Jurnal Teknologi, 45(D) Dis. 2006: 97–112

COMPLEX SHAPE MEASUREMENT USING 3D SCANNER

RAHMITA WIRZA O.K. RAHMAT[1], NG SENG BENG[2],
KAMINI A/P SANGARALINGAM[3]

Abstract. Automated inspection systems usually start from computer-aided design (CAD) techniques, and end with either generation of machining instructions required to convert a raw material into a finished product, or to obtain three-dimensional data for constructing a parametric surface model of the product for the purpose of error analysis, or to duplicate or enhance the object. It involves surface digitization of an existing part that needs inspection, CAD model creation and analyzing the inspection results. Most of the time, without the help from the manufacturer, it is very difficult to do inspection and to detect any changes of the product after being used. In addition, the original blueprints of most manufacturing products are not being revealed to the public. The main objective of this paper is to propose an algorithm that is able to extract information from digitized complex shape objects (using laser scanner), such as the medical knee implant (knee prosthesis), to generate their blueprint. It is hoped that other researchers, especially in the medical and bioengineering field, can benefit from this proposed algorithm to predict or approximate the changes of the medical ex-plant and modify its design to suit the patient needs.

Key words: Automated inspection, blueprint, prosthesis, 3D scanner, total knee replacement

Abstrak. Sistem Pemeriksaan Automatik biasanya bermula dengan teknik Reka bentuk Berbantukan Komputer (CAD) dan berakhir dengan janaan arahan mesin untuk menukarkan bahan mentah kepada produk akhir, memperolehi data tiga dimensi untuk membina model permukaan berparameter bagi tujuan analisis ralat, duplikasi atau memperbaiki objek tersebut. Ia melibatkan pendigitalan permukaan objek yang perlu diperiksa, janaan model CAD dan analisis keputusan pemeriksaan. Pendigitalan boleh dilakukan dengan teknik kuar sentuh atau pengesan tanpa sentuh. Biasanya, tanpa bantuan daripada pengeluar, adalah sukar untuk memantau dan mengenal pasti perubahan produk selepas digunakan. Tambahan pula, reka bentuk cetakan asal tidak didedahkan. Objektif utama kertas ini ialah mencadangkan suatu algoritma yang mampu mengekstrak maklumat daripada objek berbentuk kompleks yang telah didigitalkan (dengan menggunakan pengimbas laser), misalnya cangkukan lutut, untuk menjanakan reka bentuk cetakannya. Diharapkan penyelidik lain, terutamanya dalam bidang perubatan dan bio-kejuruteraan mendapat manfaat daripada algoritma ini untuk meramal dan menganggar perubahan bekas cangkukan perubatan dan seterusnya mengubah reka bentuknya untuk memenuhi kehendak pesakit.

Kata kunci: Pemeriksaan automatik, reka bentuk cetakan, cangkukan lutut, pengimbas 3D, gantian lutut total

[1,2 & 3]Multimedia Department, Faculty of Computer Science & Information Technology, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor Darul Ehsan, MALAYSIA. Email: rahmita@fsktm.upm.edu.my

1.0 INTRODUCTION

Complex surfaces can be seen in many modern mechanical parts. The design of complex surface is of great importance to modern industry and bioengineering parts. As the work piece becomes more complex, the role of 3D digitizers becomes more important. Since the inspection time, cost, and measuring errors depend on the employed automated inspection systems, the development of an optimal inspection strategy is required for a more accurate and faster inspection. Automated inspection systems will include the determination on how the raw inspection data is to be evaluated and how these results are to be presented. The 3D digitization of a part or a whole surface can be achieved by using either contact probing or non-contact sensing techniques. A Coordinate Measuring Machine (CMM) represents an example of the contact-probing device. It returns the scanned object's surface coordinates upon the probe touching it. On the other hand, a 3D scanner represents a non-contact sensing device, which projects a laser beam onto the part's surface and optical sensors will receive the reflected beam. With a triangulation procedure, the 3-D coordinates of data points on the part surface are calculated at a considerably greater speed compared to contact probing techniques, but nevertheless this method is sensitive to shiny and dark surfaces.

Meanwhile Total Knee Replacement is a surgical procedure in which injured or damaged parts of the knee joint are replaced with artificial parts. The procedure is performed by separating the muscles and ligaments around the knee to expose the knee capsule (the tough, gris-like tissue surrounding the knee joint). The capsule is opened, exposing the inside of the joint. The ends of the thigh bone (femur) and the shin-bone (tibia) are removed and often the underside of the kneecap (patella) is removed.

