

HIGH ACCURACY DIMENSIONAL MEASUREMENT USING NON-TARGETED OBJECT FEATURES

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ABSTRACT

In industrial measurement applications: a great variety of tasks require the measurement of non-targeted ("natural") objects. This paper describes a novel approach to the Multi-Photo Geometrically Constrained (MPGC) matching algorithm which allows for high accuracy dimensional positioning of these features. Depending on the quality of the feature definition a relative accuracy of 1:25000 is attainable. The major algorithmic aspects will be addressed. An example from the measurement of a test object will demonstrate the performance and potential of this new approach.

KEY WORDS: Industrial inspection, image matching, edge measurement, high accuracy

1. INTRODUCTION

It has been shown that under ideal conditions image edges can be measured with very high accuracy (e.g. 0.006 pixels in *Raynor, Seitz, 1990*). In many practical applications, in particular in dimensional industrial inspection tasks, the highly accurate measurement of natural, non-targeted object features (e.g. edges) is required. With the current off-the-shelf sensor-, camera-, signal transfer- and A/D conversion technology we anticipate a relative accuracy of 1:25000 in object space to be attainable. This paper describes a new automatic measurement algorithm which can potentially deliver such accuracies. The algorithm is applied in a 3-D-vision system for precise measurements of industrial parts. The algorithm is a modification and extension of the MPGC algorithm. It finds the edge, matches respective patches in multiple images (theoretically unlimited in number) and determines 3-D object coordinates simultaneously. The paper gives a short description of the basic algorithm, its implementation and the results of a practical accuracy test. A complete algorithmic treatment can be found in *Gruen, Stallmann, 1991*.

The main features of this algorithm are:

- The free selection of image edge templates (synthetic or real, varying edge spread functions, different edge types, straight and curved edges).
- Use of collinearity constraints for the imaging rays, to reach a high precision and reliability and substantial reduction of the solution space.
- Additional image space constraints to force translations of the edge template to be perpendicular to the edge in the image.
- An unlimited number of sensor frames to be included in the matching procedure.

- The simultaneous estimation of object space coordinates with measures for quality control of the algorithm.
- The application of the algorithm for an image/object tracking procedure.

A typical part to be measured is an aeroplane engine nozzle as shown in Figure 1 with 25 cm diameter and 5 cm height. This type of object has a complex surface shape with pulse and step edges, corners, surface paint patches, different surface orientations and mixed surface

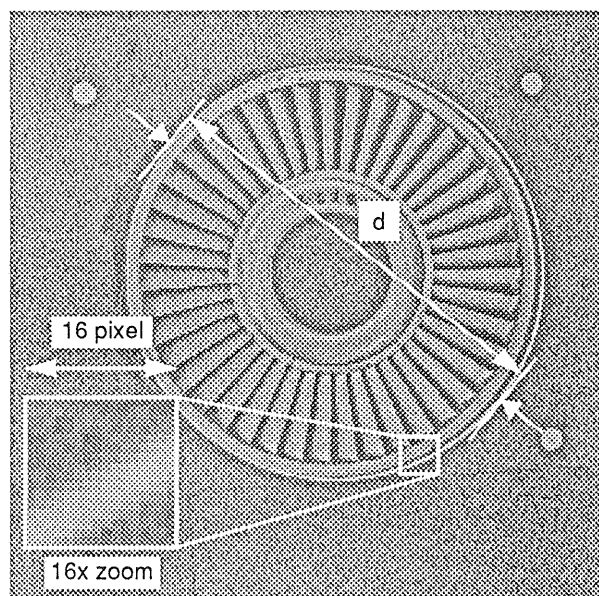


Figure 1 Aeroplane engine nozzle. Image acquired with a Videk Megaplus camera (1024 x 1024 pixels), image brightness and contrast enhanced with a Wallis filter.

geometry. The development of an algorithm for high accurate measurement of non-targeted but well-defined image edges was to be achieved. For inspection the checking of the diameter d between the outer flanges is of interest. With a diameter of 25 cm an accuracy in diameter measurement of 10 μm was requested. Because the method gives 3-D coordinates and the measurement is done in a plane the standard deviation of a single coordinate translates to 7.1 μm . A partial report on this project can be found in *El-Hakim, 1990* and *Gruen, Stallmann, 1991*.

