Freeform surface measurement and characterisation using a toolmakers microscope

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Key Words: Freeform surface design, Freeform surface production, Surface inspection, Dimension feature recognition, Toolmakers microscope, Artificial intelligence

Abstract. Current freeform surface (FFS) characterization systems mainly cover aspects related to computer-aided design/manufacture (CAD/CAM). This paper describes a new approach that extends into computer-aided inspection (CAI).The following novel features are addressed:

- Feature recognition and extraction from surface data
- Characterisation of properties of the surface's M and N vectors at individual vertex
- Development of a measuring plan using a toolmakers microscope for the inspection of the FFS
- Inspection of the actual FFS produced by CNC milling
- Verification of the measurement results and comparison with the CAD design data

Tests have shown that the deviations between the CAI and CAD data were within the estimated uncertainty limits.

1. Introduction

There is a need to compare the actual produced with those specified by the CAD (Computer Aided Design) part model freeform surfaces. Several investigators have reported on the question of the measurement of free form surfaces on a CMM ([1], [2], [3], and [4]), specialized measuring machine Talysurf PGI1240 [5] and special-purpose-built NANOMEFOS measurement machine [6] using the CAD part model as the reference. Another approach of three dimensional measurement is through the X-Y stage of a TMM (toolmakers microscope) with a Z attachment. A laboratory grade [7] provides ZKM 01-250C yielded an accuracy of $\pm(1.8+L/120+HL/17000)$µm along both x and y axes, where L is the measured length in mm and H is the height in mm of the measuring plane above the measuring table. Likewise, it has been claimed that one can achieve an accuracy of $\pm(3+L/200)$µm along X, Y axes just by using a typical workshop grade measuring microscope. A 60 mm long range probe with errors under 0.1µm without compensation and 0.05µm with linear length-error compensation [9] which could work for the measuring system of Z attachment of a TMM. According to a review conducted by Carbone [1] on CMM accuracy, the typical 1D length measuring uncertainty is $U_1 = (2.2+L/300)$µm, where L is the measured length in mm. A workshop grade TMM with an appropriate Z attachment would yield comparable accuracy levels of a CMM. TMM uses a non-contact approach that sidesteps problems associated with the probing geometry in CMM. The goal of the work reported in this paper concerns mainly the task of measuring a freeform surface against its CAD model by means of a non-CMM measurement approach (using a TMM) which has long been ignored.

2 Feature recognition and extraction from surface data

In our tests, the freeform surfaces were modelled using an AutoCAD system. Each freeform surface was subdivided into m and n patches in u and v directions respectively. Figure 1 shows the flow diagram for feature recognition and extraction from surface data.

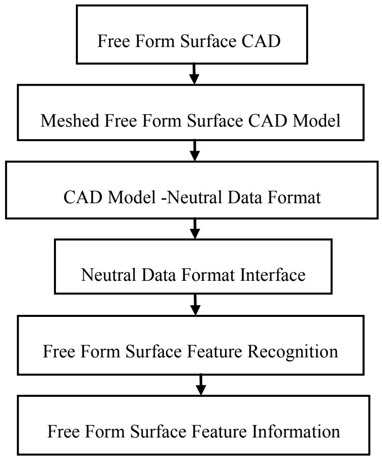


Figure 1 Flow diagram for feature recognition and extraction from surface *data*

2.1 Neutral Data Format File Interface

The objective of this module is to translate the CAD data of the target part to a computer readable neutral data file. The input to the module consists of a CAD file of part to be inspected. IGES (Initial Graphics Exchange Specification) is the first and still the most popular amongst neutral formats. Subsequently, a series of data exchange standards have been (or being) developed, e.g., VDAFS, SET, PDDI, XBF, PDES, ESPRIT Project 322: CAD*I, STEP and DXF.

2.1.1 DXF neutral format

The DXF (Drawing Interchange File) interface is an important part of an Autodesk system. DXF translators have been built into all versions of AutoCAD. DXF is an open sourced CAD data file format supporting both ASCII and binary forms. DXF output created with the earlier versions can also be opened with later releases of DXF. DXF provide flexibility in managing data and translating AutoCAD drawings into a file format that could be read and used by other CAD systems. In the present work, AutoCAD and DXF file format were selected as the CAD system and neutral data format in view of their popularity.