The artificial parts are then cemented into place. The new knee will consist of a metal shell on the end of the femur, a metal and plastic through on the tibia, and if needed, a plastic button in the kneecap. The metal, which is the femoral component, is usually made of chromium, cobalt and molybdenum, which is inserted in the body and has good mechanical property. The tibia component is often made of titanium, which is lighter, stronger and leaves more space for the plastic bearing surfaces. The plastic is made from ultra high molecular weight polyethylene (UHMWP), chemically similar to ordinary polythene but immensely hard and very smooth.

Total knee replacements are usually performed on people suffering from severe arthritic conditions. Most patients who have artificial knees are over the age of 55, but this procedure is also performed on younger people. About 85 - 90 percent of total knee replacements are successful up to ten years. The major long-term problem is loosening. This occurs because either the cement crumbles or the bone suffers lyses and then desorbs from the cement. By ten years, 25 percent of total knee replacements may look loose on x-ray, and about 10 percent will be painful and require re-operation [1]. Several articles [2] having reported studies on total knee joint replacement with various problems, but most of them probably do not have the original design or blueprint of the artificial knee.

There is a variety of Knee Joint Implant design, where each design is suitable for people from different ages, body size and gender. Among them is Low Contact Stress (LCS) knee, which was designed to address the existing problem of wear of polythene material within the prosthesis. The Anatomic Modular Knee (AMK) is another successful system design, which has the ability to compensate for varying degrees of bone loss, by combining various wedges and stems depending on the condition of the joint. There are several other designs in the market, which fulfil the needs of orthopaedic surgery. With several articles [2] having reported studies on total knee joint replacement with various problems, it seems that there is a need to investigate the creep deformation and wear of the articulating surface of each of the knee prostheses, with equally accurate measurement and definition of complex geometry [3].

The objective of this project is to propose an automated system that is able to develop blueprints for complex shape objects, such as the medical knee implant (knee prosthesis). By using Microsoft Visual C++ as the developing platform and OpenGL as the graphics library, it is hoped that the blueprint of the knee implants that was produced by this proposed algorithm can be used as further research for others to determine the changes of the knee ex-plant or reproducing a new design of implant. In this paper, we refer our C++ computer programme using the proposed algorithm to generate the blueprint as "programme" and "the proposed system".

2.0 RESEARCH BACKGROUND

The use of a CMM has been widely accepted for dimensional inspection of objects with complex surfaces. There exist several terms of automated inspection systems for complex surfaces using CMM. For example, [4 - 7] refer to it as automated inspection planning; Kim and Kim [8] refer to it as CAD-directed measuring strategy; Ip and Loftus [9], refer to the system as the surface coordinate measurement method; Skalski *et al.* [10] call it the scanning measurement technique; Hsieh *et al.* [11], just refer to it as reverse engineering that uses CMM; [12] refer to it as CAD-model based inspection; [13] refer to it as computer integrated inspection system using CMM; [14] refer to it as an off-line measurement planning system for inspection automation, and there are several other terms. In general, the objectives may be divided into two categories:

(i) To obtain three-dimensional data for constructing a parametric model of the product, and
(ii) To inspect a milled complex surface for error analysis

Most of the automated inspection systems include the measuring error analysis of a ball type probe, optimal selection of measuring points, path generation of the CMM probe, and approximation of the surface, which fits the measuring points or compares the measuring points with the CAD data. Since inspection time, cost and measuring errors depend on the employed inspection planning method; development in this area is desired. Many published materials introduce and discuss the methods relating to the integration of computer-aided design with automatic or semi-automatic off-line programming systems for CMM.

Generally CMM is designed to move a probe that measures and determines the coordinate of an object. CMM is not object dependent and can be widely used on any type of object. CMM can be fully automated and the output could easily be linked to a CAD system. CMM is comprised of four components: The machine itself, the measuring probe, the computer system, and the computer software.

CMM probes are transducers that convert physical measurements into electrical signals. The probes are available in three main forms: touch-trigger, displacement measuring, and proximity or non-contact probes.

Touch-trigger probes are the most common type of probe. They actually touch the surface of the work piece, and upon contact, they will send a signal with the coordinates of that point to the CMM. The probe is then backed off and moved to the next location where the process is repeated depending on how many points we want. The movement and the orientation of the probe movement can be controlled using the list of Computer Numerical Control (CNC) instruction code which can be produced either manually or from the output data file of the programming system which was introduced by Wirza *et al.* [2].