2. EDGE MATCHING ALGORITHM

The used edge matching method is a modification and extension of the MPGC matching algorithm. This image matching algorithm is based on least squares matching (LSM) and belongs to the class of area based matching methods. In an iterative least squares adjustment process the algorithm matches multiple images, finds the edge and determines 3-D object coordinates simultaneously. More detailed descriptions of the mathematical concepts of LSM are published in *Gruen 1985*, MPGC matching in *Gruen 1985* and *Gruen, Baltsavias 1988* and edge matching in *Gruen, Stallmann 1991*. Operational details on MPGC can be found in *Baltsavias, 1992*.

2.1 Mathematical concept of MPGC matching

The LSM is a method to find similar structures in two corresponding image windows, the reference patch (template) and a search image (patch). The patch is transformed upon the template such that the squared sum of grey value differences is minimised. The location of the patch against the template is described by a shift vector. The template can be an artificial pattern for point location, or a real window of an image to find homologous image windows for parallax measurement. In our case of edge matching it is a synthetic ramp edge.

The systematic differences between the template and the patch, caused by perspective and sensor effects, can be modelled by geometric and radiometric transformations. Since the radiometric parameters are largely orthogonal to the other system parameters, the radiometric correction can be applied prior to the adjustment. Due to the small patches the bundles of rays are very narrow and for the geometric transformation the strict perspective projection can be approximated by an affine transformation and modelled by six linear parameters. The radiometric fit is done by two parameters to form a linear function. This leads to equal brightness and contrast of the patches and the template.

The LSM model uses only the grey value information. But very often additional information is available, which can be used to support the model. If the sensor geometry for each object point is based on perspective projection the collinearity conditions can be formulated. These conditions allow us to replace stereo LSM with MPGC matching, using a theoretically unlimited number of patches simultaneously for matching. Additionally, the object coordinates can be determined simultaneously. The geometrical conditions are formulated as observation

equations with usually high weights and integrated into the adjustment system.

The joint system is solved in a least squares adjustment. Because of the non-linearity of the functional model the final solution is obtained iteratively, whereby approximate values for the parameters are required: the geometric transformation parameters for each patch and the object coordinates of the object point. The iterations are stopped if each element of the solution vector falls below a threshold.

2.2 Modifications for edge matching

In order to convert the MPGC algorithm into an optimal and non-biased procedure for the measurement of edges, the following modifications and extensions had to be introduced:

- Introduction of a synthetic edge template.
- Reduction of the image shaping parameters to those which are safely determinable by the given image edge structure.
- Additional image space constraints for the shifts to prevent a movement of the template along the edge.
- Creation and pre-rotation of individual templates for each image.

The used templates are synthetic straight ramp edges from dark (grey value 30) to light (grey value 226) with varying linear ramp steepness (Figure 2).

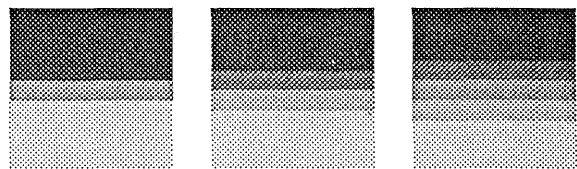


Figure 2 Synthetic straight ramp edges with varying ramp widths (1, 2 and 3 pixels)

The geometrical transformation of the patch has to be restricted, because the character of the image edges does not allow the determination of all six parameters. They allow a rotation of the patches without a scale change. A scale perpendicular to edge is implicitly included by the linear radiometric fit.

