VISUAL CAD-BASED MEASUREMENT AND PATH PLANNING FOR FREE-FORM SHAPES

Iain Ainsworth, Mihailo Ristic and Djordje Brujic

Imperial College of Science, Technology and Medicine
Mechanical Engineering Department, Exhibition Road, London SW7 2BX, United Kingdom
Tel: (0171) 594-7048; Fax: (0171) 584-7239
<i.ainsworth, m.ristic, d.brujic>@ic.ac.uk

ABSTRACT

Dimensional inspection of engineering components comprising free-form surfaces demands accurate measurement of a large number of discrete points, such that the actual shape may be fully characterised. This paper presents a methodology for measurement planning and collision-free probe path generation to perform measurement using a co-ordinate measuring machine. The measurement process involves the following main steps: registration, definition of measurement points, probe path generation, path optimisation and verification, and measurement. By employing the CAD model at every step, the implemented methodology maximises the measurement accuracy and achieves accurate control of the overall measurement process. In addition, the implemented tools for probe path simulation and verification provide a high level of confidence when dealing with complex engineering component geometry.

Keywords: measurement, visualisation, animation, registration, CMM, free-form shape, NURBS.

INTRODUCTION

This paper attempts to demonstrate an efficient, yet flexible, measurement planning methodology for components that are comprised partly or solely from free-form surfaces. The motivation for this work has been provided by the needs of the modern manufacturing industry, particularly in the aerospace and the automotive sectors. Inspection of free-form components such as aero-engine turbine blades and car body panels involves measurement of a sufficiently large number of points, with an appropriate point distribution, in order to enable a subsequent comparison of the actual shape in relation to its nominal model. As part of this process, it is also becoming increasingly important to reconstruct the actual shape in a required CAD format and to analyse the component performance using the available aerodynamic, structural and other computational analysis tools.

A computer controlled CMM (co-ordinate measuring machine), equipped with a touch-trigger probe, represents the standard measuring instrument for dimensional inspection. This is due to its high accuracy and the widely available operator skills. Measurement accuracies of the order of 3-5μm are readily achievable using modern CMMs.

Measurement of free-form shapes using a CMM poses considerable difficulties. First, the commonly used ‘teach-by-showing’ method for CMM programming is inadequate in situations involving measurement at a large number of points, particularly when the required local point distribution is dictated by the local object shape. Second, the contact probe tip is usually a sphere of a finite radius, meaning that the CMM measures the co-ordinates of the sphere centre and not those of the point of contact. The conventional CMM methodology is based on the assumption that the direction of the surface normal at the point of contact is á priori known so that the compensating offset can be calculated. This method is acceptable for prismatic parts, but when dealing with free-form shapes it can be a large source of measurement error. Third, registration, which establishes the relation between the CMM co-ordinate frame and that of the CAD model, can prove to be difficult because free-form objects generally do not possess clearly identifiable reference features.

In addition, the nature of CMM operation demands development of suitable tools for probe path planning, verification and optimisation, particularly in relation to collision avoidance. The measurement cycle for each point starts and ends at a suitable point located a safe distance away from the object and involves a slow approach to the surface and then retraction from it. The probing speed must be low in order to limit the stopping distance of the CMM after contact has been made, to avoid crashing with the part. The measurement sequence therefore consists of a series of point-to-point moves between the stand-off points and probing cycles performed for each measurement. The overall measuring speed is clearly maximised by minimising the stand-off distance, but since this severely increases the risk of collision and damage most operators would adopt a conservative, large stand-off.

The CAD-based measurement planning methodology proposed in this paper was designed to address these issues. This paper first covers component registration. Next is the definition of the measurement points, where the number of measurements and their distribution are controlled by a number of relevant factors. The implemented methods for automatic probe path generation are presented and discussed, including the implementation of measurement simulation, as the means of verifying the probe path prior to execution. Finally, we propose a practical method for automatic collision detection which was designed to complement graphical visualisation tools and we describe its implementation.

REGISTRATION

Since the measurements on the object are made relative to the co-ordinate frame of the CMM, while the nominal CAD model is defined relative to some arbitrary co-ordinate frame, it is necessary to establish the relationship between the two frames through registration. In principle, registration evaluates the transformation (rotation and translation) that needs to be applied to the nominal model in order to align it with the actual object. Accurate registration enables the CMM to negotiate the correct path around the object and also provides the basis for subsequent error analysis.

Conventional registration techniques generally follow one of two approaches. First, if the component has three orthogonal planes as a reference feature, then such a component can be readily registered using six points (3, 2 and 1 on each plane respectively). Second, if such features are not available, the method is to identify and subsequently measure six or more arbitrary points, each corresponding to a point defined on the model [Sahoo&Menq 91]. Using the information about the corresponding points allows the transformation matrix to be found.

