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GEOMETRIC REVERSE ENGINEERING USING A LASER PROFILE SCANNER MOUNTED ON AN INDUSTRIAL ROBOT

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Abstract: *Laser scanners in combination with accurate orientation devices are often used in Geometric Reverse Engineering (GRE) to measure point data. The industrial robot as a device for orientation has relatively low accuracy but the advantage of being numerically controlled, fast, and flexible and it is therefore of interest to investigate if it can be used in this application. We have built a measuring system based on a laser profile scanner mounted on an industrial robot. In this paper we present results from practical tests based on point data. We also show how data from laser profiles can be used to increase accuracy in some cases. Finally we propose a new method for plane segmentation using laser profiles.*

Keywords: Geometric Reverse engineering, 3D measurement systems, laser scanning, segmentation, region growing.

1. INTRODUCTION

Geometric Reverse Engineering (GRE) is concerned with the problem of creating CAD-models of real objects by fitting 3D point data measured from their surfaces. An introduction to GRE which is often referred to is a paper by Varady [1]. See also [2] and [3]. Measurement systems for this purpose are often based on laser range finders in combination with mechanical devices for orientation. For industrial applications it is preferable that the orienting device is possible to control numerically, so that point clouds can be created without human interaction. This leads to the idea of using an industrial robot as the orienting device.

Figure 1: The measuring system

To test this idea we have designed and built a measuring system based on a profile scanner and an industrial robot ABB IRB140 with a turntable see figure 1. To integrate the two systems and control the movement of the scanner, we use Varkon, an open source CAD system; see [4] and [5].With a measurement system of this kind, a point on the surface of an object is:

$$P = P_r + N_r * d \qquad (1)$$

Where P_r the current 3D position of the robot tool centre is N_r is the direction of the laser range finder and d is the distance from P_r to the surface of the object. Industrial robots are usually less accurate than laser range finders and 3D point data calculated according to (1) will thus be limited in accuracy by the robot. If a profile scanner is used however, some GRE operations can be performed without involving the orientation of the robot. A profile scanner creates a profile on the surface of an object with a line laser and uses a camera to capture the image of the profile. 2D image processing is then applied to identify the pixels in the image that represent the profile and a calibration table is finally used to map pixels to a 2D coordinate system. See figure 2.

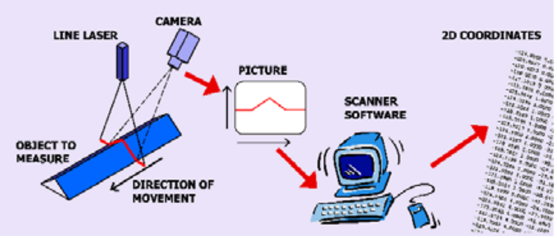

Figure 2: From pixels to profiles

A plane surface in 3D space will appear as a straight line in the 2D profile and this property can be used to measure distances within the camera picture with relatively high accuracy since the orientation of the robot is not involved. GRE of 3D surfaces is not possible without involving the orientation of the robot but we believe that if the information in the 2D profiles is used wisely we can still achieve an accuracy which is better than the accuracy of the robot. To illustrate this we will first investigate traditional GRE of planar surfaces based on 3D point clouds calculated using (1). We will then present the result from an experiment where the radius of a cylinder is established using information from a 2D profile only. This experiment shows that 2D profiles can be used to measure distances within a single camera picture without loss of accuracy. We will finally propose an alternative to traditional segmentation of planes based on 2D profiles instead of 3D point data.

2. GRE BASED ON POINT CLOUDS

A well established method for GRE of planar surfaces is to start with an unordered set of 3D points and sort them spatially so that they can be connected into a triangular mesh, see [6], [7], [8] and [9]. The triangulation algorithm we use is described in [4]. Next, segmentation is used to identify regions of coplanar triangles. Finally, planes are fitted to the segmented regions. See [6] and [10] for surveys of segmentation methods. A segmentation method that is well suited for GRE of planar surfaces is region growing. A seed triangle is first identified and adjacent triangles are then added to form a planar region. In [11], Sacchi et al. propose a method to identify seeds based on scalar curvature values computed for each triangle using information from surrounding triangles. We have implemented this method and added a growing criterion based on the direction of normal vectors. The resulting GRE algorithm includes the following steps:

1. Join neighboring points into a triangular mesh. This is relatively easy since the points from the profile scanner are ordered sequentially within each profile and profiles are ordered sequentially in the direction the robot is moving.
2. Calculate scalar curvature estimates for all triangles using the Sacchi algorithm. An intermediate step in the algorithm is the calculation of approximate normal vectors and these are saved to be used in step 3 below.
3. Use the triangle with lowest curvature as a seed and add connected triangles to the region as long as their normal vectors are reasonably parallel with the normal of the seed. A cone angle is used as a threshold for the normal deviation; see [2] and [12].
4. When no more triangles can be added to the current region, search the remaining triangles for the one with the lowest curvature and start the growing procedure again with a

new region until all triangles have been processed.