Since the image edges to be measured are essentially unidirectional, a linear template edge would slide continuously along the edge during matching. This effect is compensated by restricting the shift vector of one patch approximately perpendicular to the local edge direction.

The restrictions of the number of the reshaping parameters and the shift vector condition are also formulated as observation equations and added with a high weight to the least squares equation system (for a complete algorithmic representation see *Gruen, Stallmann, 1991*).

The orientation of the corresponding edge elements in the frames differ depending on the camera orientation. Therefore the template must be pre-rotated into the

approximate edge direction of the patch (Figure 3). The only difference between the pre-rotated template and the "original" is the rotation angle. The approximate edge direction is derived from the maximum edge gradient direction, which in turn is computed from the Sobel gradients in a 3 x 3-pixel window.

Essentially LSM and MPGC are area-based matching techniques. For high accuracy edge matching the method is transformed into a combination of an area-based and feature-based technique. This is achieved by introducing as reference template a synthetic (or real) edge pattern, which is to be matched with the actual image edges. Compared to the conventional feature-based matching techniques our method does not require the extraction of image edges, but matching is done directly by using the original grey value edges.

2.3 Edge tracking

The edge measurement procedure has been extended to an edge tracking technique, which automatically tracks and measures the full edge. The new approximate match point for the next patch of the first image is determined by using the previously matched position, its local edge direction and a user-defined incremental distance (a certain number of pixels). In the other images the previously determined position is used for the new start position. The edge tracking stops either after the measurement of a user-specified number of edge points or if matching fails, e.g. because of the end of an edge is reached. Other termination conditions can be formulated. The result of tracking is a polyline which approximates the full edge. An additional advantage is the automatic determination of good initial values through which the

number of iterations to determine the unknown parameters can be decreased. The tracking is basically done in image space. Through the simultaneous computation of consistent object space coordinates this generates implicitly an object tracking procedure.

3. IMPLEMENTATION OF THE EDGE MATCHING ALGORITHM

The previously described algorithm is implemented as a module in DEDIP (Development Environment for Digital Photogrammetry, Gruen, Beyer 1991). The following functional features and options are realised in the program:

- Interactive measurement of image coordinates in digital images.
- Visualisation of the edge matching on the display (Figure 4).
- Interface to bundle block adjustment program in DEDIP.
- Single-point edge matching and edge tracking with an unlimited number of images.
- Edge matching with and without collinearity constraints.

A stand-alone version of the program is also available which allows a higher execution speed, since the time-consuming visualisation is not used.

Figure 4 shows the visualisation of the edge matching. In the top row are the corresponding image regions around the matching point with the start and final positions and the epipolar line from the first image. The frames and crosses show the size and the position of the template and

