Segment Based Freeform Surface Measurement for Computer Aided Measurement

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ABSTRACT

In freeform surface measurement, the measurement accuracy is partially governed by the density of measuring points. Making a uniformly dense sampling is a very time consuming measurement process. This paper presents a Segment Based Freeform Surface Algorithm for selecting the measuring point that will convert the section of surface to two-dimensional curves. Tolerance specification, degree of change of curvature, and machining condition are the parameters used to define the measuring point selection in different areas of the part's surface under measurement. This process will establish the optimized solution to generate the sampling points for a CMM measurement program, to save the measuring time and improve the quality control of the final product

Keywords: computer aided measurement, freeform surface, segment base.
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1 INTRODUCTION

In freeform surface machining, a CAD/CAM system is important to provide the modeling data to generate the NC tool path and transfer a NC program to a CNC machine to perform the machining process. The selected cutting tool, cutting parameters, tool-path method and accuracy of the CNC machine are key factors of the machining condition in controlling the profile tolerance and surface finish quality of the machined part. In the machining process, tool-life of the cutting tools is limited and affects the accuracy of the machined surface, sometimes resulting in out of tolerance performance. Another key factor is machining accuracy in a high speed cutting process. When the machined profile has high curvature of change, the CNC controller limits the cutting speed by reducing the interpolation of sample points forming the physical tool-path. The machine error thus affects the dimensional and geometric tolerance of a machined part.

The final measurement procedure is important in obtaining consistent dimension results to decide if the part is within a dimension and tolerance specification. To determine the acceptance of a machined part, the coordinate measuring machine "CMM" is adopted and the accuracy of the surfaces can be evaluated from the measurement results based on a rational sample point distribution. The sampling points should be sufficiently dense to capture all the geometric details of the part, in particular the key features with detail tolerance requirements. In a perfect case, the result of the measured surface should fall within the predefined threshold so that any inaccurate samples would be rejected. A proper sampling process is needed for this research.

The Segment Based Freeform Surface Measurement Algorithm is proposed for freeform surface measurement process planning. This is based on the surface shape, machining parameter and tolerance specification to design the measurement strategy to minimize the number of sampling points and increase the effectiveness of the measurement process. Demonstration of the proposed algorithm with an example and discussion of the results is also presented.

2 REVIEW

Nowadays, a Coordinate Measuring Machine "CMM" is commonly used in measurement of mechanical parts. It is a mechanical system equipped with a probe to obtain the three-dimensional positioning data of the surface of mechanical parts. A CMM consists of four parts: the machine structure, the measuring probe "contact type" or optical head "non-contact type", the control system and the measuring system software. The probe is driven by user input via the software system and controlled by the control system to detect the surface of the parts such that the coordinates of the x, y, z axes can be obtained. Since it is not realistic to measure all points on the surface, a CMM will detect sample points of the surface to create a surface model based on the measured sample points. In previous research, Kim and Raman [1] stated that there are two problems: data collection and data fitting. The data collection problem relates to the selection of the sample size and the selection of the sample point location. The data fitting problems relate to the matching of these sample points to form the surface model and then evaluating the model against the CAD model with the prescribed tolerances. ElKott and Veldhuis [2] stated that a CMM is a complex system that includes hardware and software such that many measurement errors can be created when obtaining the measuring data. Much research was conducted to find the best combination of sampling strategy including sampling method and sampling size. However, it remains a challenge to define a measurement sampling strategy that can perform well in both accuracy and time.

Optical and laser are examples of non-contact probing methods while CMM and robot arms are examples of tactile measuring methods. Xi and Shu [3] mounted a laser scanner on a Brown and Sharpe CMM for path planning. Kramer et al. [4] suggested using FBICS (Feature-Based Inspection and Control System), which is usually used for planning and controlling of machining, as the controller of a CMM. Li and Gu [5] reviewed the inspection of a free-form surface and suggested using a non-contact sensor such as laser together with CMM to improve the performance while maintaining high measurement accuracy. Mahmud et al. [6] suggested using a plain laser sensor working together with a CMM to obtain the sample point of the surface such that the measurement can be non-contact. The originality of this work lies in the development of a strategy to determine a sensor path taking into account both the metrological properties of the sensor and the dimensional and geometrical specifications of the inspected part.