5. For each segmented region, fit a plane using Principle Components Analysis, see [13].

The behavior of the algorithm depends on three parameters that need to be set for each object in order to avoid too many regions to be identified (over segmentation) or too few (under segmentation).

1. Maximum seed curvature value, $Kseed_{\max}$. A value too high will contribute to over segmentation; a value too low will contribute to under segmentation.
2. Minimum number of triangles in a region, $nt_{\min}$. A value too high may result in under segmentation while a value too low may cause over segmentation.
3. Maximum normal deviation (cone angle), $Ndev_{\max}$. Increasing this parameter will increase the number of planes that are added to a region. A value too high may result in a region that is bigger than the actual plane while a value too low may exclude so many planes that the minimum number of triangles in a region is not reached.

Figure 3: The measured object

Figure 3 shows an object that has been used by Varady [14] and others [11], [10] and [2] as a reference. We have manufactured a copy of this object using an Objet Eden 250 high accuracy rapid prototyping machine and then measured the object using our system based on the robot and profile scanner. After a few initial tests, we processed the measured data using $Kseed_{\max} = 0.015$, $nt_{\min} = 55$ and $Ndev_{\max}$ = 3 degrees.

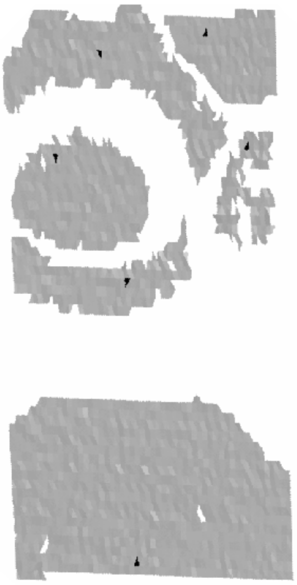

Figure 4: Segmented object

The result is shown in figure 4. Black triangles are the seeds and grey areas are the corresponding regions. The number of points was 25920 and all 6 planar regions were correctly identified. Processing time on a 1.2 GHz AMD Athlon was 56 seconds from start of segmentation until all 6 planes were fitted. The segmentation code is written in MBS language, an interpreted high level language for geometric modeling included in the Varkon CAD system [5]. Translating the code to C/C++ would reduce the processing time considerably. For each of the planes we computed the error in vertical position E_v by comparing the position of a point on the plane in the centre of the region with its true value measured using a Mitutoyo CMM. We have also computed the error in normal direction E_n as the angle between the fitted plane normal and the true normal. The positional accuracy of a plane seems to be close to 0.5 mm and the accuracy of the normal approximately 0.1 degrees. This is also the accuracy you would expect from the robot. The relatively high accuracy of the profile scanner does not influence the results. Although it is a natural choice, we have not seen the combination of seeds calculated using the Sacchi algorithm and the region growing based on normal deviations published earlier. It is our impression that it performs well and should be investigated more in depth.

3. GRE BASED ON PROFILES

In [15] we show that an accuracy of 0.05 mm or better is possible when fitting lines to laser profiles.

We also show how intersecting lines from the same camera picture can be used to measure distances with high accuracy.

In a new series of experiments we have investigated the accuracy in measuring the radius of a circle. We measured an object with cylindrical shape and took pictures with the scanner head orthogonal with the cylinder axis. The cylinder will then appear as a circular arc in the scan window. We used a steel cylinder with $R = 10.055mm$ measured with a Mitutoyo micrometer (0-25mm / 0.001mm) and the experiment was repeated 100 times with *D* increasing in steps of 1 mm thus covering the scan window. To make it possible to distinguish between systematic and random errors each of the 100 steps was repeated *n*=10 times, and in each of these the scanner head was moved 0.05 mm in a direction collinear with the cylinder axis to filter out the effect of dust, varying paint thickness or similar effects. The total number of pictures analyzed is thus 1000.

For each distance *D* we made an LSM fit of a circle to each of the *n* pictures and calculated the systematic and random errors using Esq.'s. (2) and (3). The result was plotted in figure 5 and 6.

$$E_s = R - \frac{\sum_{i=1}^{n} R_i}{n} \qquad (2)$$

$$E_r = \frac{\sum_{i=1}^{n} abs(R_i + E_s) - R}{n} \qquad (3)$$

E_s and E_r are the systematic and random radius errors. R and R_i are the true and measured radius and n the number of profiles for each *D*. The maximum size of the random error is less than 0.02 mm for reasonable values of *D*.