However, many free-form components do not possess suitable reference features and the application of the 3-2-1 registration procedure implies development of special purpose reference jigs, which would hold the component and provide the necessary datum. Although common in practice, this solution is expensive and inflexible. Furthermore, the application of the second method is also fraught with problems because it is difficult to guide the CMM to measure at precisely the defined corresponding points. Thus the detailed procedure for establishing point correspondences must be developed specifically for each new shape, again resulting in an inflexible and costly solution.

Proposed Registration Method

The principle of the proposed solution for the registration problem involves least squares alignment of the measurement data with nominal surface entities of the model. However, our method uses offset surfaces of the nominal CAD model (offset being equal to the radius of the probe tip) which are aligned with the raw measurement data (raw data being the co-ordinates of probe sphere centre). This eliminates introduction of any probe compensation errors at the registration stage and it is in direct contrast with the conventional methodology which uses compensated measurements for registration.

The offset NURBS surfaces are calculated by:

1. sampling the corresponding NURBS entity of the model with a sufficient density (empirically derived optimum was found to be 3 points per knot span) and recording their parameter values,
2. offsetting these points in the direction of the surface normal, then
3. fitting a NURBS surface in Least Squares fashion

Fitting is performed iteratively using the existing CAD entity as the starting point of the process. This fitting is performed to within a user-defined tolerance and knot insertion may be applied if necessary.

Following this, registration was realised through an implementation of the ICP (Iterative Closest Point) method, which was reported by the authors in [Ristic&Brujic 97] and verified in [Brujic&Ristic 97]. As the name suggests, the ICP method minimises at each iteration step the collective square distances between the measured points and their closest points on the surface. The ICP algorithm was shown to converge in the presence of measurement noise and for reasonable initial misalignments of several millimetres in position and several degrees in orientation.

However, when the model and the part are initially grossly misaligned, convergence of the ICP algorithm cannot be guaranteed. For this reason it is necessary to bring the two closer together by some other means, as the first alignment step. In our work this was readily achieved through a slight variant of the conventional corresponding point method. Simply, this means that 6 or more points are identified on the nominal model and then measured on the actual object by driving the CMM manually. The corresponding points on the nominal surface are then aligned to the measured data in least squares fashion. Clearly the objective in this step is to align the two shapes only approximately, so it is not important that the two point sets correspond exactly. In our experience with a variety of engineering parts, this approach was found to produce sufficiently good initial alignment quickly, allowing full subsequent ICP registration to proceed.

It is also worth noting that the registration accuracy will be greatly increased if a large number of points is used for registration. We therefore suggest that a larger number of points be used for ICP registration than for the initial alignment and to repeat this process once the full measurement data set is obtained, in order to maximise the overall registration accuracy.

DEFINITION OF MEASUREMENT POINTS

The required distribution of the measurements is determined by the shape of the object in question, the type of defect that is of interest and by the requirements for subsequent processing and analysis of the data. The required local measurement density is primarily dictated by the local surface curvature. This may be determined on the basis of the nominal CAD model and it may be further increased to account for the type of surface defect that is of interest. Bearing in mind that real data always contains noise, the surface sampling density may then be further increased to facilitate subsequent filtering of the measurement noise.

A conventional way to define discrete measurement points on a measured entity is to define a 2-dimensional rectangular grid (parallel to one of the primary planes) within the 3-dimensional model environment. Once the grid has been positioned and the number of points on the grid specified, the grid points are then projected on the model surface, as shown in Figure 1.

Each point of intersection between the projection lines and the model will specify a

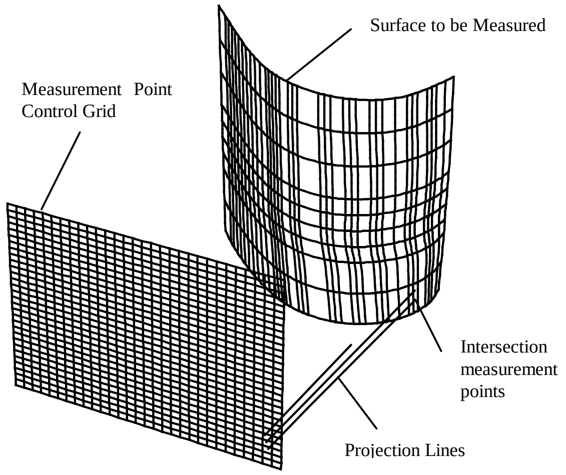

Figure 1: Existing Method of Measurement Point Generation.

measurement point to be taken during the measurement cycle. It can be seen that in some simple situations this method of specifying the measurement points would work reasonably well. However, trying to use this method to measure more complex components is very difficult. It is particularly difficult, and often impossible, to position the grid such that it will produce good coverage over a surface with high curvature or large aspect ratio. Therefore, if surfaces such as these were to be measured, then it would have to be done in a number of stages. This would obviously further complicate the procedure and incur considerable time and cost penalties.

