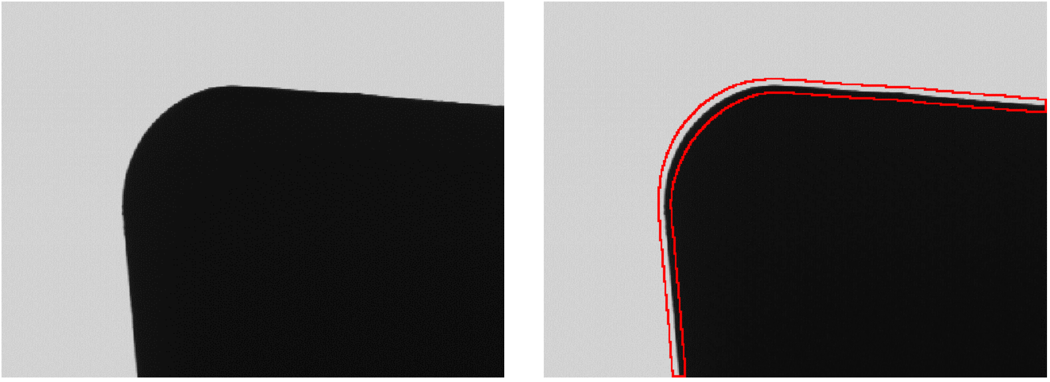

Figure 4: Image of a cutting tool (left side) and region of interest for edge detection (right side, red)

3.2 Image Preprocessing

The tools have to be measured with high accuracy. The accuracy is reached by a subpixel precise extraction of the contour of the tools. This subpixel procedure is very time consuming. To save time, it is mandatory to reduce the region of interest for the subpixel extraction to a region around the edge. This region of interest is created in HALCON by a fast and only pixel precise detection of the edge with a following dilation. Figure 4 shows on the left side a typical image of a cutting edge and on the right side the extracted region (red).

3.3 Subpixel Extraction

Inside the region of interest, the subpixel precise extraction of the edge is carried out. The edge detection algorithm is based on the approach to regard edges as lines in the gradient image [5]. In 2D, lines are modeled as curves that exhibit a characteristic line profile in the direction perpendicular to the line. Line points are given by the points where the first directional derivative in the direction of the line vanishes and the second directional derivative is of large absolute value. The direction of the line is obtained from the eigenvector corresponding to the largest eigenvalue of the Hessian matrix of the image convolved with a Gaussian smoothing kernel. The zero crossing of the first directional derivative is obtained with subpixel accuracy by extrapolating it from a local second-order Taylor polynomial. The whole process is implemented in HALCON as one operator, determing a subpixel precise contour.

An example for a subpixel precise edge detection is shown in Figure 5. It is a magnification of the edge of the cutting tool from Figure 4 with the extracted contour in subpixel precision as the red line.

To demonstrate the accuracy of the HALCON edge detection we have performed several experiments. They show, for example, that edge shifts of one twenty-fifth of a pixel can be detected with better than 99.9%. The absolute error (Figure 6) calculated as the difference of the extracted edge position and their regression line is better than one thirtieth of a pixel [6].

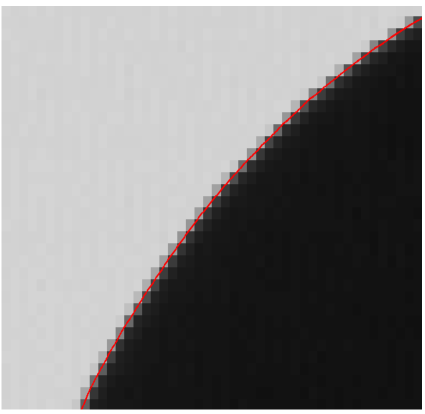

Figure 5: Edge of the cutting tool and subpixel precise edge (red line)

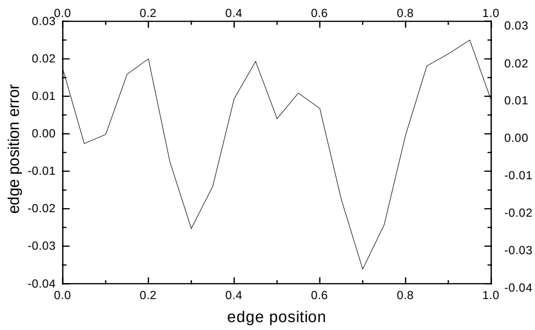

Figure 6: Absolute error of the edge position

3.4 Contour Splitting

After the subpixel precise detection of the contour of the tools, the features have to be calculated. In the case of cutting tools these are the direction of edge segments (i.e., the angle between the edge and the x-axis), the intersection points and angles of different edges or the radius of a circular arc. To do so, the contour has to be split into lines and arcs.