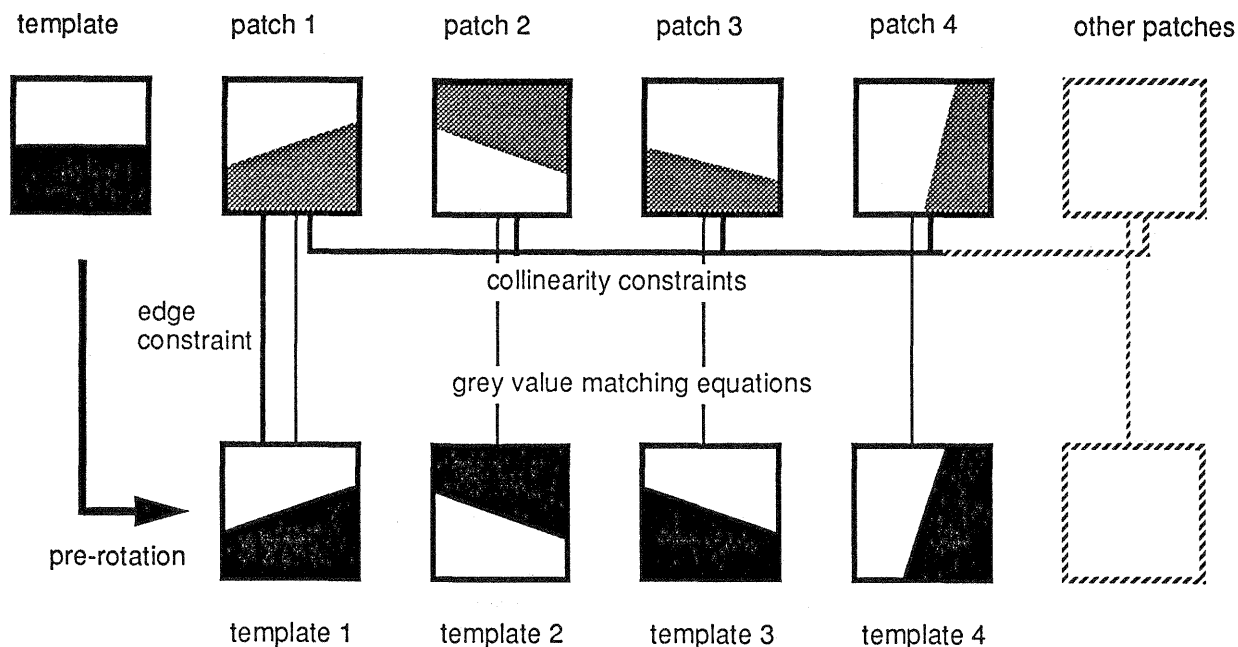


Figure 3 Edge matching as implemented

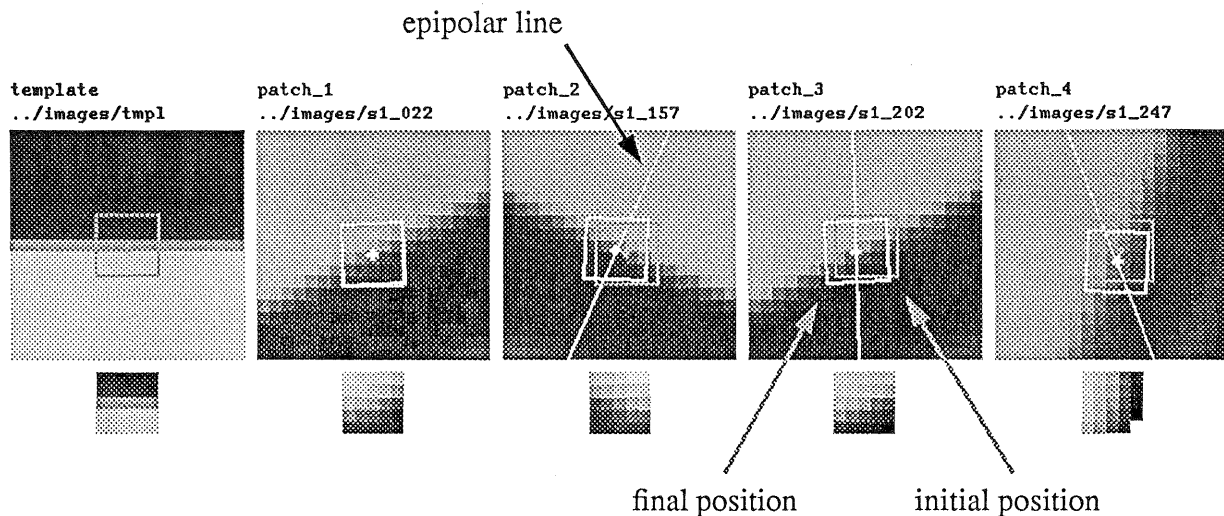


Figure 4 Visualisation of the edge matching procedure using four images

the patch in the images. In the bottom row are the template and the geometrically and radiometrically transformed patches.