Other major research directions are part measurement based on CMM machine measurement such as inspection point selection by Lu et al. and Karniel et al. [7] [8], and part orientation using dimensioned visibility map by Kweon and Medeiros [9].

Many researchers tried to find the best measuring strategy including the sampling method and sampling size. However, setting a measuring strategy that can perform well in both accuracy and measurement time is difficult. Kim and Raman [10] have used four different kinds of sampling methods (the Hammersley sequence sampling, the Halton–Zaremba sequence sampling, the aligned systematic sampling, and the systematic random sampling) together with five sample sizes (4, 8, 16, 32 and 64) and showed from the results that the accuracy of flatness will be increased when the sample size is increased. The most accurate sampling method may not be the most efficient one. There needs to be a compromise between accuracy and efficiency. Therefore, they suggested that there will not be a best generic sampling method when considering the accuracy of flatness and the shortest CMM probe path. Woo et al. [11] stated that the larger the sample sizes, the smaller the error. The results also showed that the Hammersley sampling sequence and Halton-Zaremba sampling sequence perform better than the one using uniform, random or stratified sampling. However, there is no big performance difference when using the Hammersley and Halton-Zaremba sampling sequence in two-dimensional space.

Maheshwari [12] tried to use design of experiments (DOE) approach to find the best combination of sampling method, sample size and evaluation method. Five different sampling methods (uniform sampling, random sampling, stratified sampling, Hammersley Sampling, Halton-Zaremba Sampling), nine different sample sizes (4, 8, 16, 32, 64, 128, 256, 512, 1024) and two form evaluation methods (the minimum zone, the least squares) were used. It was shown from the results that accuracy increases when the sample sizes increases. Also, using the least squares algorithm as the evaluation method performs better than the one using minimum zone. However, as shown from the results it is difficult to determine which sampling method is the most accurate.

After collecting the data of the sampling points, these sampling points will then be converted to form a surface to represent the real part. The representation of the shape can be in surface representation (polygonal or parametric) or in volume representation (octree, B-Rep or implicit functions). Meyer and Marin [13] suggested that segmenting the point cloud into elementary surfaces can improve geometric and dimensional control.

In freeform surface measurement, the measurement accuracy is partially governed by the density of measuring points. Making a uniformly dense sampling is a very time consuming measurement process. In this thesis, a Segment Based Freeform Surface Algorithm is proposed in selecting the measuring point that will convert the section of surface to two-dimensional curves. Tolerance specification, degree of change of curvature, and machining condition are the parameters used to define the measuring point selection in different areas of the part's surface under measurement.