Proposed Methodology

A typical nominal model of a component would constitute one or more NURBS surfaces. To present the most general case the discussion will focus on measuring one single NURBS surface. However, the methodology implemented will cater for multiple surfaces or smaller regions within a single surface.

As already mentioned, the sampling of the surface of interest must be such that it produces the required measurement point distribution. The adopted method involves adaptive subdivision sampling of the nominal model entities, in order to ensure the required coverage according to local surface topology and regardless of its orientation.

Several surface sampling criteria have been identified and implemented, to be employed by the user individually or in a combination. These are the following:

- Uniform sampling in the u and v parametric directions. This is the simplest criterion, resulting in the surface being broken down into a rectangular grid, with even u-v parametric spacing across the whole of the surface.

- Chord-height criterion. Local sampling density is controlled by specifying the maximum chordal deviation, this being the largest distance between the line connecting any two adjacent points and the surface. The resulting point density is therefore dependent the local surface curvature and, as Figure 2 shows, this criterion allows a higher point density at locations of high curvature.

- Minimum sample density criterion. This criterion specifies the maximum allowed distance between any two neighbouring points. This was found to be necessary because the chord-height criterion will often result in relatively flat surface regions being sampled at an undesirably low density. An example of chord-height criterion combined with minimum sample density can be seen in Figure 3.

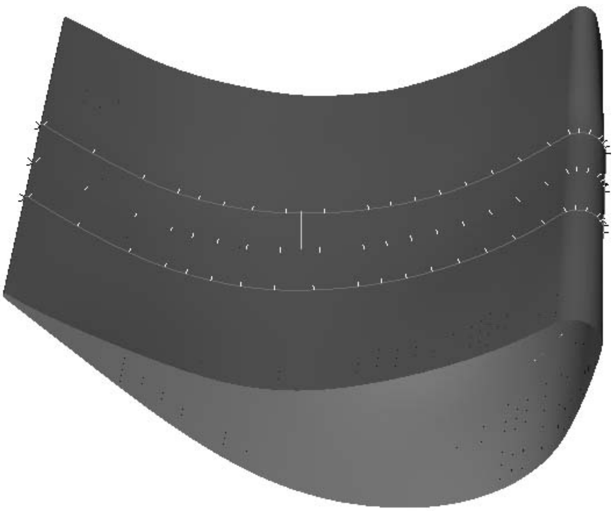

Figure 2: Point Generation Based on Local Curvature.

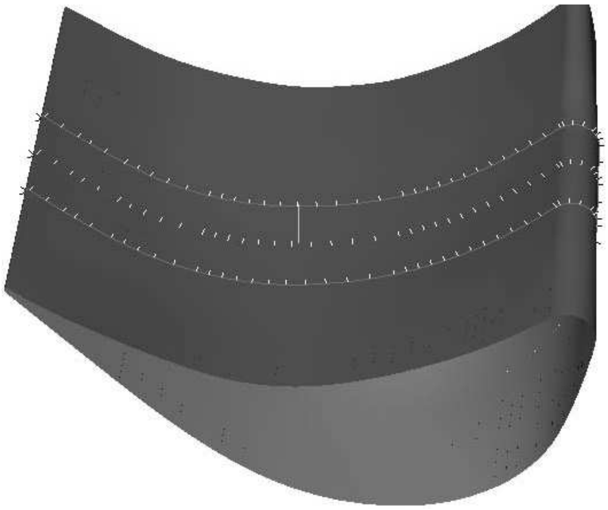

Figure 3: Point Generation Based on Curvature with Maximum Distance in U Set to 2mm.

- Parameterisation-based sampling criterion. Least squares fitting of a NURBS surface through point data requires that there is at least one point situated within each knot span. This sampling criterion is therefore based on the model parameterisation, with the required number of samples per knot span being specified by the user.