The matching algorithm is only usable for fine measurement, because the LSM requires good approximate values for the iteration process of the least squares adjustment. The initial values consist of image coordinate pairs of corresponding image points in all images. The initial values must be delivered, e.g. by an operator or automatically from a given CAD model. Currently only the manual mode is implemented. The images are displayed and the approximate image coordinates of a corresponding point are measured with the cursor. For measuring of more edge points the edge tracking is used. The average pull-in range is half a patch size.

In a possible automatic mode the initial edge points in image space can be computed by resections of the model edge point using the known camera orientation. In order to exclude those images in which the edge points are invisible a hidden-surface algorithm must be applied.

4. ACCURACY TEST

The primary aim of this test was to verify the accuracy of the edge matching algorithm. For this it must be well understood that the accuracy of edge matching depends - among other parameters (orientation, etc.) - on the definition of the edge in object space, the contrast of the edge and the edge strength in image space and the amount of noise in the image data. Therefore it is of utmost importance to have an almost ideal object edge for accuracy testing available and to control illumination and imaging in an optimum way.

The test object is a short knife edge (125 mm) with an exactly polished edge for controlling the planarity of surfaces. The technical specification for the planarity tolerance of the edges is $2.5 \mu\text{m}$ (probability $P=95\%$),

defined by DIN 874 (German Industrial Standard). All points determined in object space should thus lie on a straight line defined by the knife edge.

4.1 Set-up

To test of the algorithm a single camera/multiple frames set-up was used (see Figure 5). A CCD camera was mounted on a optical bench construction and pointed towards the object. The object was supported by a rotating table, and fixed in a 3-D calibration field which was used to determine the camera orientation. By rotating the table an arbitrary number of CCD frames could be produced. The calibration field consists of a black coloured plate (56 cm x 56 cm) and towers (10 and 30 cm height) with retro-reflective targets. The targets are illuminated with a specially designed fibre-optic lighting system around the camera lens. The images are taken with a SONY XC77-CE CCD camera with a Schneider XENOPLAN 1:1.7/17 lens and a Datacube MAX-SCAN framegrabber. The framegrabber is controlled by a Sun-3E workstation. From there the data is transferred via Ethernet to a network of Sun workstations for further processing.

The framegrabber uses the composite video signal for digitisation. The effective image size is 592 (H) x 574 (V) pixels with a pixel spacing of $13.5 \mu\text{m}$ (H) and $11.0 \mu\text{m}$ (V). At each camera position 4 images are acquired and their average is used for further processing.

For the test 12 images are acquired: 8 images with a 45° -interval table rotation and 4 images with a 90° rotation of the camera about its axis (κ rotation). Figure 6 shows one of the images used for orientation and edge matching. The height-base-ratio is $h/b = 8.81$ and the average image scale is 1:44, i.e. $10 \mu\text{m}$ in object space correspond to $0.23 \mu\text{m}$ in image space or 0.017 pixel with $13.5 \mu\text{m}$ pixel spacing.