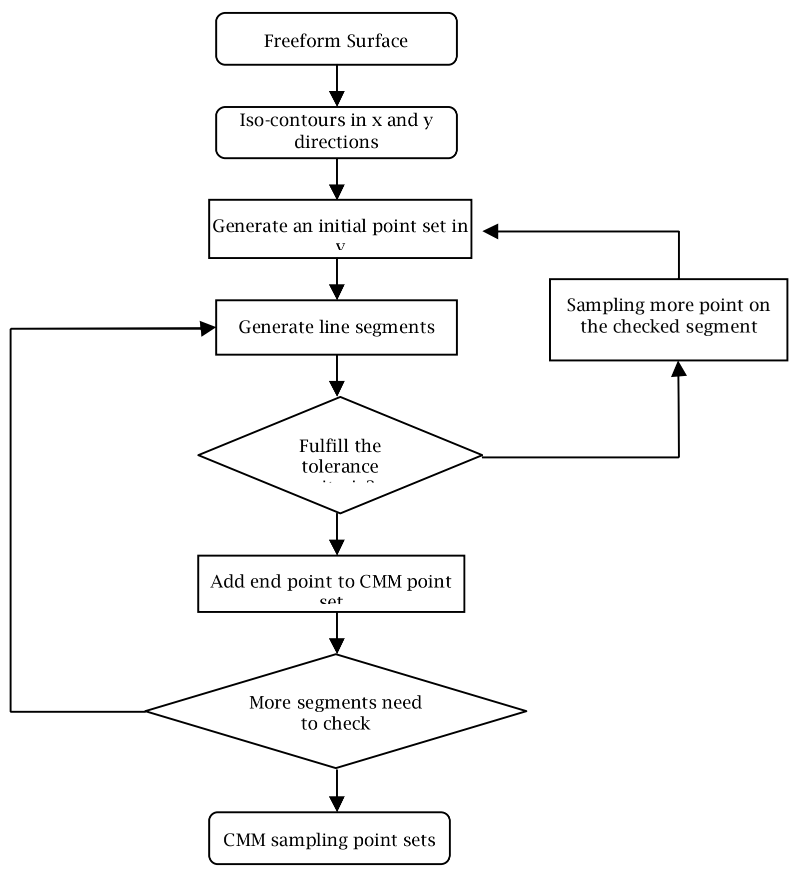

Fig. 1: The flow chart of the proposed sampling method.

3 SEGMENT BASED FREEFORM SURFACE MEASUREMENT

The proposed Segment Based Freeform Surface Measurement Algorithm provides an effective measuring solution in freeform surface measurement. Selecting sampling points for the measurement process is based on the curvature of the measuring surface in conjunction with the tool life condition to define the measurement strategy. Fig. 1 shows a process flowchart of the proposed algorithm.

Firstly, the curvature based Iso-contours in parametric “u” in “x” direction of a measured surface are generated. Referring to the profile tolerance specification, the parametric “v” in “y” direction Iso-contours are also generated. An initial point set of each Iso-contour in parametric “v” is discussed in more detail in a later section.

These initial sample points are then checked again to determine whether the predefined profile tolerance criteria can be fulfilled. If the criteria cannot be achieved, more sample points will be added. The process is then repeated until all the criteria are met. Then, a set of sample points for the CMM process will be obtained.

3.1 Relationship between Tool Life and Tolerance

The tool life is not a constant value as the cutter dimension changes during the machining process. It can change with different cutter materials, cutting speeds and cutting lubrication. The cutter wears during the machining process and is a key issue in the increase of the dimensional tolerance variation of a machined part. Normally, tool life can be represented by meters of cutting length and for carbide cutting tools, a general tool life of 20~40 meters is expected. Fig. 2 shows a relationship diagram between tool life and tool dimension change in a machining process [14]. In tool life TL_1 state, the cutting tools provide a stable machining condition (stable cutting length) to maintain the accuracy of the machined part. When the tool life reaches TL_2 state, the tool has worn and the machining condition may not be stable, affecting the machining accuracy of the machined parts. Since tool life is related to the material machining length, the nose radius should decrease over tool life with a slower rate at the beginning of the tool life and rapidly decrease towards the end of the tool’s life.

Current CAM systems are limited in handling the tool life issue, therefore the proposed algorithm has to consider the tool life separated into a number of tool life regions with a finer tool life profile in the latter regions.

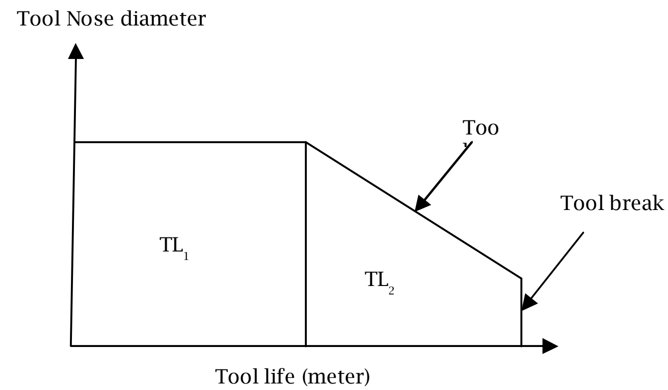

Fig. 2: Relationship between Tool life and Tool Nose Diameter.

