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Automatic registration method for multisensor datasets adopted for dimensional measurements on cutting tools

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Abstract

Multisensor systems with optical 3D sensors are frequently employed to capture complete surface information by measuring workpieces from different views. During coarse and fine registration the resulting datasets are afterward transformed into one common coordinate system. Automatic fine registration methods are well established in dimensional metrology, whereas there is a deficit in automatic coarse registration methods. The advantage of a fully automatic coarse registration procedure is twofold: it enables a fast and contact-free alignment and further a flexible application to datasets of any kind of optical 3D sensor. In this paper, an algorithm adapted for a robust automatic coarse registration is presented. The method was originally developed for the field of object reconstruction or localization. It is based on a segmentation of planes in the datasets to calculate the transformation parameters. The rotation is defined by the normals of three corresponding segmented planes of two overlapping datasets, while the translation is calculated via the intersection point of the segmented planes. First results have shown that the translation is strongly shape dependent: 3D data of objects with non-orthogonal planar flanks cannot be registered with the current method. In the novel supplement for the algorithm, the translation is additionally calculated via the distance between centroids of corresponding segmented planes, which results in more than one option for the transformation. A newly introduced measure considering the distance between the datasets after coarse registration evaluates the best possible transformation. Results of the robust automatic registration method are presented on the example of datasets taken from a cutting tool with a fringe-projection system and a focus-variation system. The successful application in dimensional metrology is proven with evaluations of shape parameters based on the registered datasets of a calibrated workpiece.

Keywords: automatic registration, three-dimensional metrology, cutting tools

(Some figures may appear in colour only in the online journal)

1. Introduction

The demand for a fully automatic registration method for three-dimensional surface data is steadily growing as time efficiency and repeatability are becoming more and more important. For the inspection of technical workpieces for example Optical 3D metrology enables measurements of objects such as technical workpieces without damaging their
surface (for an overview on optical range sensors see e.g. Beraldin et al. (2003), Besl (1988), Blais (2004) and Häusler (1999)). In order to determine the relevant shape parameters during quality inspection, commonly surface measurements from different views, with different resolutions, and partly different measurement principles have to be performed with an optical multisensor system and the acquired information has to be combined. For this purpose, the resulting datasets have to be transformed into one common co-ordinate system. This procedure is called registration. While the 3D data acquisition might be automated, the registration procedure is generally not.

Registration is usually divided into two parts: coarse and fine registration. Coarse registration describes the approximate alignment of two datasets and ensures sufficiently small deviations between the datasets to guarantee a successful fine registration. Latter optimizes the alignment result. While fine registration is well established and commonly performed with an iterative-closest-point (ICP) algorithm, originally proposed by Besl and McKay (1992), an automatic coarse registration is often still a time-consuming or unreliable process, if existing at all.

In dimensional metrology, the established methods for coarse registration are mostly semi-automatic. Interactive determinations of corresponding points by the user (see e.g. Weckenhann et al. 2009)) or a placement of fiducial markers (reference points) on the object (see e.g. Cuypers et al. 2009)) have been widely used. These methods are time consuming, mostly due to their preparation time, and the results are strongly influenced by the operator. If the sensors are integrated into a moving platform (e.g. coordinate measuring machine or robot), also the calibrated position of the sensor can be used to register the datasets (see e.g. Zacher et al. 2002)). In this case, the coarse registration is automatic, but bound to an inflexible test stand.

Depending on the registration task, i.e. to which class the measured object belongs, there are some solution approaches for an automatic coarse registration. For example, if an object has many salient points, i.e. noticeable surface points which can be used for registration, as is the case for human faces, a feature-based registration method such as presented by Schön and Häusler (2006) can be employed to automatically align such datasets. Kaminski et al. (2007) describes a registration of surfaces with almost constant curvature, such as lenses. Furthermore, such registration methods can e.g. be found in Gelfand et al. 2005), Johnson and Hebert (1997), Stein and Medioni (1992), Faugeras and Hebert (1986) and Mian et al (2006).

