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FREE FORM SURFACE MEASUREMENT USING NON-CONTACT MEASUREMENT METHODOLOGY

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Abstract − Quality control is applied to almost every procedure during the manufacturing process in industry. However, it is not used commonly in restorative dental practice[1,2]. The surface contour or shape of the tooth is very irregular, a 'so called' free form surface. Measurement of such a free form surface needs a specified strategy[3,4,5] to satisfy the measurement accuracy. This paper attempts to propose an optimal measurement strategy to measure the occlusal molar tooth surface, in order to achieve a degree of measurement and quality control in restorative dental practice.

Keywords: free form surface, non-contact measurement, quality control.

1. INTRODUCTION

Parts produced by manufacturing engineering processes differ quite considerably from those found in human development. Usually such parts are developed to create the shape required for the desired engineering product. In contrast, human 'components' have been evolved rather than developed, as 'free-form' parts and systems which are, therefore, dissimilar to most engineered products. A free form surface can be defined as a surface that cannot be described by a single mathematical equation. A molar tooth surface is one of those complex free form surfaces.

This study was directed to the measurement of such a complex free form tooth surface by using an optical triangulation based measurement system.

2. MEASUREMENT METHODS

2.1. Model design

The form and dimensions of a molar tooth viewed from the top is shown at the left hand side in Fig.1. The approximate dimensions of the crown are 12mm wide × 12mm deep × 6mm high. The top surface of the crown (called the occlusal surface), consists of cusps (peaks) interspaced by fissures (valleys). The slopes form a modified pyramid from the tips of cusps to the fissures, and become more spherical in shape from the cusp tips to the outer surfaces of the tooth.

As optical measurement has a limitation of being able to provide wrong readings at the inappropriate operation of a measurement, such wrong information cannot easily be identified on a free form surface. Therefore, it is necessary to evaluate a measurement strategy on a simulation model to prove the effectiveness of a system that is based on a geometrical shape.

The optimal measurement strategy for measuring an occlusal surface of a molar tooth was investigated from a simulation model. Fig.1 shows the simulation model consisting of four stainless steel balls 6mm in diameter, which represent four cusps of a molar tooth.

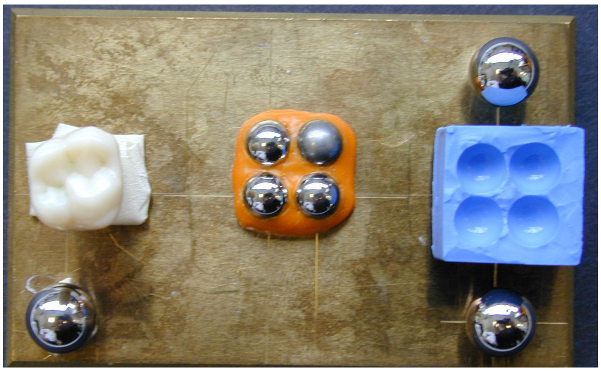

Fig.1: Four-ball-bearings arranged as a simulation model

2.2. Assembly

Four stainless steel balls with a diameter of 6mm were randomly selected, and rigidly assembled and secured on a steel plate. The surrounding area to the four balls was covered with wax to mask the uneven texture of the area. The relative distances and heights between each ball were deliberately made unequal, to imitate the distances between the cusps on the occlusal surface of a molar tooth, as shown in the centre of the Fig.1. Three attached balls at the three corners on the metal plate can be used as datum device for comparative measurement during sequential comparative measurement. Fig.1 shows the simulation model in the middle, the occlusal surface of a molar tooth at the left, and an impression of the model at the right hand side.

In this model, the four centres of the balls define three planes, but the angles between the planes are not critical as long as they differ from each other, and they do not have to align with any of the machine axes planes, as it is the case with a molar tooth surface.

2.3. Surface treatment

It was found that a stainless steel ball has a too reflective surface to enable the laser probe sensor (OP2) to operate properly. The OP2 probe on the sensor collects only a diffusely reflected laser beam. When the surface is shiny, the reflection of the laser beam is in a mirror direction only, and the detector of the probe receives either too little light when it is out of the path of reflection, or too much light when it is facing the direction of reflection. To avoid such an optical scenario, various surface treatment methods have been tried, such as spraying or painting techniques. Unfortunately these techniques have no control in the ability to produce an even distribution of the painted surface of the materials.

As this study is aimed towards an *in vivo* clinical trial, the samples of dental trials would be impressions from patients' teeth (the inverse image). Therefore, in this study we concentrated on the impressions moulded from the model rather than the model itself.

2.4. Measurement system

An optical triangulation based probe (OP2, Renishaw, UK) was connected with a probe head (PH9, Renishaw, UK), and fitted on a co-ordinate measuring machine (CMM, Merlin II, IMS, UK).

The OP2 is a laser probe (wavelength of 830nm) with a resolution of 1µm and spot size of 25µm. The PH9 has an orientation flexibility in two axes: one is along the optical axis in a range of -180° to +180°, and the other is in a tilting direction in a range of 0° to 105°. The CMM has an axial length measuring accuracy of 4.0+L/275, where L is the measured length.