3.1.1 *Iso-contours on the surface*

In current CAD systems, a surface can be represented by parametric values u and v and a number of Iso-contours (i.e. with u or v values being constant within the whole contour) can be generated. In the proposed algorithm, a number of Iso-contours that have a constant u-value are first created as shown in Fig. 3. Then, the changes in curvature along the Iso-contours are evaluated. The Iso-contours will be approximated by polylines such that the tolerance between the polyline and the original contour is smaller than a predefined threshold value that is within the tolerance specification limit. Fig. 4 shows the v-value of each point of the polyline which will be recorded. Based on these v-values, a group of constant v-value Iso-contours are then created and sample points are obtained from these Iso-contours.

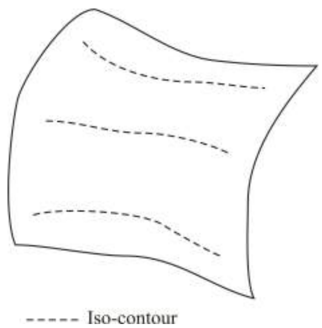

Fig. 3: Some Constant u in Iso-contours vector "x"

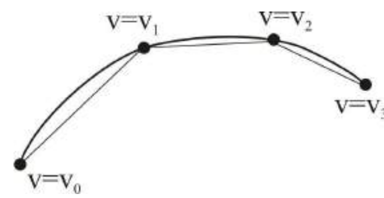

Fig. 4: Polyline for approximating an Iso-contour and the v-values of the points.

3.2 Sampling Points Selection

Presented in this section is a method to select sampling points for freeform surface measurement based on evaluating freeform surface geometry. It is intended to contain the initial point sets of each Iso-contour within a required profile tolerance specification and to add critical sample points at each Iso-contour to cater for sharp curvature change. Finally, relating to tool life condition, an increase in sampling points at the special measuring surface region is important to improve the accuracy of the measurement result. It is a critical part of the "Segment Based Freeform Surface Measurement Algorithm" in this research.

3.2.1 Initial point sets

After obtaining a group of constant "v" Iso-contours shown in Fig. 5, the initial points of each Iso-contour will be generated. These initial points are selected the start and end points of an Iso-contour are set as the initial set.

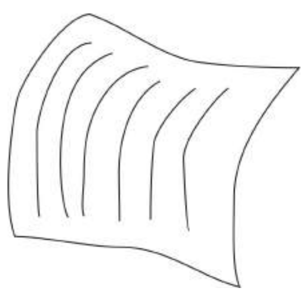

Fig. 5: A group of constant v Iso-contours in vector "y".

3.2.2 Criteria for sampling points

A polyline for an Iso-contour $v=v_i$ can be generated using the initial points set. For each line segment of this polyline, the following criteria will be checked:

1. The maximum dimension deviation between the line segment ($d_{max,i}$) and the corresponding Iso-

contour. The threshold tolerance level ε is predefined by the user. The maximum deviation will be compared with the predefined tolerance level to establish whether or not the deviation is too large.

2. The number of sampling points in the regions that are defined by this line segment. The line segment can be represented by points (u_j,v_i) and (u_k,v_i), the region can be represented by $(u_j,(v_i+v_{i-1})/2$, $u_k,(v_i+v_{i+1})/2)$ where v_{i-1} and v_{i+1} are the Iso-contours next to the Iso-contour $v=v_i$. The number of sampling points (N_{tpi}) within this region will be counted and this number will be compared to the predefined sampling point threshold (N_{tp}) to establish whether it can fulfill the requirement.

For the regions that have a higher rate of change of curvature, more sampling points should be generated for the machining process. The machining error could also be larger since the cutting depth in this region should be more non-uniform. This region will have a greater opportunity to be inaccurate and should be inspected more carefully. Therefore, more points should be obtained in this region. A parameter N_{tp} is set and the number of sampling points within a region must be smaller than this predefined threshold.

In order to reflect the effect of tool life at different stages in the machining process, more points should be obtained if the region is machined with tools having a longer cutting time after tool grinding.