For technical workpieces, however, these methods generally cannot be transferred, since these objects usually do not provide sufficiently many salient points. They rather consist of an arrangement of the planar surface parts, as is the case for engine blocks. For such objects, a segmentation-based registration would be suitable, as presented by Maier and Häusler (2006).

While the method by Maier and Häusler (2006), which will be explained below, produces good results for workpieces with planar parts pointing in all three linearly independent directions, the method shows weaknesses when applying it to the technical workpieces of interest for this paper: cutting tools. Although the rotation of two datasets is calculated correctly, their translation onto each other is very sensitive to the directions of the plane normals. The more the including angle between the normals deviates from 90°, the more instable, or even impossible, the registration becomes. Since there are a number of technical workpieces such as transmission and coupling housings which show this behavior, the registration method proofs inapplicable. In this paper, a novel, robust automatic registration method is proposed which is an adaptation to the procedure presented by Maier and Häusler (2006), enhanced by an optimized translation calculation.

The paper is organized as follows. First, the original automatic coarse registration method based on segmentation is briefly described and its weaknesses are explained. Then, the novel method is presented which eliminates these weaknesses. Afterward, experimental results of the automatic coarse registration of multisensor datasets of cutting tools are shown. Here, datasets captured with the same as well as with different measurement principles and resolutions (chosen according to the measurement task) are considered. Furthermore, it is demonstrated that, based on the coarse registration results, fine registration and fusion can be successfully performed. Some dimensional evaluations confirm the efficiency of the novel adaption for the automatic coarse registration method. A conclusion and a discussion complete the paper.

2. Original segment-based registration method

Maier and Häusler (2006) published a registration method based on segmentation. The key idea is to detect the corresponding plane segments in two triangulated 3D datasets which need to be aligned. Plane segments have the advantage that they are robust against size deviations in the two datasets. Even if they have different sizes, they still share the same information about the planar part of the object. Theoretically, three plane segments are sufficient to perform the registration.

2.1. Process flow of the method

The method consists of the following five steps (see figure 1). In the first step, a Gaussian filter is applied to smooth both datasets. In the second step, a series of sub-steps are performed. (i) Vertices are classified by its surrounding triangles in flat and non-flat. A vertex is declared flat if the variance of the normals of the neighboring triangles is smaller than a given threshold $t_{flat}$ in mm². According to the setting of this threshold also surface areas with slight curvatures can be classified as flat. To ensure consistent flatness information for datasets measured with sensors with different measurement ranges and resolutions, the variance calculation is normalized by the area of the triangles. (ii) Only flat vertices are selected which have enough adjacent flat vertices. (iii) Vertices are clustered with every adjacent flat vertex. (iv) They are post-processed by discarding too small clusters. (v) Segments are created by selecting the triangles determined by the clustered vertices.
Figure 1. Process flow of the original segmentation-based registration method.

Each segment is represented by its centroid and its weighted average normal, yielding its Hessian normal form description

\[ n \cdot p = d, \]

where \( n \) is the unit normal, \( p \) is a 3D point (in presented case, the centroid) and \( d \) is the distance to the origin of the segment. In the third step, subsets of at least three segments of each dataset are formed and their plane parameters compared in order to determine the corresponding segments. The selected segments have to fulfill the condition that the angle between their normals is bigger than a given threshold \( \theta_{\text{normals}} \) in degrees to provide information for a reliable determination of corresponding segments. For this purpose, a measure which is independent of rotation and translation in space is applied to the normals:

\[ I_1(A', B') = \frac{1}{q} \sum_{i=1}^{q-1} \sum_{j=i+1}^{q} ||n_i^n - n_j^n|| - ||n_i^B - n_j^B||^2, \]

where \( A' \) and \( B' \) are subsets of segments in datasets \( A \) and \( B \), respectively, and \( q \) is the cardinality of the subsets. The minimum of \( I_1 \) yields the corresponding segments. In the fourth step, the rotation is determined by employing quaternions (see e.g. Kuipers (2002)). In the fifth step, the translation is determined based on the calculation of the intersection points for the planar segments of each subset.