2.1.2 Data structure of DXF

A typical DXF output is composed of a multiplicity of groups, each of which occupies two lines [10]. The first line of the group consists of the group code whereas the second line encodes the group data. The format used depends on the type of group as specified by the group code. In turn, the specific assignment of the group code depends upon the item being described in the file. The type of the value of the group may be derived from the group code.

2.1.3 Development of DXF interface program

A crucial phase in CAD and inspection process planning (CAIPP) integration is the ability to automatically dump, read, and interpret the CAD database. The DXF file structure consists of two-line groups. The first line of each group is an integer representing the group code. The second line captures the data. Predicates and clauses were developed to read the DXF output. Some examples of these predicates and clauses are shown below.

Read integer group	Read real group	Read string group
check(A,i(B)):- 60<=A, A<=79, readint(B).	check(A,r(B)):- 10<=A, A<=59, readreal(B).	check(A,s(B)):- 0<=A, A<=9, readln(B).

2.2 Free Form Surface Feature Recognition
This process concerns the extraction of the freeform surface information from the DXF file input: (i) M: the number of vertices in the M direction, (ii) N: the number of vertices in the N direction, and (iii) the coordinates of all vertices on the freeform surfaces. Rules were developed to match the following conditions to enable the extraction of freeform surface information from DXF.

Freeform face *if* the following conditions are met: **data** are within "**Entity Section**" *and* the group code is **100** and the data type next line is **string** and the string is "**AcDPolygonMesh**" *and* the group code is **10** and the data type next line is **real** number and the real number is the **X** coordinate value of its first vertex in M direction and N direction *and* the group code is **20** *and* the data type next line is **real** number *and* the real number is the **Y** coordinate value of its first vertex in M direction *and* N direction and the group *code is* ***30*** *and* the data type next line is real number *and* the real number is the **Z** coordinate value of its first vertex in M direction and N direction *and* the group code is **71** *and* the data type next line is **integer** *and* the integer is the number of vertexes in M direction *and* the group code is 72 *and* the data type next line is **integer** *and* the integer is the number of vertexes in N direction.

Vertex of a freeform surface *if the following conditions are met*: **data** are within "**Entity Section**" *and* is a member of the freeform surface *and* the group code is **100** *and* the data type next line is **string** *and* the string is "**AcDPolygonMeshVertex**" *and* the group code is **10** *and* the data type next line is **real** number *and* the real number is the **X** coordinate value of this vertex *and* the group code is **20** *and* the data type next line is **real** number *and* the real number is the **Y** coordinate value of this *and* the group code is **30** *and* the data type next line is real number *and* the real number is the **Z** coordinate value of this vertex.

2.3 Free form surface feature information report
The content of the internal database "f" storing the data obtained from the feature recognition process consists of "no. of faces", "no. of vertices", and "indexed vertex with coordinates". The database is stored and saved as an external text file

3. Post-processing the data obtained from feature recognition
Next the data obtained from feature recognition are further processed for (i) inspection process planning, and (ii) the calculation of the M and N vectors at each vertex.

3.1 Generating the inspection process plan
The X, Y, Z coordinates of each vertex point are generated from the database as a text file or in the form of a spreadsheet for inspection process planning.

3.2 Calculation of the M and N vectors
$M_{(i,j),(i+1,j)}$ is the vector within the boundary of the surface from vertex(I, J) to vertex(I+1,J) in direction M, where $M_{(i,j),(i+1,j)} = A_i+Bj + C_k[X_{(I,J)},Y_{(I,J)},Z_{(I,J)}]$ are the X,Y and Z coordinates of vertex(I,J).

[X((I+1),J),Y((I+1),J),Z((I+1),J)] are the X,Y and Z coordinates of vertex((I+1),J), where $A= X_{((I+1),J)}-X_{(I,J)}$, $B= Y_{((I+1),J)}-Y_{(I,J)}$, and $C= Z_{((I+1),J)}- Z_{(I,J)}$.