In HALCON first the subpixel contour is approximated by polygons [7] [8]. Straight parts of the contour are found correctly as lines by this step. However, curved parts of the contour are split into small line segments. Starting from this oversegmentation, neighboring line segments are merged into circular arcs in an iterative process, if this is a "better" approximation of the contour.

The fit of line segments to a contour is done in a minimization of the squared distances between the contour points and the approximated line. To reduce the influence of outliers, every contour point is weighted. This results in an eigenvalue problem which is solved with the approach of Tukey for the weighting factors [9].

The general approach for curved parts is a fit with elliptic arcs [10]. A ellipse F is described by a second order equation with two variables $\boldsymbol{p}$ = (x,y) of the form:

$$F(\boldsymbol{a},\boldsymbol{p}) = a\,x^2 + b\,x\,y + c\,y^2 + d\,x + e\,x + f \qquad (5)$$

From the vector $\boldsymbol{a}$ = (a,b,c,d,e,f) the parameters of the ellipse (centerpoint, major axis, orientation) are calculated. The fit of the ellipse is done by a minimization of the algebraic distance between the ellipse and the contour points. In the easier case of a circle approximation (5) is simplified to the circle equation and the algebraic distance between the circle radius and the distance of the contour points and the circle center is minimized.

An example for the contour splitting is shown in Figure 7. From the subpixel contour of the cutting tool two lines and one circle are extracted (red marked).

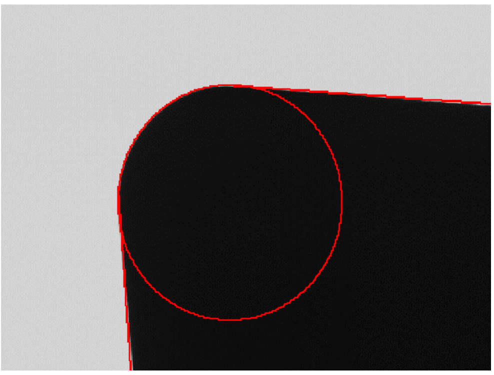

Figure 7: Splitting of the contour in lines and circles (red)

4 Results

The described system is realized in a machine by the company Zoller for the high precision measurement of tools. Figure 8 shows a photograph of this type of machine. Camera and lighting are clamped to the ends of a U-holder (dark blue). Between them, the tool is mounted on a revolving platform. The U-holder is movable in the xy-direction with position accuracy better than 1µm. This guarantees an exact positioning of the camera and a correct link between measured and moved distances. The field of view of the camera is about 6.7x9.0 mm. The distance between the tool and the camera is about 200 mm.

An impressive demonstration of the high precision of the whole system is shown by the following experiment with the Zoller machine. A stick is moved over distance of 50 µm and the thickness is measured every 0.5 µm. The measured thickness is plotted as a function of the position (Figure 9). It is not constant as might be expected, but shows regular variations. A detailed analysis of the oscillations reveals that the period is of the same size as one pixel in world coordinates. The oscillations can be explained as follows: between the single elements of the CCD chip is a small, non-sensitive space. If one edge of the stick falls in this space no change in the

Figure 8: Machine for high precision measurements of tools with HALCON image processing