Following this, the recursive subdivision sampling algorithm may be summarised as follows:

for *u* and *v* parametric directions
{
- sample the *start point* and *end point* of the surface.
- examine the segment for prescribed criteria (e.g. chordal error)
if any criterion is not within tolerance {
SubDivide(*start point, end point***)**
}
}
SubDivide(*previous point, next point***)**
{
- sample another *new point* half way between the *previous point* and the *next point.*
- examine the segment between *previous point* and *new point* for prescribed criteria.
if any criterion is not within tolerance {
SubDivide(*previous point, new point***)**
}
- examine the segment between *new point* and *next point* for prescribed criteria.

```
    if any criterion is not within tolerance {
        SubDivide(new point, next point)
    }
}
```

The algorithm therefore ensures that the local sampling density is never lower than that prescribed by the above criteria.

PROBE PATH GENERATION, MODIFICATION AND VERIFICATION

Generating the probe path involves producing all the machine instructions necessary to guide the CMM hardware through the measurement cycle. It should be performed in such a way that enables the machine to negotiate each measurement point, whilst ensuring that there are no areas of collision between the probe sensor and the component. The CMM used in this work was LK G-90C, equipped with Renishaw PH-10 indexing head and Renishaw TP2-5W touch trigger probe.

Probe Path Generation

There are a number of issues to consider when striving to achieve an efficient probe path, requiring that the user be provided with programming tools that would enable him to exercise his judgement and realise explicit control over all aspects of the measuring process. In our work we adopted the approach that the model entities define the regions of the object to be measured and that the measurement should be performed for each entity in turn. In some situations it may be desirable that two or more entities be measured as a single surface and this can be readily achieved by stitching adjacent NURBS surfaces into one. This functionality is readily available in modern CAD/CAM systems.

The order in which the measurement points are negotiated clearly needs to be adapted to the geometry in question. With each entity being essentially sampled over a grid of points, the measurements may be performed in unidirectional or bi-directional scans (Figure 4), where the former is generally better suited for closed and/or highly folded

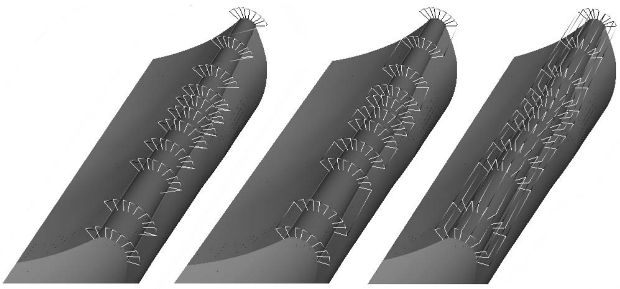

Figure 4a, b, & c: a) Unidirectional scan path in u. b) Bidirectional scan path in u. c) Bidirectional scan path in

surfaces (such as turbine blade airfoils), while the latter is more suited for relatively flat, open surfaces. It is also highly desirable to optimise the path in order to reduce the number of probe head re-orientations, since re-orientation is a relatively time consuming operation and the CMM needs to be calibrated for each orientation used. Finally, as each probing cycle of a touch-trigger probe involves a very low approach speed, there is a need to reduce the stand-off distance in order to optimise the overall measuring time. However, reducing the stand-off distance increases the risk of collision between the probe and the part and this demands careful verification of the generated path.

Using the CAD model and the generated sampling points as the input, the implemented path planning software initially generates a measurement path for each selected entity, based on the default parameters set by the user. These include the scan direction (u or v), scanning pattern (unidirectional or bi-directional) stand-off distance, probe head orientation and others. The path is displayed as a set of line segments, together with the 3D model of the part. Following this, the system allows the user to interactively modify any of the path parameters. The user may also select any of the segments and modify the stand-off distance and probe orientation. Segments may be deleted or edited to introduce additional 'via points' through which the probe will pass when executing point-to-point moves and/or re-orientation.

Finally, the defined measurement path is post-processed into machine executable programming code. We adopted DMIS (Dimensional Measurement Interface Standard) as the machine instruction language, being the most widely supported standard for CMM programming.

Probe Path Verification

Verification of the machine movements prior to downloading instructions to the CMM is critical for providing the user with full confidence in the in the validity of the generated measurement path. This was realised through implementation of a simulation and full 3D graphical animation of the measuring process. The input for the simulation is provided by the DMIS code produced by the path generation module. The code is interpreted and executed to emulate the operation of the actual CMM. This approach also allows simulation of externally generated CMM programs.

It was decided that the animation should provide full 3D rendering, as opposed to wire frame graphics, in order to ensure that the depth of the scene and the probe/part interaction are always comprehensible. The animation is dynamic, allowing the user to zoom and rotate the scene whilst the animation is running. Any part of the animation can be rewound and replayed, if it is deemed to be of particular importance. The complete animation can be controlled using a slider bar, allowing the operator to rapidly move through the measurement cycle. Hence, using this option the operator could easily verify a path containing thousands of movements. Having this kind of facility was found to be of immense practical value, allowing the operator to visually validate the measuring cycle and to identify any unforeseen problems, such as collisions between the probe and the part.