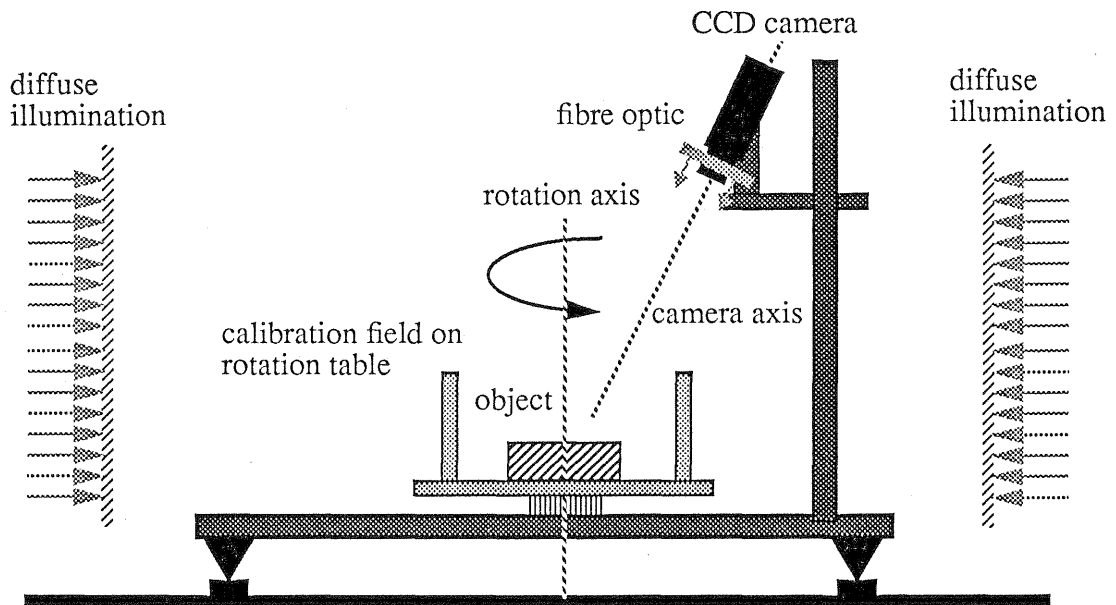


Figure 5 Image acquisition arrangement for testing

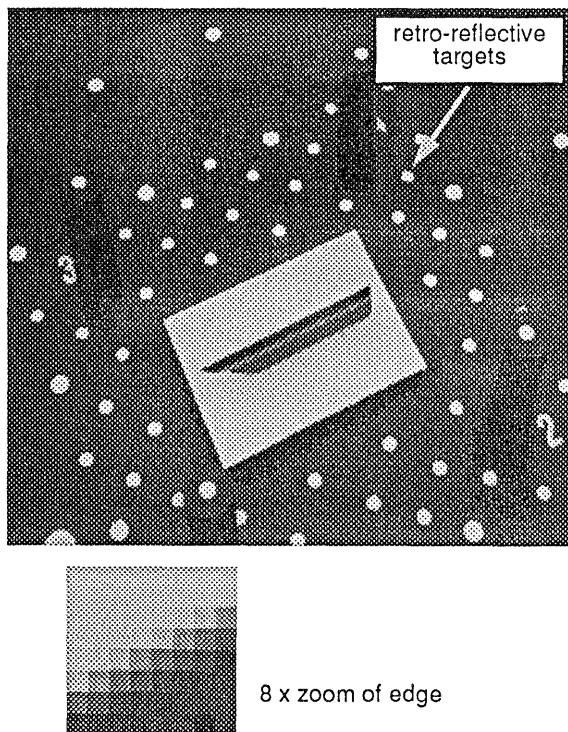


Figure 6 CCD frame with knife edge

4.2 Illumination

The chosen lighting conditions have a decisive influence on the image quality. An optimal brightness and contrast

can only be reached by a good illumination. Bad lighting can fade features into the background, make edges fuzzy and produce pseudo edges by shadows. The lighting depends on the surface shape, surface texture, surface reflectance and surface colour of the object, furthermore on the physical constraints imposed by the manufacturing environment, the light level and the light character (e.g. polarised light). The problems of surface texture, reflectance and colour can be avoided by a special surface treatment. The knife edge has a dazzle-free edge and the nozzle a special surface treatment.

In the accuracy test there are two objects to be measured: the object and the targets of the calibration field. The illumination must be chosen such that both are well illuminated. To reach this aim a different illumination for each of the two objects has been used. The retro-reflective targets need only a weak illumination. They are illuminated with a specially designed fibre-optic lighting system arranged around the camera lens. The fibre-optic system is adjustable and thus an optimal target illumination can be selected.

The use of diffuse lighting allows a uniform illumination of the object and produces little shadows and reflections. The diffuse lighting is achieved by a white curtain around the whole set-up and an illumination with high frequency fluorescent tubes.