2.5. Measurement strategy

Using an optical triangulation based probe to digitise a surface, several digitisation parameters are involved. These include scan direction, sampling interval, scanning speed, optical threshold setting, and probe orientations.

This paper concentrates on the selection and implementation using multiple probe orientations. The rest of the parameters are reported in other papers [6,7].

2.6. Multiple probe orientation scan

It has been found that the digitisation quality is strongly influenced by the setting up of the probe orientation in relations to surface normal [6]. It is suggested that it is necessary to make the optical plane perpendicular to the probe scanning direction, and the angle between the surface normal and optical axis needs to be within 30.3° to eliminate the digitisation error of not more than ±10µm[8]. Therefore, four probe orientations were designed to scan one hemisphere, as shown in Fig.2.

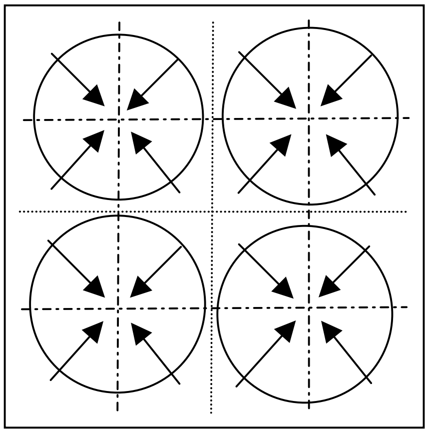

Fig.2: Four probe orientations were used to digitise each hemisphere

The model surface consisted of four hemispheres. Each of the hemispheres was divided into four quadrant hemispheres, and allotted an identifying code. This resulted in a total of 16 segments, and each one was scanned using a specific probe orientation. To scan these 16 segments, it was not necessary to define 16 individual probe orientations, as the geometrical features of the balls were the same. Hence, only four probe orientations were required for each quadrant of the hemisphere. These were defined as I (30°, 135°), II (30°,-135°), III (30°,45°) and IV(30°, -45°). These same probe orientations were used for each of the four balls.

Each segment scan was started at the highest point of the hemisphere. This was to avoid early termination occurring during the scan, as the largest surface contour changes are at the circumference of the sphere, and over the sphere the contour changes continuously. The method provided an uncomplicated digitisation procedure, but then required much more complex data re-arrangement, as the string of data co-ordinates was not in the right order between segments, in respect of the scanning direction. All scanned segment data was stored in a temporary storage layer, and produced a total of 16 layers in all. When the digitisation procedure was completed, the co-ordinate order was rearranged, and each segment was merged to provide data to reconstruct the complete hemisphere.

2.7. Digitisation data re-arrangement

It was possible to simplify the procedure, since four probe orientations could be used without re-addressing, if the scanning process was arranged to scan the quadrants hemispheres where they are at the same position for the four balls. After the first segment scan, it was necessary to reverse the data string order, and scan the second quadrant segment following the order of the first part data string. In this manner the third and fourth segment scan data could be followed and saved in the same data buffer (layer), which avoided the subsequent data re-ordering previously required between the first and second segments.

This method was extended to the other three segments over the remaining three balls, so that the temporary storage layers reduced from 16 to 8, and the subsequent data re-arrangement was also reduced from 16 to 8 layers. This way it was possible to save the operation time and to substantially reduce the usage of computer memory.

3. RESULTS

The imaging results revealed a successful digitisation strategy of the four ball model. The shape and dimensions were proved correct from data analysis of the reconstructed image, as shown in Fig.3 and Fig.4.

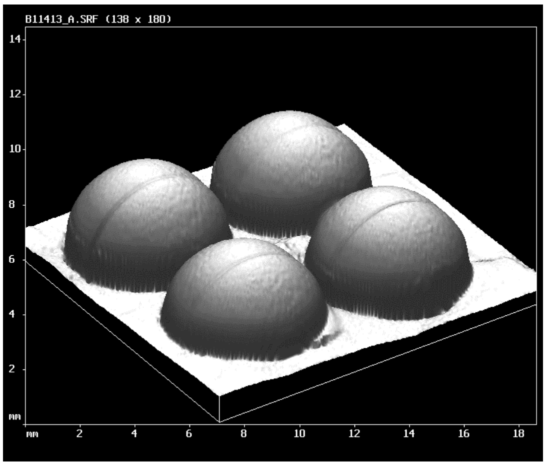

Fig.3: A scan image of the four ball model

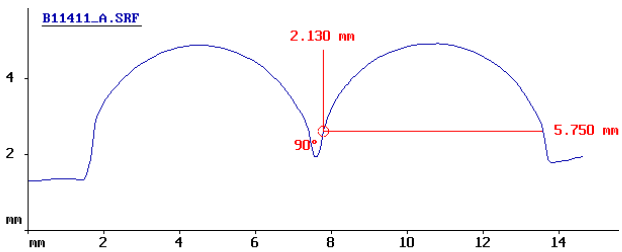

Fig.4: A profile from the image in Fig.3

It must be noticed that a defect along the middle of the sphere were revealed in Fig.3, where the probe orientation was changed. In fact this was what has been expected as each hemisphere was scanned by four probe orientations, and a re-positioning error revealed the defects. Again this defect did not necessarily effect the geometrical measurement, as show in Fig.4 at the top of the profiles, but affects the quality of the image, in terms of the data density which would be captured.