Displacement measuring CMM probes are also referred to as scanning probes. This method generally involves passing the probe over a target surface. As the probe scans the surface, it transmits a continuous flow of data to the measurement system. Proximity or non-contact probes function similarly to displacement measuring CMM probes, but they use laser, capacitive or video measurement technology.

However, using a CMM can be very complicated and it requires training. Using the touch-trigger probe for measuring complex shape objects requires full attention for the probe might be broken when touching and retracting the difficult parts. The same attentions are also needed when using the displacement-measuring probe; the possibility of breaking the probe is high while scanning the difficult surface. And in most cases, the technician who is responsible for handling the CMM is an expert in the machine and the measuring probe only. They usually have little knowledge of the computer system and the computer software, which are attached to the CMM.

However, a 3D scanner, which represents a non-contact sensing device, projects a laser beam onto the scanned object's surface and optical sensors receive the reflected beam. As mentioned earlier, by applying a triangulation procedure the 3-D coordinates of data points on the part surface are calculated at a considerably greater speed compared to CMM. Even though this method is sensitive to shiny and dark surfaces, using the 3D scanner is not as complicated as CMM.

3.0 METHODOLOGY

3.1 Scanner Selection

Before displaying and obtaining the blueprint of the plastic knee prosthesis (see Figure 1) in the proposed system, a set of 3D input data is required. This can be done with the aid of 3D scanners such as the CMM and the laser scanner. At this stage the effectiveness and accuracy of these scanners have to be taken into consideration.

Figure 1 Plastic knee prosthesis

The CMM machine, as mentioned earlier, is accurate but slow. The surface points detected with the CMM machine are in sequence order following the on-line list of instruction keyed in by the user. In that case there is no need to organize and sort the surface points. The biggest problem with the CMM machine is that each scan can be done on one surface only. Figure 2 shows the proposed system's output with the points obtained from the CMM machine. It took almost six hours to finish scanning one of the surfaces [2].

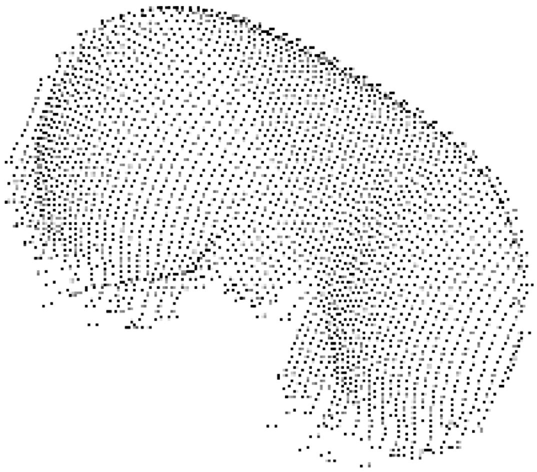

Figure 2 Points detected with the CMM machine

Meanwhile, the laser scanner is fast but inaccurate [15] and sometimes garbage points may appear. Many factors will affect the output data of each scan, such as the reflective surface of the scanned object and the interference of the surrounding light. We need to scan the object from different angles and orientations in order to get the surface points of the whole object. Then the points from each scan are aligned and combined. The final output data will be thousands of unsorted points. These points need to be pre-processed before they are ready for use. This process will give much burden on the proposed system and will increase the processing time. Figure 3 shows the proposed system's output with the points obtained from the laser scanner. It only needed three hours for the process of obtaining and refining the scanned data.

After a few scans with the CMM and the 3D laser scanner, considering the time taken to do the measuring and the difficulties to explore and understand the CMM attached computer software and the list of CNC code, we have decided to use the 3D laser scanner, Cyberware Model 3030 for digitising the prosthesis. This decision was made because we need to obtain many sample points easier and faster to implement in the proposed system. In addition, we need to create a function that is able to normalize inaccurate input data.

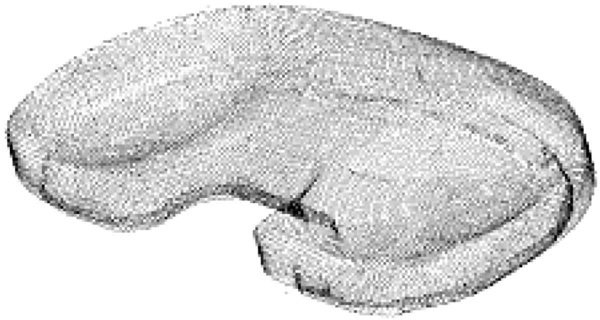

Figure 3 Points detected with the laser scanner

3.2 Digitizing Process

We begin the digitizing process by painting the prosthesis with a white coating to reduce unwanted points generated due to its reflective surface. This was done by assuming that the molecule of the white paint will not affect the accuracy of the measurement. The prosthesis was then placed on the scanner's platform. A clip was used to hold it in place with a certain orientation that the laser can detect most of the object edges and surfaces.