$N_{(i,j),(i,j+1)}$ is the vector within the boundary of the surface from vertex(I,J) to vertex(I,J+1) in direction N, where $N_{(i,j),(i,j+1)} = E_i + F_j + G_k [X_{(I,J)},Y_{(I,J)},Z_{(I,J)}]$ are the X,Y and Z coordinates of vertex(I, J).

Journal of Physics: Conference Series **483** (2014) 012004 doi:10.1088/1742-6596/483/1/012004

[X(I,(J+1)),Y((I,(J+1)),Z((I,(J+1))] are the X,Y and Z coordinates of vertex((I,(J+1)), where $E=X_{((I,(J+1))}- X_{(I,J)}$, $F= Y_{(I,(J+1))}- Y_{(I,J)}$ and $G= Z_{(I,(J+1))}- Z_{(I,J)}$.

4. Implementation and testing

The algorithms were implemented, tested, and verified using the following steps:

1. Design of a test part with a freeform surface
2. Manufacture of a real part by the CAM process.
3. Development software for feature recognition
4. Generation of the inspection process plan
5. Measurement of the test parts on a toolmakers microscope
6. Measurement of the test parts on a CMM

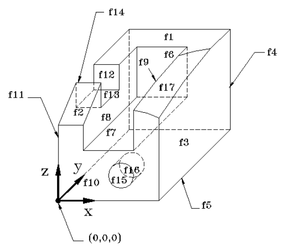


Figure 2

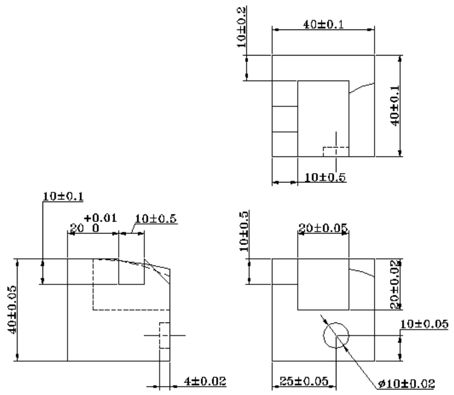
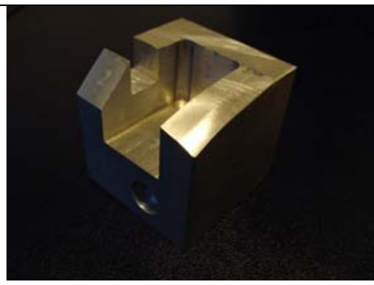


Figure 3



Actual part produced by CNC machining

Figure 4

4.1 Design of a test part with a freeform surface

The test part (setting gauge) shown in Figures 2 and 3 was designed and modelled on an AutoCAD Mechanical workstation. The test part consisted of 17 faces. Note that the part includes a freeform surface (f17).

4.2 Manufacture of a real part using CAM

The CAD model was exported as an IGES file. The CNC part programme was generated by Mastercam software based on the IGES file of the part model. The program was implemented on a CNC milling machine: Mikron WF21 which is easily readable for further processing by a computer program. AutoCAD databases provide curved surface data in a polygon mesh form arranged in M rows and N columns in u and v directions respectively. Thus, the database of each polygon mesh has M×N data. In our work, the polygon mesh was automatically extracted by means of the Prolog algorithm presented in section 2.2. The machining conditions were: cutter diameter 10mm, tool radius 5mm, spindle speed 1000 RPM, and feed rate 300 mm/min.

4.3 Development of software for feature recognition

The CAD model of the test part was exported in DXF format. AutoCAD databases provide curved surface data in a polygon mesh form arranged in M rows and N columns in u and v directions respectively. Thus, the database of each polygon mesh has M×N data. In our work, the polygon mesh was automatically extracted by means of the Prolog algorithm presented in section 2.2.