2.2. Weakness of the original segmentation-based method

The weakness of the existing method is caused by the fifth step, the calculation and application of the translation. Basing the transformation on the calculated intersection point of segments is an instable procedure, as it strongly depends on the geometry of the selected segments. When the normals of the plane segments are almost linearly dependent, the intersection point can be rather far away from the location of the planar parts. Almost linear dependence means that the normals are nearly located in one plane. A small deviation in the calculation of a normal then leads to a large shift of the intersection point.

In figure 2, the instability of the procedure is demonstrated. Two 3D datasets taken from different views of the same workpiece were segmented and the intersection points were calculated. In figure 2(b), the 3D view of the object produces an intersection point (depicted as a circle) which lies very close to the object surface. The intersection point calculated for the 3D view depicted in figure 2(c) lies far from the object surface and is too instable for a successful transformation.

3. Optimization of the registration method

Each of the resulting segments from the segmentation process is represented by its normal and centroid. The translation vector is calculated from these features to perform the translation process as described in the previous section. However, for the above-mentioned limitations the result of the translation is not robust.

To improve the robustness of the registration, we extended the method by an alternative calculation for the translation vector and a final quantification of the result. In the adopted method, the translation vector is additionally calculated from
the positions of the centroids of the corresponding segments. Once the rotation is performed, a translation vector is calculated for each corresponding pair of segments of both datasets. Each of these vectors joins the centroids $p$ of a pair of segments from datasets $A$ and $B$:

$$t_{\text{centroid}}^i = p^B_i - p^A_i, \quad \text{for } i = 1, ..., q.$$  (3)

The number of translation vectors increases linearly with the number of corresponding segments considered in the process (in most cases three plus the translation vector calculated with the intersection point method). The following diagram shows the process flow of the optimized registration method (see figure 3).

In order to determine the transformation for the dataset to be registered, the rotation is calculated as described in step 4 and the potential translation vectors are computed (step 5a). Consequently, the number of potential registration results equals the number of corresponding segment pairs (as described above) plus one (for the result obtained for the original method).

The comparison and quantification of the potential translation results are performed (step 5b) based on a distance measure between all transformed corresponding segments:

$$I_k(A', B') = \frac{1}{q} \sum_{i=1}^{q} |d^A_i - d^B_i| = \frac{1}{q} \sum_{i=1}^{q} |n^A_i \cdot p^A_i - n^B_i \cdot p^B_i|.$$  (4)

To calculate the distance between the corresponding segments $A'$ and $B'$, the Hessian normal form of a plane is used (equation (1)). The sum of the distances between all the corresponding segments is considered for each vector. The vector with the smallest sum becomes the best and final translation vector, which is automatically applied to the dataset to be transformed.

4. Experimental results

In the following section, the adopted automatic registration method and its robustness will be presented, considering datasets measured with the same as well as different measurement principles. The latter is important, since for a workpiece, some parameters of interest can only be determined from shape elements of different scale. This requires the application of different measurement principles (as well as different resolutions and measurement ranges).

$$t_{\text{flat}} = 0.95 \times 10^{-3} \text{ mm}^2$$  
$$t_{\text{flat}} = 0.115 \times 10^{-3} \text{ mm}^2$$  

(a)  
(b)  
(c)  
(d)  

Figure 4. Segmentation results achieved with different thresholds. (a) and (b) Dataset fringe-projection system. (c) and (d) Dataset focus-variation system.