4. REPRODUCIBILITY

The reproducibility of the measurement process was assessed by scanning the same model five times repeatedly. The superposed images are shown in Fig.5. Volumetric measurements were calculated between the second, third, forth and fifth images related to the first image, and are listed in Table 4.1.

Table 4.1: The volume measurements based on pairwised scan images over an area of 150 mm^2

	1 & 2	1 & 3	1 & 4	1 & 5
File name	B11411 & B11402	B11411 & B11403	B11411 & B11404	B11411 & B11405
Volume (mm^3)	**0.715**	**0.777**	**0.799**	**0.950**

These volume differences are mostly concentrated at the middle of each sphere where the probe orientation changes as shown in the Fig.5.

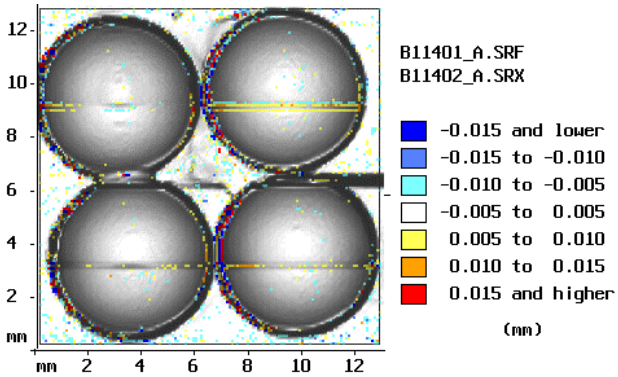

Figure 5: A colour coded image shows the Difference between second and first scans

Pairwise colour coded image is shown in Fig.5. The reproducibility of ±10µm is indicated. The errors happened mostly along the changes of the probe orientation, due to the relocation of the probe, influenced by the mechanical deviation.

5. DISCUSSION

A defect appeared at the position where probe changes its orientation. It is inevitable to have a degree of displacement in a mechanical system. Fortunately this displacement is the position of data capturing, rather than the digitisation value (the height). Therefore such displacement is not influence the digitisation accuracy, but the density of data that can be captured or where data can be captured.

6. APPLICATION

This strategy has been used for scanning an occlusal molar tooth surface, to quantify its wear over a period of time as show in Fig.6.

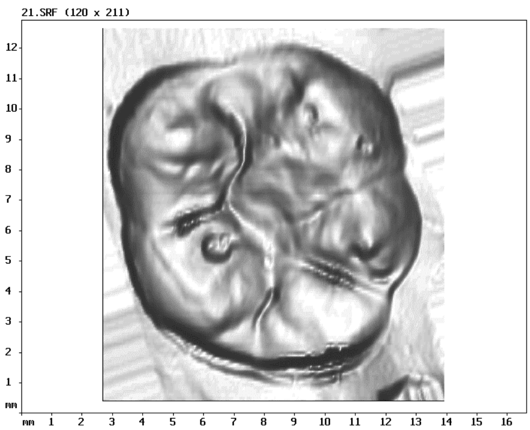

Fig.6: The image of an occlusal molar tooth

From the results and application, a satisfactory digitisation procedure using an optical triangulation based measurement system has been demonstrated.

REFERENCES

[1] Allred H, "A series of monographs on the assessment of the quality of dental care", The London Hospital Medical College, 1977.

[2] Seymour K, Samarawickrama D Y D, Zou L and Lynch E, "Assessing the quality of shoulder preparations for metal ceramic crowns", Euro. J. of Prosth. and Rest. Dent., vol. 7, pp. 125-9, 1999.

[3] Osanna, P H, Rezaie K, Durakbasa N M and Heiss C P, "Form measurements – A bridge between production metrology and bio-mechanics", International Journal of Machine Tools and Manufacturing, Vol.35, No.2,pp165-8,1995.

[4] Cho M W and Kim, "New inspection planning strategy for sculptured surfaces using co-ordinate measuring machine", Inter J of Prod Res, Vol.33, No.2, pp427-44, 1995.

[5] Che C and Ni J, "A ball target based extrinsic calibration technique for high accuracy 3-D metrology using off the shelf laser stripe sensors", Precision Engineering, Vol.24,pp210-9, 2000

[6] Zou L, An optical measurement system for free form surfaces, PhD thesis, University of London, 2002.

[7] Zou L, Yang Q P, Jovanovski V, Tay WM and Lynch E, Measurement of tooth morphology using a laser probe fitted on a co-ordinate measuring machine; International measurement confederation; Laser metrology for precision measurement and inspection in industry, Proceedings IMECO TC No.14, pp11-20, 1996.

[8] Feng H Y, Liu Y X and Xi F, Analysis of digitising errors of a laser scanning system, Precision Engineering, Journal of International Societies for Precision Engineering and Nanotechnology, vol.25, pp185-91, 2001.

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