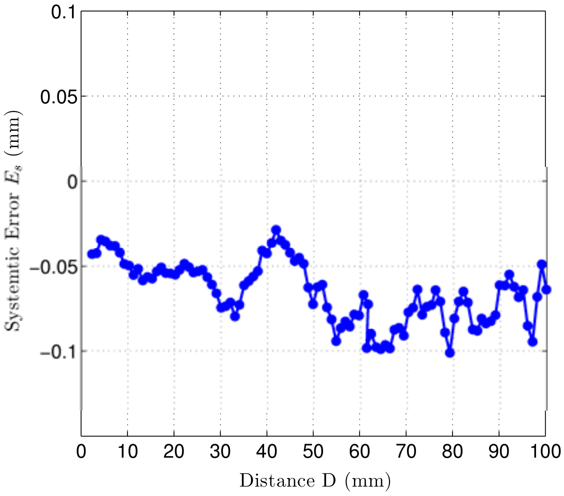

Figure 5: Systematic error in radius

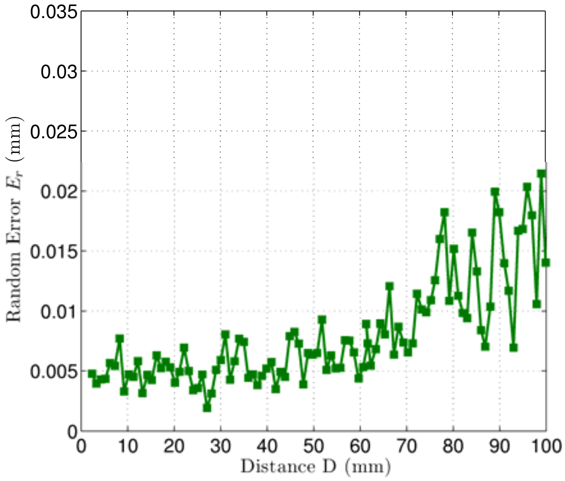

Figure 6: Random error in radius

4. A COMBINED METHOD

Traditional plane fitting as described in section 2 does not require more information from the measuring system than 3D coordinates. If we have access to laser profiles however, it should be possible to adopt an alternative strategy. As shown in [15], line fitting based on profiles can be done with relatively high accuracy. An object with one or more planar surfaces will give rise to profiles with one or more straight line segments. We believe that well known segmentation methods as described in [16], [17] and [18] can be used to find these lines, still with relatively high accuracy. As the robot moves along a scan path each profile created will be associated with a specific 3D orientation, see figure 7. We know each orientation but only with the relatively low accuracy of the robot.

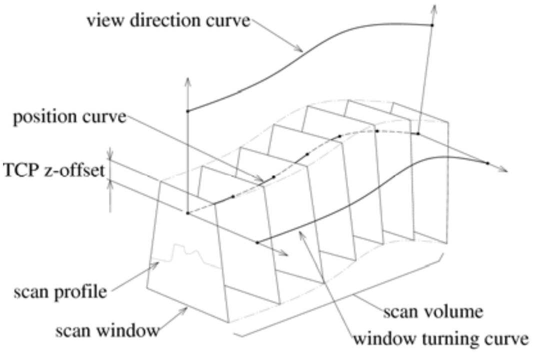

Figure 7: Non parallel scan profiles

It is reasonable to believe that the relative error between two consecutive orientations along a scan path is smaller than the overall absolute accuracy of the robot. It should therefore be possible to investigate if line segments from two consecutive profiles belong to the same plane with an accuracy that is better than the overall accuracy of the robot. Two lines in the same plane indicate that a plane actually exists. Grouping all segmented lines into planar regions will create segmentation similar to the one described in section 2 based on regions growing.

5. CONCLUSION

The industrial robot with a laser profile scanner is an interesting alternative in applications where high speed and flexibility combined with low cost is important. Plane segmentation based on 3D data requires points to be triangulated and normal or curvature for each triangle to be estimated using approximation. If the accuracy of the measuring system is high relative to the size of the smallest plane we want to fit these approximations are acceptable. The accuracy of an industrial robot used as a 3D point measurement system is relatively low, but if the GRE software has access to camera data, we have shown that fitting of lines and calculation of distances within the same camera picture can be done with higher accuracy. We believe that this possibility can be used to increase the overall accuracy of the system also for plane segmentation. If 2D laser profiles are segmented into lines and lines from adjacent profiles are used for plane segmentation in a similar way as normal's or curvatures are used in region growing we believe that the result will be better. This is due to the fact that lines fitted from 2D profiles are more accurate than normal's or curvatures approximated from triangular meshes.

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