Next we have to determine how many times the platform will rotate for each scan (360 degrees). A set of data is collected for each angle of rotation. It is considered a complete scan when the scanner finishes all the scans between 0 degrees and 360 degrees.

After each scan, we need to omit unwanted points or noises such as the surface points of the clip. Then only we can merge data sets from scans of all angles. The scanning and merging process is repeated until the merged data are considered to have achieved the optimum accuracy and has the minimum lost of data. Lastly, holes or hidden surfaces (if exists) in the combined scanned surface were patched with computer-generated surfaces before exporting into a desired file format. Figure 4 shows the flowchart of digitizing the plastic knee prosthesis using the 3D scanner.

3.3 Pre-processing

This proposed system is a fully automated inspection system. That means there is a need to automatically pre-process the input set of data. The surface points must be in a desired order so that formulas can be applied to obtain useful information such as the width, height, curvature, tangent and diameter. Figure 5 shows the stages and calculations involved in the pre-processing phase.

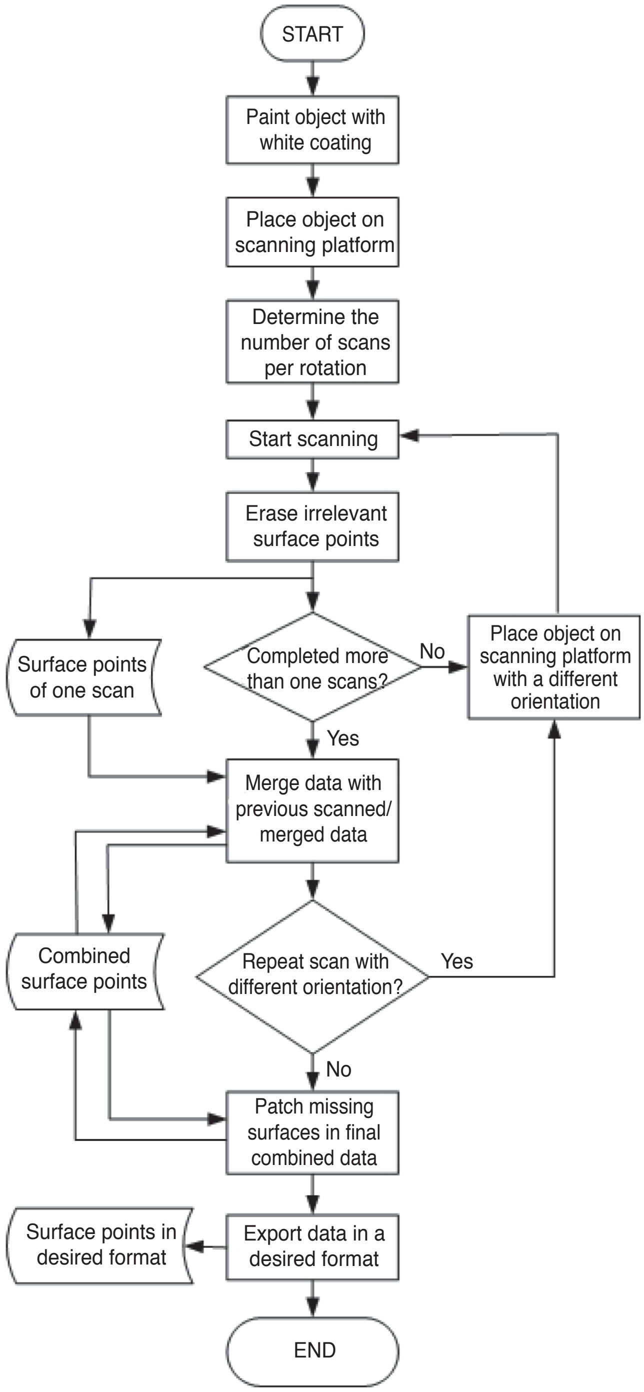

Figure 4 Scanning process with a laser scanner

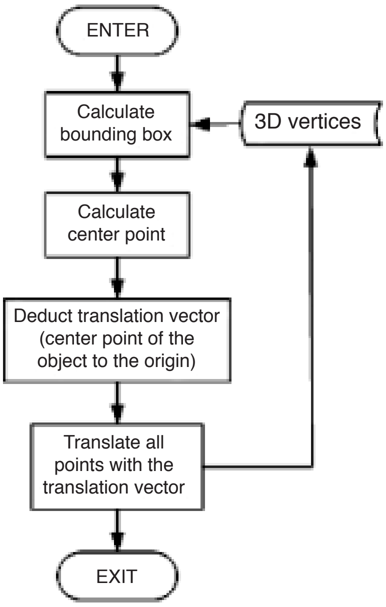

Figure 5 Pre-processing procedure

First, the coordinates of the surface points are taken in from an input file. They must be in the sequence of x, y and followed by z. In order to find the bounding box of the prosthesis, we just have to detect the minimum and maximum value of each axis. Next, we calculate the centre point of the prosthesis using the formula below.

$$\text{Centre point, midi} = \frac{(\min_i + \max_i)}{2}, \qquad \text{where } i = \text{x,y,z} \tag{1}$$

Next we need to obtain the translation vector (t_x, t_y, t_z). It is the vector from the object's centre point to the origin. By using this vector, all the surface points were translated to the origin to ease the process of displaying and navigating. After all the pre-processing steps are completed, the proposed system displays the output.

3.4 Display

This proposed system is able to display the object in four different windows. Each window displays the prosthesis from a particular view, namely top, front, left and perspective (see Figure 6). Users are also able to navigate around the object with transitions along all 3 axes (x-axis, y-axis and z-axis) using translations, clockwise or counter clockwise rotations and zoom in or zoom out. Please refer to Figure 7 which shows the flowchart of the display process.