4.1. Results of automatic coarse registration

The implemented method will be demonstrated on datasets acquired from a cutting tool with two optical 3D sensors: a fringe-projection system (see e.g. Halioua et al (1984) for the measurement principle) (measurement range 41.1 mm × 31.3 mm × 10 mm, lateral resolution 25 μm, vertical resolution 3 μm) and a focus-variation system (measurement field of 2.9 mm × 2.2 mm, resolution 2.2 μm, max. vertical traverse path 100 mm) (Krenn 2007). Both have proven to be adequate measurement systems to capture relevant geometries on cutting tools (Weckenmann and Shaw 2009). The datasets were captured with a sufficient overlap to ensure a successful detection of the corresponding segments. Three segments in each dataset were selected for the calculation of the correspondences. Figure 4 shows segmentation results for the datasets of both measurement systems applying different thresholds $t_{\text{flat}}$ for the segmentation. Each segment is depicted with its normal vector and in a different color. The results underline the importance of choosing right segmentation parameters for a successful registration. A larger threshold value $t_{\text{flat}}$ results in fewer segmented planes (figures 4(a) and (c)) in comparison to applying a smaller threshold value $t_{\text{flat}}$ (figures 4(b) and (d)).
The value of $t_{\text{flat}}$ has to be chosen in such a way that at least three corresponding segments are detected in the overlap of the two datasets.

The advantage of the implemented optimized method becomes clear in figure 5. Two datasets of the fringe-projection system are registered. For the dataset A, the threshold $t_{\text{flat}} = 0.1 \times 10^{-3}$ mm$^2$ was applied. For the dataset B, the threshold was chosen with $t_{\text{flat}} = 0.2 \times 10^{-3}$ mm$^2$. Depending on the view the dataset was taken from, a different number of segments were detected. The threshold was chosen in such a way that at least three segments are available in the overlapping area. The calculated corresponding planes/segments are color coded and the measure distance is given for all possible translations. The smallest distance is calculated with the centroids of the segments named ‘b’ ($I_2$-centroid blue). In comparison with the other segmented planes, these segments are robust against small changes of the threshold for the segmentation because of their size. Furthermore, their centroids are stable, as the size of the corresponding segments in datasets A and B only slightly varies. The biggest distance is obtained with the translation parameters calculated applying the intersection points of the segments. This result confirms the instability pointed out in section 2.2.

Figure 6 shows the registration result for two datasets where the intersection point of the segments leads to the smallest measure distance and therefore to the ideal translation vector. Both presented coarse registration results are sufficient to successfully run the ICP algorithm during fine registration as shown in section 4.2.

As could be demonstrated, the ideal method to determine the translation vector was automatically chosen to successfully register the datasets depicted in figures 5 and 6. While the datasets depicted in figure 6 have segmented planes with normals pointing in almost orthogonal directions, the resulting normals of the datasets depicted in figure 5 are almost linearly dependent. As a consequence, the original ‘intersection-point’-based method yields good results for the datasets shown in figure 6 but proofs rather unstable, or even inapplicable, for the ones shown in figure 5. A bigger distance calculated with the ‘intersection-point’-based method than with the ‘centroid’-based method points out this instability. For all the datasets tested with this adopted algorithm so far, the reason for the instability was always an intersection point which was located too far from the datasets. For the user of the algorithm this knowledge is not necessary, as the program automatically decides according to the smallest distance which translation vector to apply during coarse registration. In the case when the original method is chosen, the result is independent of the segment size (this also explains why the distance measure $I_2$-intersection point in figure 6 is much smaller than $I_2$-centroid blue in figure 5). Although the new ‘centroid’-based approach depends on the segment size, the registration could be performed and the result can also successfully be fine registered employing an ICP algorithm. Consideration of all corresponding segments for the calculation and an automatic detection of the smallest distance ensures that the most stable translation vector (determined from corresponding segments of similar sizes) is applied for the final registration. This adopted coarse registration approach becomes relevant whenever such non-orthogonal flanks are measured and need to be aligned, as is the case for cutting tools.

As mentioned above, a robust coarse registration method is also important for an application to datasets captured with different measurement systems. Figure 7 shows the successful result of a coarse registration of the datasets.
depicted in figure 4, of the fringe-projection system and the focus-variation system, applying the introduced method. The coarse registration was conducted with the segmentation results achieved by applying a threshold of $t_{th} = 0.95 \times 10^{-3}$ mm$^2$ (dataset fringe-projection system) and $t_{th} = 0.115 \times 10^{-3}$ mm$^2$ (dataset focus-variation system). The smallest measured distance between the datasets after coarse registration was calculated applying the intersection point method for the calculation of the translation vector.