The cutting time for the tool involved is calculated and weights (w_l where $0 \le w_l \le 1$) of the sampling points (SP_l) will be added. A smaller weight is added to the sampling points that are in the latter part of the toolpath such that more sampling points can be assigned to that region. These weights are determined from the tool life graph of the tool. For example, $w_l = 1$ may be added addition number of sampling points within the TL_1 region, while $w_l = 0$ may be added double for sampling points within the TL_2 region. (Refer to Fig. 2)

The start point and end point of a line segment are accepted as the sample points if $d_{max,i} \le \varepsilon$ and $N_{tpi} \le N_{tp}$. If the requirement of one or both criteria cannot be fulfilled, more points should be added.

3.2.3 Adding more points

If the line segment cannot fulfill the profile tolerance requirements of the predefined criteria, more points will be required for this segment. The number of points to be added is predefined by the user and these points are added evenly to the segment (Fig. 6). These newly added points, together with the original points of the line segments, form a new polyline as shown in Fig. 7. The line segments of this newly formed polyline will be checked to establish whether they fulfill the requirements of the predefined criteria. If some of the line segments cannot fulfill the requirements of the predefined criteria, more points will be added. The procedure will be repeated until all line segments fulfill the requirements of the predefined criteria. Then, a set of sample points for the surface can be obtained.

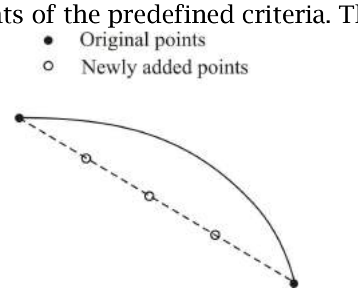

Fig. 6: Example to evenly add three points onto the line segment.

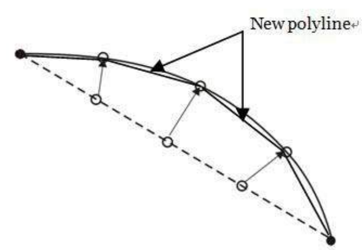

Fig. 7: The newly added points are projected onto the Iso-contour and a new polyline is defined by these projected points and the original points.

4 CASE STUDY

In order to demonstrate the application of the Segment Based Free-form Surface Measurement Algorithm, Unigraphics advance programming interface API is used to develop the prototype software to support the Computer-Aided-Measurement demonstration. Fig. 9 shows an example of a fan blade mould insert to demonstrate the proposed algorithm in the measurement process planning for computer aided measurement. In this experiment, a Brown & Sharpe CMM with PC-DIMS operation system is used.

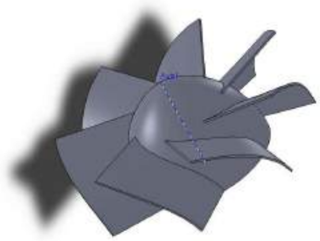

Fig. 8: Case study Cooling Fan.

Fig. 9: Mould Insert for Single Fan Base.

4.1 Traditional Measuring Method

The first step of the case study experiment uses a traditional measuring method with 0.5mm and 2mm point to point distances over the measured surface (Fig. 11 and Fig. 12). Fig. 10 shows the measurement results and includes the number of points measured, maximum and minimum measured tolerance compared with nominal values, root mean square error "RMSE" and measured time.

Measured Distance	2mm	0.5mm
No. of points	420	1352
Max. distance between measured point and normal value (mm)	0.00213	0.00656
Min. distance between measured point and normal value (mm)	-0.0085	-0.011
RMSE	0.00435	0.00478
Measuring time (min)	84	270

Fig. 10: Measurement Results of Transitional method.

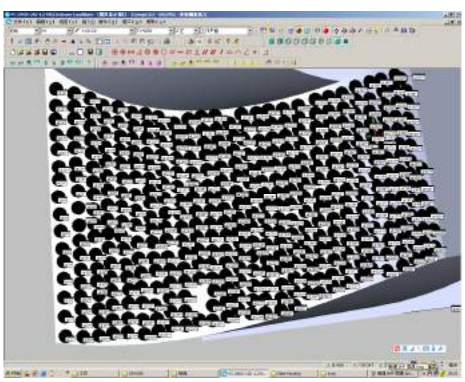

Fig. 11: Measuring Point to Point Distance 2mm.