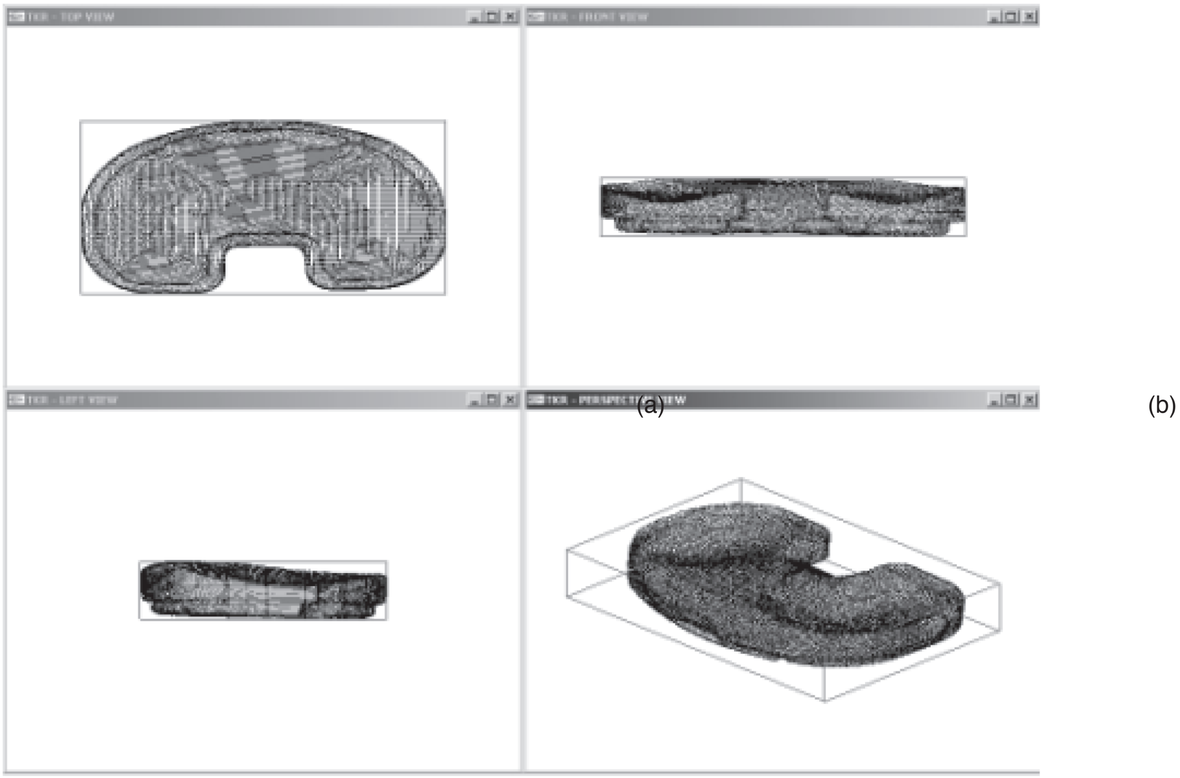

Figure 6 Display of prosthesis in four different views

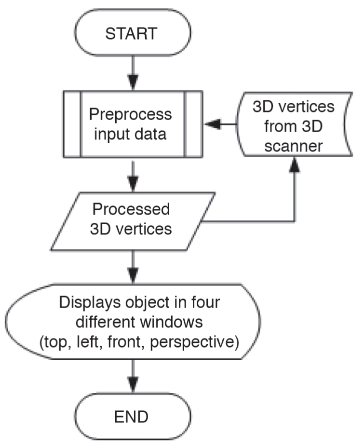

Figure 7 Flowchart of the display process

3.5 Edge Detection

The next step for this proposed system will be edge detection. It is to find the edge points for constructing the boundary of the prosthesis. Below are the steps to obtain the edge points of the prosthesis from a cloud of unsorted input data:

(1) Divide the points into columns using the casting method in C++.
(2) Sort points in each column along the vertical axis.
(3) Perform vertical scan lines to detect edge points and then store them into an output file Figure 8 shows the points detected with the vertical scan line.
(4) Divide the points into rows using the casting method in C++.
(5) Sort points in each row along the horizontal axis.
(6) Perform horizontal scan lines to detect edge points and then store them into the same output file as step 3. Figure 9 shows the points detected with the horizontal scan line.
(7) Combine points obtained from both the vertical and horizontal scan lines. Figure 10 shows the combined points of both vertical and horizontal scan lines.

Figure 8 Edge points from vertical scan line

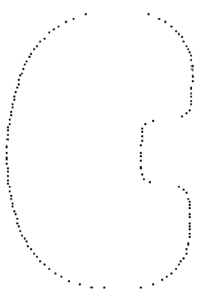

Figure 9 Edge points from vertical scan line

Figure 10 Combination of detected edge points

(8) By using radial sort, arrange the edge points clockwise from the top with θ as the parameter attribute of each point from the origin.

$$Orientation,\ \theta = atan(x/y) \tag{2}$$