4.3 TEST RESULTS

All tasks of image acquisition, target location, bundle block adjustment with self calibration and the edge matching were performed with the program DEDIP.

The measurement of image target location for orientation was done with least squares template matching. The camera orientation information was determined by a bundle block adjustment, using 10 additional parameters for compensating systematic image errors. All 12 frames were used. Minimum datum information was applied. The adjustment gave the estimated image coordinate errors as $\mu_x = 0.50 \mu\text{m}$ (0.037 pixel) and $\mu_y = 0.61 \mu\text{m}$ (0.055 pixel) with a system redundancy of $r = 430$.

The camera orientation parameters were introduced in the edge matching as deterministic. The edge matching was done with 4, 6 and 8 frames respectively. For the edge tracking function a 3 pixel wide template ramp and a patch size of 5 x 5 pixels were used. 173 edge points were measured.

A straight line was fitted through the object points projected onto the X-Y-plane and the X-Z-plane. The differences between the observed coordinates and the mean line (DXY, DXZ) are plotted in Figure 7 and their minimum and maximum values and root mean square errors (RMS) derived (Table 1). Additionally, the standard deviations of the determined object coordinates are plotted and their average values derived as

$$\overline{SY} = \sqrt{\frac{\sum SY^2}{n}}, \overline{SZ} = \sqrt{\frac{\sum SZ^2}{n}}$$

and also listed in Table 1.

As evidenced by the RMS values of Table 1 the deviations of the estimated knife edge points from an adjusted straight line stay with $6 \mu\text{m}$ well within the 1:25000 relative accuracy measure as far as the horizontal distance (Y) is concerned. The respective Z-(depth-) values exceed this specification, but they are not of interest in the original application example. The estimated standard deviations of the related object coordinates, with values of about $14.5 \mu\text{m}$ in Y and $28.0 \mu\text{m}$ in Z, are less precise, because they also include errors in the orientation of the CCD-frames and are dependent on the datum choice. Since in many inspection tasks the accuracy of location and orientation of measured object features is only of minor interest, these absolute precision estimates are mostly of little value here.

This accuracy test and other tests with different set-ups, camera configurations, templates etc. allow formulation of some more general observations:

- If big differences between the template and the patches occur, e.g. at corners, junctions and occlusions, the