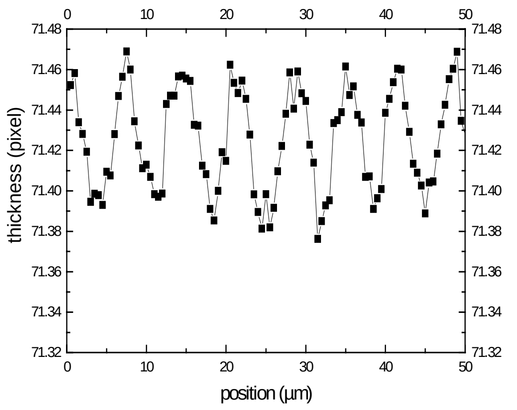

Figure 9: Thickness oscillations of a stick measured over a distance of 50 µm

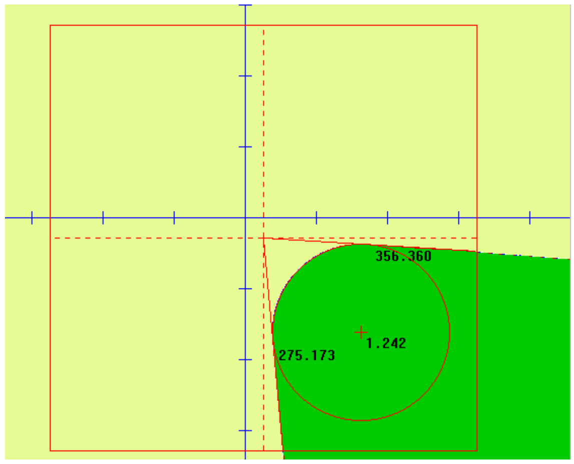

Figure 10: Results of the survey of a cutting tool

intensity of the neighbouring pixels occur. The measured thickness is smaller than when both edges are on the sensitive parts of the chip. This effect can only be seen with very sharp edges.

Based on the results of the image processing, different parameters of the cutting tool are computed by simple geometric calculations. Figure 10 shows a typical example, where the radius, the angles of the two straight edges, and their theoretical intersection points are measured.

The precision of the whole system for this kind of measurements, including the xy position system, is better than two microns in the whole field of view. The evaluation times on a standard PC with 200 MHz for a complete survey of the tool is about 100 ms. This is much faster than a human can perceive the results. All other tasks including simpler measurements, like the edge position in a fixed line with subpixel precision, are done with video frequency.

5 Conclusions

A system for the high precision measurement of tools based on standard hardware was described. All components of the system were evaluated and their influence was discussed. The different steps of the image processing were shown. The camera calibration eliminated the distortions of the images due to the optics of the system. The region of interest was generated by standard image processing operators, and the following subpixel operation allowed a precise detection of the edge. Finally, the extracted contour was approximated by lines and circular arcs, and the desired parameters of the tools were calculated. The system was realized in a machine by Zoller, leading to high precision measurement of tools based on HALCON.

[1] H. A. Beyer: Linejitter and geometric calibration of CCD-cameras; in: *ISPRS Journal of Photogrammetry and Remote Sensing*, 45, (1990), 17-32

[2] R. Lenz, D. Fritsch: Accuracy of videometry with CCD-sensors; in: *ISPRS Journal of Photogrammetry and Remote Sensing*, 45, (1990), 90-110

[3] S. Lanser, C. Zierl, R. Beutlhauser: Multibildkalibrierung einer CCD-Kamera; in: Mustererkennung 1995, G. Sagerer, S. Posch, F. Kummert (Editors), Informatik aktuell, Springer-Verlag (1995), 481-491

[4] J. Wenig, P. Cohen, M. Herniou: Camera Calibration with Distortion Models and Accuracy Evaluation, *PAMI*, 14(10), (1992), 965-980

[5] C. Steger: *Unbiased extraction of Curvilinear Structures from 2D and 3D Images*; PhD thesis, Fakulät für Informatik, Technische Universität München, Herbert Utz Verlag München (1998)

[6] C. Steger: Analytical and Empirical Performance Evaluation of Subpixel Line and Edge Detection; in: *Empirical Evaluation Methods in Computer Vision*, Kevin J. Bowyer, P. Jonathon Phillips (Editors), IEEE Computer Society Press (1998), 188-210

[7] P. L. Rosin, G. A. West: Nonparametric Segmentation of Curves into Various Representations; in *IEEE Trans. On Pattern Analysis and Machine Intelligence*, 17(12), (1995) 1140-1153

[8] S. Lanser: *Modellbasierte Lokalisation gestützt auf monokolare Videobilder*; PhD thesis, Fakulät für Informatik, Technische Universität München (1997)

[9] F. Mosteller, J. W. Tukey: *Data Analysis and Regression*, Addison-Wesley Publishing Company (1977)

[10] A. Fitzgibbon, M. Pilu, R. Fisher: Direct Least Squares Fitting of Ellipses, in *ICPR13*, IEEECSP, (1996) 253-257