Producing fully rendered animations of scenes containing NURBS entities is a computationally intensive task. The graphics library used to develop the software was OpenGL. Figures 5 and 6 are still frames of an animation that runs in real time on standard Pentium II PC hardware platforms that do not have any specialised graphics acceleration. The required computational efficiency in generating the animations was achieved by generating a polygonal model of the part before passing it to OpenGL for rendering, rather than passing the NURBS entities. In generating the polygonal model, the original NURBS entities are sampled according to the criteria based on the local surface curvature, as outlined above, to produce a model that is accurate to within a specified tolerance. The quality of the animated scene was further improved by the implementation of smooth shading of the polygon segments.

Figure 5: Probe Path Verification.

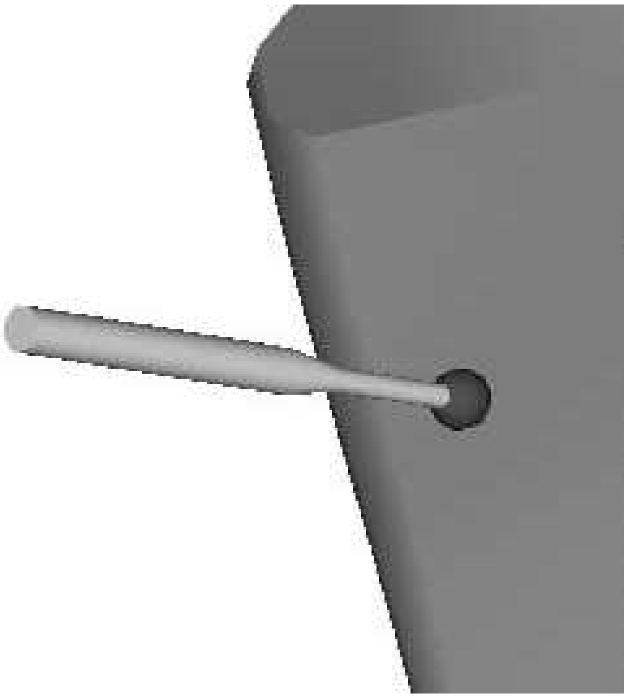

Figure 6: Probe Path Verification, an Alternative View.

AUTOMATIC COLLISION DETECTION

Visual examination of the simulated probe path is adequate in many cases, in particular when examining for gross path errors, such as collision of the probe head with the object and its surroundings. However, in situations involving dense measurements, in the vicinity of small features and with a small stand-off distance, it was found that visual path verification is still difficult. In such cases a collision detection tool that would automatically detect collisions with the object and highlight the offending path segments is highly beneficial.

The collision detection algorithm considers collision between the probe tip and the nominal model. Instead of examining each probe movement for collision between the probe sphere and the surface of the model, considerable gains in computational efficiency were realised by examining for intersection between the trajectory of the sphere centre and the offset model surfaces (the offset being the sphere radius) [Yan&Menq 91]. Figure 7 shows a schematic of this solution..

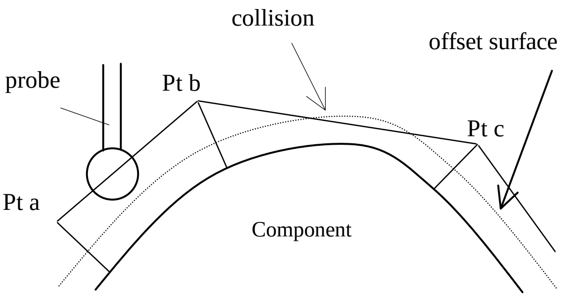

Figure 7: Automatic Collision Detection.

CONCLUSION

The paper has presented an implementation of a methodology for measurement planning and collision-free probe path generation to perform measurement on a free-form shape using a CMM and a touch-trigger probe. The method utilises the CAD model of the part at each step, with NURBS being the principal modelling entity. Offset surface entities were employed in order to improve the computational efficiency in carrying out certain tasks. Accurate component registration was identified as a key requirement and the performance of the proposed registration method was demonstrated. Adaptive subdivision sampling according to several relevant criteria was employed to define the required measured points. Interactive graphic tools for probe path generation, modification and verification were developed. Fully rendered computer animation of the measurement process and the automatic collision detection are considered to be necessary practical tools and a key to providing the user with confidence in the generated results. The methodology and the system have been applied to measurement of various engineering parts, including aeroengine turbine blades, whose dimensional inspection is generally difficult to perform.

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