Journal of Physics: Conference Series **483** (2014) 012004 doi:10.1088/1742-6596/483/1/012004

The free form surface (f17) was modelled with 6 meshes in the u direction and 6 meshes in the v direction. Thus, there were 36 meshes in total with 49 vertices (see Figure 5). The coordinates of the individual mesh vertices of the free form surface as well as the corresponding individual relative positions within the free form surface were captured as described below. Mesh vertex (0,0) was used as the reference position of the surface. The location of this vertex was directly extractable (in 14 decimal places) from the CAD model of the part in 14 decimal places as: mesh vertex (0, 0) = 30.00000000000000, 25.00000000000000, 39.99999999999999.

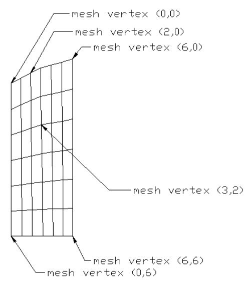


Figure 5 Meshes of the freeform face f17

4.4 Generation of inspection process plan

The inspection process plans for the measurement of the free form surface on a toolmakers microscope for measurement of the Z coordinate at (X, Y) location of each vertex was generated in table form. The inspection process plans for the measurement of the free form surface on a CMM for the measurement of the Z coordinate at the (X,Y) location of each vertex was generated using the coordinates of the vertices extracted from the CAD model.

4.5 Measurement of the test part by TMM

All the 49 vertices of the free form surface f17 were measured on a TMM: Make/Model: Mitutoyo/TM321.

Specifications of the measuring microscope: Measuring range: 100mm (X) × 50mm (Y) × 150mm (Z); Resolution: 1μm; Linear scale accuracy for X and Y axis: 3+3*L*/1000μm, *L* in mm.
Accuracy of the Z axis: 0.00015” by a digital comparator (= 3.81μm).
Estimated linear scale accuracy in X, Y and Z axis over the range of the test piece: 4μm
Estimated volumetric error of the part: $(4^2 + 4^2 + 4^2)^{1/2}$=7μm

4.6 Measurement of the test part on a CMM

All the 49 vertices of the free form surface (f17) were measured on a Brown & Sharpe/MicroVal PFx CMM with the following specifications:
Measuring range: 457mm (X) x 508 mm (Y) x 432 mm (Z)
Probe: 1μm resolution; 3+3*L*/1000μm linear accuracy (*L* in mm)
Estimated linear scale accuracy for the part: 4μm
Volumetric performance: 10μm over 330mm

5. Results

The machine specifications indicated a linear accuracy of 20μm along X, Y, and Z axes. Hence, the error in point-t-o point in space within the work envelope was estimated as $(20^2 + 20^2 + 20^2)^{1/2}$= 35μm. The profile error due to the translation error of the machine and other factors was therefore estimated to be of the order of 50μm. All the 49 vertices of the free form surface f17 were measured on a Mitutoyo/TM321 TMM. It was found that the volumetric error of measuring equipment was 7μm. Thus, the overall profile error limit of the vertex obtained from toolmakers’ microscope could be taken to be is $(50^2+7^2)^{1/2}$=50.5 μm≈51μm. An almost identical result of 50.99 μm≈51μm was obtained when the procedure was repeated on a Brown & Sharpe MicroVal PFx CMM.

Journal of Physics: Conference Series **483** (2014) 012004 doi:10.1088/1742-6596/483/1/012004

6 Conclusion and discussion

Traditional CAI (Computer Aided Inspection) practices directed at free form surface production have required CNC machining followed by the measurement of the resulting surface(s) on a CMM [11]. However, owing to the high price and skill requirement associated, CMM use is rare even in modern CAM shops. This paper has outlined an effective alternative that sidesteps the need for a CMM by utilizing a TMM─a much less expensive and more easily managed alternative. Among the issues addressed in this paper are the development of software for geometric feature recognition and the generation of a computer aided inspection process plan (CAIPP). Measurements conducted on identical test parts containing free form surfaces have shown that, notwithstanding the fact that it is less expensive and managed more easily, the new methodology based on tool-room microscopy is as effective technically as the traditional approach based on the use of a CMM.

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