After the coarse registration there are clearly visible deviations between the datasets, which can be explained with the method to calculate the translation vector. For datasets in different scales the position of the corresponding segments does not necessarily need to correspond due to the different measurement fields. In the case of the cutting tools, this can be seen at the cutting face. The segmented plane in the dataset of the fringe-projection system (larger measurement range) is located at a different position than in the dataset of the focus-variation system (smaller measurement range). This results in a displacement of the intersection point, which is of a similar magnitude as the offset of the two corresponding segments. Nevertheless, the remaining deviation was proven small enough for a successful fine registration (figure 7(b)).

### 4.2. Results of automatic fine registration and data fusion

For an application of the introduced automatic coarse registration method in dimensional metrology, the correct results of shape parameters after registration have to be proven. For this, measurements from different views of a calibrated cutting tool, captured with the fringe-projection system, were automatically coarse and fine registered and afterward fused to one data model, on which the dimensional evaluations of relevant parameters were conducted.

The measurement strategy for the holistic measurement of the cutting tool is selected under consideration of the chosen measurement procedure and the necessary overlapping area between two neighboring views (datasets). As shown in figure 8(a), measurements from six views have proven to be the optimal choice. During the measurement, the cutting tool is positioned on a rotary table and turned $60^\circ$ between each measurement. The fringe-projection sensor is positioned in a way that cutting and flank face of the tool are measured under the same angle.

The segmentation parameters were applied as described in section 4.1. As threshold for the necessary angle between normals of the segments of one dataset $\theta_{\text{normals}} = 10^\circ$ has been proven optimal. During coarse and fine registration, one dataset was fixed and the other datasets were pairwise registered to this dataset. After the pairwise fine registration a global fine registration was additionally applied. The fine registration and data fusion methods are part of the commercially available software SLIM$^3$D (3D-Shape GmbH, Erlangen, Germany).

The results of the dimensional parameters presented in table 1 were evaluated based on 20 repeatable measurements and subsequent registrations and fusions. For the evaluations, the parameters ‘inscribed circle’ $d$ and ‘corner angle’ $\varepsilon_r$ are chosen, since these parameters would be affected in the case of the incorrect registration and fusion of the datasets. The measurement uncertainty was calculated based on DIN EN ISO 15530–3:2009–07 (with a coverage factor $k = 2$). It applies a calibrated workpiece, on which the repeatable measurements are conducted. For the measurement uncertainty listed in table 1 the standard uncertainty from the measurement process

### Table 1. Results for relevant parameters of a cutting tool applying interactive and automatic coarse registration.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\varepsilon_1$ (°)</th>
<th>$\varepsilon_2$ (°)</th>
<th>$d$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration value</td>
<td>56.7</td>
<td>56.6</td>
<td>9.590</td>
</tr>
<tr>
<td>Standard uncertainty</td>
<td>0.2</td>
<td>0.2</td>
<td>0.001</td>
</tr>
<tr>
<td>calibration $u_p$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Results of interactive registration</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard uncertainty</td>
<td>0.1</td>
<td>0.1</td>
<td>0.028</td>
</tr>
<tr>
<td>measurement process $u_p$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Systematic deviation $b$</td>
<td>0.2</td>
<td>0.2</td>
<td>0.002</td>
</tr>
<tr>
<td>Mean of measurements</td>
<td>56.9</td>
<td>56.8</td>
<td>9.589</td>
</tr>
<tr>
<td>Measurement uncertainty $U$</td>
<td>0.6</td>
<td>0.6</td>
<td>0.056</td>
</tr>
<tr>
<td>Results of automatic registration</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard uncertainty</td>
<td>0.1</td>
<td>0.1</td>
<td>0.014</td>
</tr>
<tr>
<td>measurement process $u_p$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Systematic deviation $b$</td>
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<td>0.2</td>
<td>0.004</td>
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<tr>
<td>Mean of measurements</td>
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<td>9.586</td>
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<tr>
<td>Measurement uncertainty $U$</td>
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<td>0.5</td>
<td>0.029</td>
</tr>
</tbody>
</table>
$u_p$ as well as the uncertainty of the calibration parameters $u_{cal}$ and the systematic deviation $b$ were considered:

$$U = k \cdot \sqrt{u_p^2 + u_{cal}^2 + b^2}. \quad (5)$$

The applied workpiece was calibrated with the coordinate measuring machine Zeiss UPMC 1200 CARAT S-ACC. To judge the measurement results for the chosen parameters, the results were compared to results achieved applying an interactive registration method—see Shaw and Weckenmann (2011) for further details. This method was performed by a trained and experienced user in order to ensure high-quality parameters.

As presented in table 1, the measured values and uncertainties for the corner angles achieved with both methods are comparable. Looking at the measurement result for the ‘inscribed circle’ $d$, especially the smaller measurement uncertainty is noticeable, which is caused by the smaller standard uncertainty in the measurement process. As the coarse registration is the only step changed during the measurement process, the automatic method is likely to be the reason for the improved standard uncertainty. In comparison to the interactive registration, the deviations $\Delta$ after the coarse registration are higher but more repeatable. This can be explained by the manual determination of corresponding points during the interactive registration, which results in a higher deviation after coarse registration than the segmentation-based automatic approach.

One further advantage of the automatic method is the time reduction of the coarse registration procedure. The interactive coarse registration of two datasets of the fringe-projection system takes a couple of minutes (depending on how precise the user chooses the corresponding points), whereas the automatic method registers two datasets within 1 min. Most of this time is used for the segmentation process, which depends on the number of points in the dataset, and only a couple of seconds for the registration itself.

5. Conclusion

The presented automatic registration procedure applying an augmented segmentation-based coarse registration was proven to give robust results for datasets of technical workpieces, which are dominated by planar surface parts. The novel modification made the registration stable even for datasets of objects with non-orthogonal planar flanks, such as a cutting tool. The original method failed for these cases due to a miscalculation of the translation vector. The stabilization in the adopted method was achieved integrating additional methods for the calculation of the translation and, most importantly, evaluating the distances between the datasets after registration with a newly introduced distance measure. The automatic registration method was validated on measurements taken with the same sensor as well as with different sensors (different measurement principles and different resolutions). This way, the successful application was also ensured for datasets of multiscaled workpieces, which require different sensors to obtain shape parameters in the macro- as well as micro-scale. Furthermore, a successful application for dimensional measurements on cutting tools was proven. Compared to standard coarse registration methods in dimensional metrology, such as the interactive method applied above, the presented automatic procedure enabled a fast and contact-free alignment and a flexible application to datasets of any kind of optical 3D sensor. Furthermore, it led to a decreased user influence and therefore smaller measurement uncertainties, which is a further benefit for 3D metrology.

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References

Blais F 2004 Review of 20 years of range sensor development J. Electron. Imaging 13 231–40
Faugeras O D and Hebert M 1986 The representation, recognition, and locating of 3-d objects Int. J. Robot. Res. 5 27–52
Johnson A E and Hebert M 1997 Surface registration by matching oriented points Int. Conf. on Recent Advances in 3-D Imaging and Modeling pp 121–8
Kaminski J, Struck M, Maier T, Ettl S and Häusler G 2007 Robust automatic coarse registration of specular free-form surfaces Proc. 10th Conf. of German Branch of the European Optical Society
Krenn A 2007 Optical surface metrology-3D measurements of surfaces with steep Imaging Microsc. 1 38
Maier T and Häusler G 2006 Segmentation based fast registration of specular free-form surfaces Proc. Int. Conf. on Pattern Recognition pp 340–3
pairwise registration of range images *Int. J. Comput. Vis.* 66 19–40
Shaw L and Weckenmann A 2011 Automatic registration method for hybrid optical co-ordinate measuring technology *CIRP Ann.—Manuf. Technol.* 60 539–42