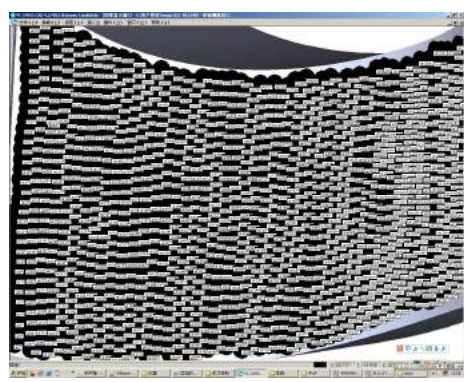

Fig. 12: Measuring Point to Point Distance 0.5mm.

4.2 Prototype Computer Aided Measurement System

Fig. 13~15 shows the result of the prototype Computer-Aided-Measurement system based on a Unigraphics platform to demonstrate the "Segment Based Freeform Surface Measurement Algorithm". The operation procedure is first to input the profile tolerance value in vector "x" (Fig. 13), then to input a profile tolerance value in vector "y", stable length tool life and any additional points in each line segment (Fig. 14). The proposed system will generate the toolpath point, although the preprocessor will translate to a suitable CMM program for CMM measurement. Fig. 15 shows the generated sampling point is not uniform to a measuring surface, which is based on the required profile tolerance, curvature change in that region and the associated tool life factor.

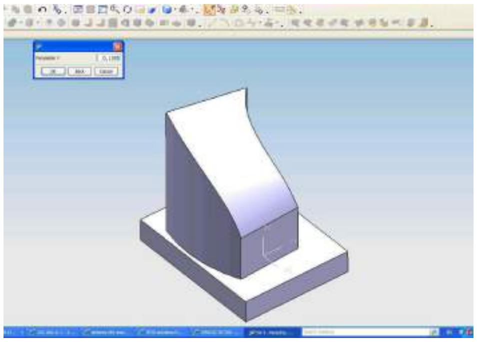

Fig. 13: Mould Insert for Single Fan Base.

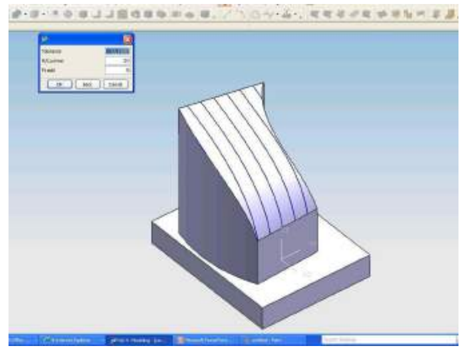

Fig. 14: Generate the Iso-contours u.

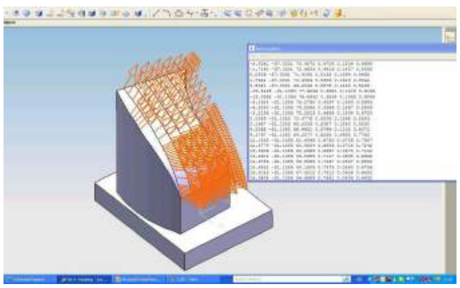

Fig. 15: Sampling Points Result of Fan Blade.

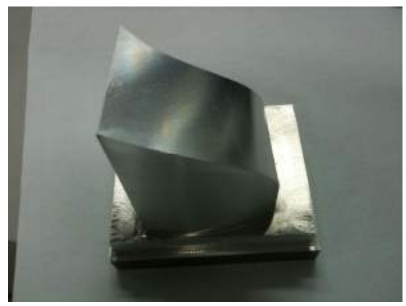

Fig. 16: Machined Fan Blade Mould Cavity.

4.3 Progress and Result

The fan blade mould cavity used to demonstrate the proposed system, uses three different values of profile tolerance to control the number of curvature lines generated. Smaller tolerance value means that the distance between the curvature lines will be shorter and more toolpath points will be generated. Therefore, the measured data point sets would be more precise. The allowed measurement error, 0.01mm, 0.02mm and 0.05mm are proposed in case study 1, along with tool life length of 20 meters (weight 0.5) and 5 additional points. Fig. 17 to 19 shows the generated sampling points and the number of sampling points is proportional to the profile tolerance requirement. Therefore, a higher number of sampling points (1839) for the 0.01mm profile tolerance case are specified.