Attribute θ, is the angle between the vertical line passing through the origin and the line connecting the edge point and the origin (see Figure 11).

(9) At this stage, if we connect the consecutive points with lines, the generated blue print will look like Figure 12.

(10) This is because there are certain angles with more than 1 edge points detected (see Figure 13).

(11) To overcome the above problem, the system will detect the area or region of the digitized points/edges that needed a second sorting. This region can be detected with a clockwise and anti-clockwise scan (see Figure 14).

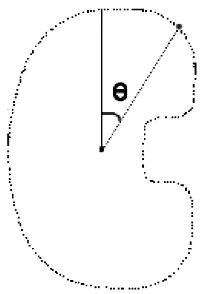

Figure 11 Radial sort with the orientation attribute

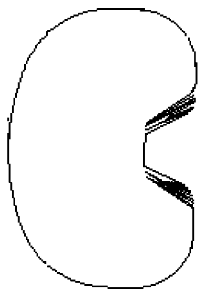

Figure 12 Output using the radial sort only

Figure 13 Three edge points detected in the same angle

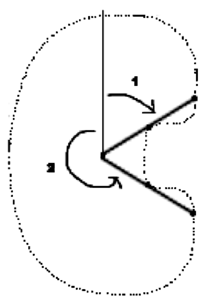

Figure 14 Area with more than two edge points

(12) Extract points in this region into a new array and perform a second sorting using the distance formula.

$$\text{Distance}_i = \sqrt{\left(\left(x_{i+1} - x_i\right)^2 + \left(y_{i+1} - y_i\right)^2\right)} \quad (3)$$

A consecutive neighbouring point is defined as the point with the shortest distance from the current point (point i).

(13) Replace the original points/edges with the sorted points/edges from the array.

(14) Connect the edge points using straight lines (see Figure 15).

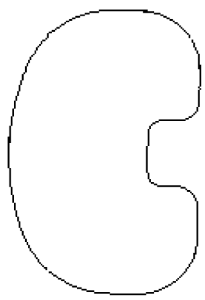

Figure 15 Output after the second sort

The summarized flow chart of the edge detection procedure can be seen in Figure 16.