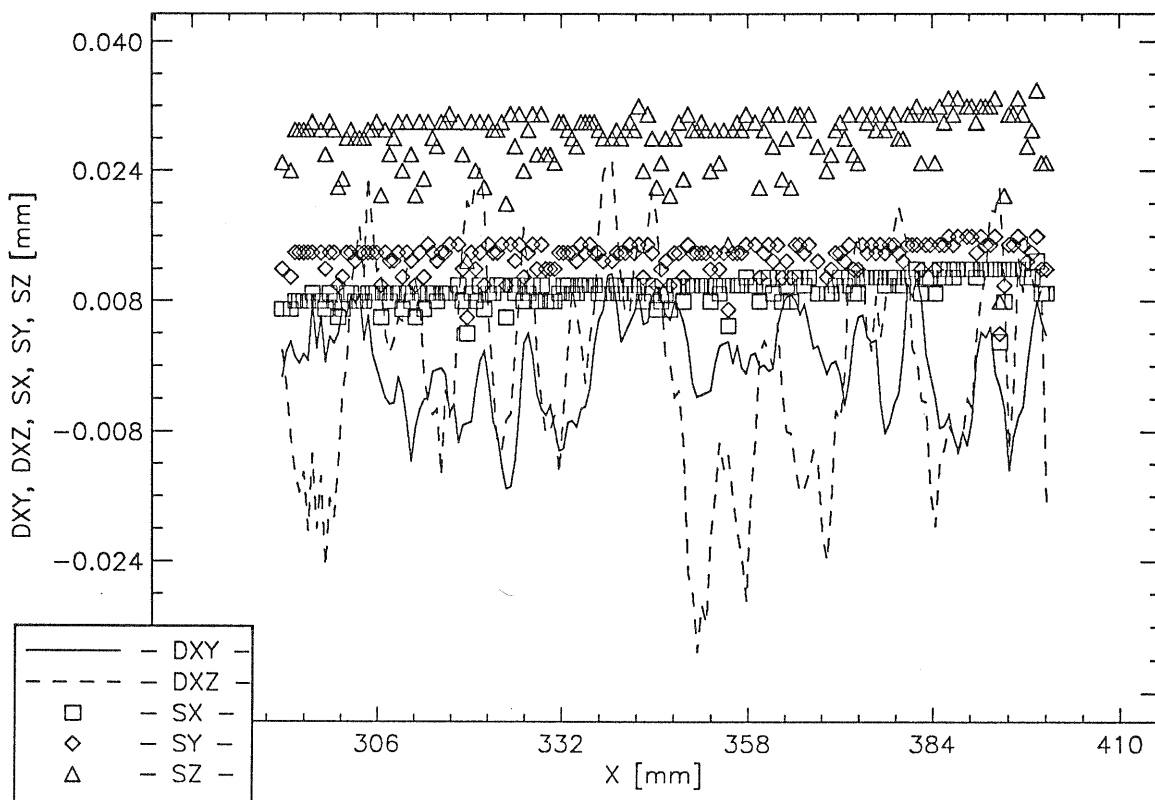


Figure 7 Edge matching results using the knife edge and six image frames. Differences DXY, DXZ between estimated and straight line adjusted edge point positions. Standard deviations SX, SY, SZ of estimated point locations.

Table 1 Edge matching results (values in μm given in object space)

number of frames	RMS DXY	minimum DXY	maximum DXY	\overline{SY}	RMS DXZ	minimum DXZ	maximum DXZ	\overline{SZ}
4	5.8	-12.0	+14.8	15.4	13.1	-40.1	+27.4	28.1
6	5.9	-15.0	+11.4	13.6	13.5	-35.0	+25.3	28.3
8	6.6	-17.7	+14.9	14.3	12.5	-36.1	+39.5	27.8

matching fails, because the adjustment solution does not converge.

- The use of more than 4 images does not result in a significant improvement of the matching results if the camera configuration is good.
- The number of iterations per matched point using the edge tracking procedure depends on the curvature of the edge and the tracking step width. For the examples with 4 images the average number of iterations was 3.
- The accuracy of LSM also depends on the design of the template. If a very steep edge template (grey level ramp, one pixel wide) is used, the radiometric corrections will also cause the patch patterns to be compressed into very steep gradients. This leads to inaccurate LSM results.
- The use of a larger patch size (7 x 7 or 9 x 9 pixel) smooths the difference curve, because for the edge matching more grey values are used along the edge. However, the improvement in the results is not significant.

The computing performance is 6.7 points/sec, measured on a Sun 4/490 workstation and relates to an average number of 4.3 iterations per matched point. The performance was measured with the program version without screen display using 4 images. 652 object points were thus matched in a total time of 97.3 sec.

5. CONCLUSIONS

As evidenced by the controlled practical test presented in this paper our algorithm has the capability to measure natural object edges with a relative accuracy of 1:25000. This translates into 0.023 pixel in image space and was obtained with standard image acquisition hardware and under non-optimized camera orientation conditions. A further improvement can be expected through the use of higher resolution CCD-imager chips, better signal transfer and digitisation hardware and more accurate camera orientations.

However, in order to obtain such high accuracies a number of prerequisites must be met, like the existence of a sufficiently well-defined object edge, an appropriate illumination, and the usage of more than two CCD frames. At this level, a close-range vision system can well compete with a CMM (Coordinate Measurement Machine), having the additional advantages of higher processing speed and non-contact measurement characteristics.

6. ACKNOWLEDGEMENTS

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