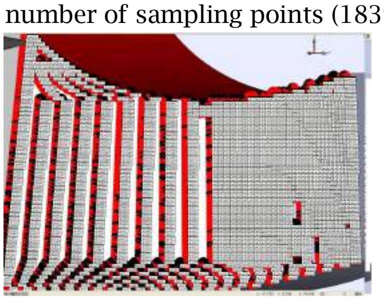

Fig. 17: Sampling Points for Profile Tolerance 0.01mm.

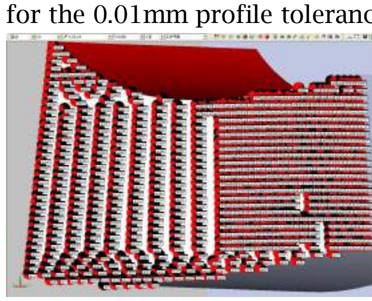

Fig. 18: Sampling Points for Profile Tolerance 0.02mm.

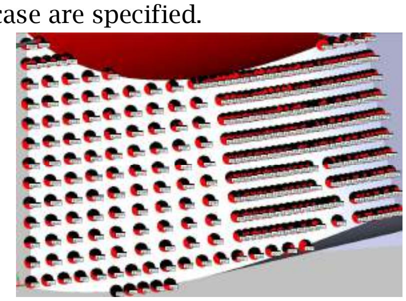

Fig. 19: Sampling Points for Profile Tolerance 0.05mm.

Allowed measurement error	0.01	0.02	0.05
No. of points	1839	916	370
Max. distance between measured point and normal value (mm)	0.009811	0.009621	0.009738
Min. distance between measured point and normal value (mm)	-0.00979	-0.009496	-0.008062
RMSE	0.003471123	0.003516513	0.003229774
Measurement time (min)	371	185	71

Fig. 20: Measurement Results of Proposed Algorithm.

Referring to Fig. 20 that compares the three measurement results, it is shown that there is no significant difference in the root mean square error (RMSE) when using different final tolerance values to obtain the sampling points. The maximum distance between measured point and normal value is around 0.009mm in all three cases. The RMSE are around 0.0035 in all three cases. However, the measurement time is significantly different from 71 minutes for 0.05mm to 371 minutes for the 0.01mm profile tolerance value. It is an important value affecting the freeform surface measurement efficiency.

4.3.1 Comparison of measurement results

Compared with the results shown in Fig. 10 for measurement results with the traditional method (0.5mm and 2mm measurement distance), there is a significant difference in the tolerance range of the machining error between both measurement results (Variation Max 0.00213mm and Min -0.0085mm with 2.0mm measurement distance. Variation Max 0.00656mm and Min -0.011mm with 0.5mm measurement distance). On the other hand, the three measurement results using "Segment Based Freeform Surface Measurement Algorithm" provide consistent measurement data with a systematic method to plan the measurement strategy based on profile tolerance, surface curvature and tool life. Case study 1 clearly demonstrates the proposed algorithm provides a cost effective solution compromising the adequacy of sampling point number to generate an accurate solution for freeform surface measurement with a reasonable measurement time.

5 CONCLUSION

A "Segment Based Freeform Surface Measurement Algorithm" has been proposed to support Computer-Aided- Measurement. It is based on curvature of change, profile tolerance requirement and machining condition to establish the measurement process plan. The experiment results show the generated toolpath samples are much more precise in measuring a freeform surface region that is potentially out of tolerance, compared with traditional methods. It also saves measuring time by referring to the profile tolerance specification of existing qualified information, an important data linkage from product design (CAD) to quality measurement. Detailed benefits of the proposed algorithm are as follows:

- The quantity of sampling points is based on the quality requirement of the measured surface.
- The measuring process plan considers machining condition (tool life) and curvature change of the measured surface to provide an optimized solution to save the measuring time without loss of accuracy.
- The algorithm generates a consistent set of surface measurement data.

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