3.6 Blueprint

The blueprint can be obtained by measuring the dimensions of the prosthesis directly using the vertices' coordinates and displaying it with the measurements in 3 floating points (see Figure 17).

4.0 CONCLUSIONS

With this programme successfully developed, it will aid researchers and medical doctors to ease the process of detecting the worn part of the plastic knee implant and also able to generate a blueprint for the reproduction of a similar prosthesis for the patients.

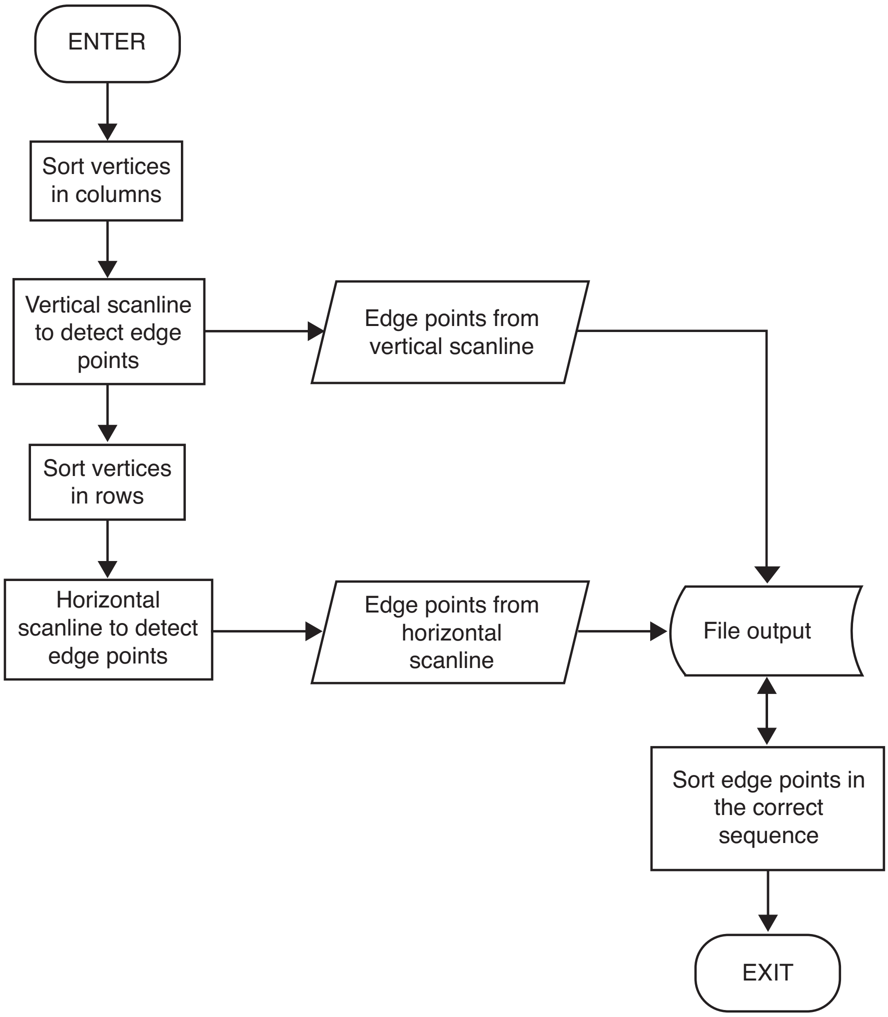

Figure 16 Flowchart of the edge detection procedure

The proposed system is still in a very early stage. There is a need to establish a more detailed blueprint, with reliable accuracy. Hopefully we will able to produce a better technique to detect the edge of complex 3D objects i.e., the plastic knee implant, without sacrificing the accuracy of the blueprint.

At this early stage, the system is unable to detect garbage (irrelevant and unwanted) input files or points. The authors are still in the stage of upgrading the system so that it will give more accurate results and fully automating the 3D digitising input with the ability to detect the garbage and unwanted data input. In future, we plan to extend this system to be able to reverse engineer almost all complex objects that need to remanufacture or reproduce a fresh blue-print.

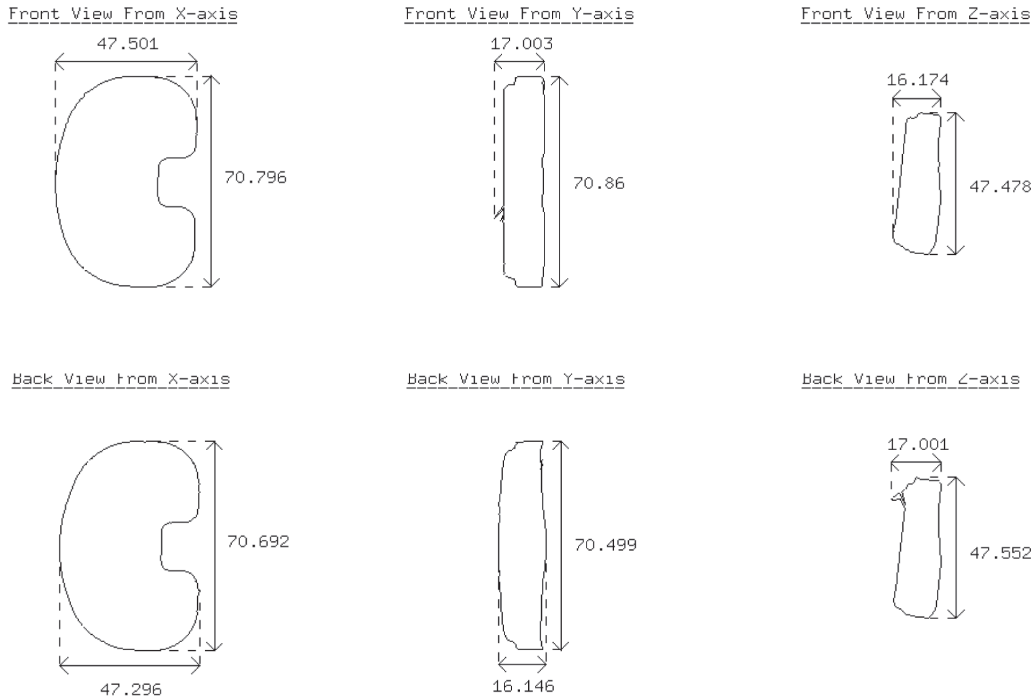

Figure 17 Generated blueprint

ACKNOWLEDGEMENTS

Special thanks to the Ministry of Science and Technology, for the financial support under IRPA grant (04-02-04-0592-EA001) with title "Surface Design of Total Knee Replacement using Virtual Manufacturing". Our gratitude to the Research Management Centre, UPM, for managing the research fund, and SIRIM for offering the measuring facilities.

REFERENCES

[1] Heim, C.S., P.D. Postak, and A.S. Greenwald. 1996. Factors Influencing the Longevity of UHMWPE Tibial Components. Technical Report. Orthopaedic Research Laboratories, AAOS.

[2] Wirza, R., M.S. Bloor, and J. Fisher. 2002. Inspection Strategies for Complex Curved Surfaces Using CMM. *Lecture Notes in Computer Science 2331*. 184-194 ff.

[3] Spicer, D., D. Pomeroy, W. Badenhausen, L. Schaper Jr, J. Curry, K. Suthers, M. Smith. 2001. Body Mass Index as a Predictor of Outcome in Total Knee Replacement. *Int.Orthop*. 25(4): 246 - 249.

[4] Legge, D. I.. 1996. Integration of Design and Inspection System - a Literature Review. *Int. J. Prod. Res*.. 34(5): 1221-1241.

[5] Cho, M. W., and K. Kim.. 1995. New Inspection Planning Strategy for Sculptured Surfaces using Coordinate Measuring Machine, *Int., J., Prod., Res*.. 33(2): 427-444.

[6] Lee, J. W., M. K. Kim, and K. Kim. 1994. Optimal Probe Path Generation and New Guide Point selection Methods. *Engng. Applic., Artif., Intell.*. 7(4): 439-445.

[7] Ziemian, C. W., and D. J. Medeiros. 1997. Automated Feature Accessibility Algorithm for Inspection on a Coordinate Measuring Machine. *Int. J. Prod. Res.*. 35(10): 2839-2856.

[8] Kim, K. I., and K. Kim.. 1996. A New Measuring Strategy for Sculptured Surfaces using Offset Surfaces. *Journal of Manufacturing Science and Engineering.* 118, 646-651.

[9] Ip, W. L.R., and M. Loftus. 1996. Adaptive and Compensation methods in free-form surface assessment. *Proc. Instn. Mech. Engrs.*. 210: 135-145.

[10] Skalski, K., R. Filipowski, W. Swieszkowski, K. Kedzior, A. Dabrowski, and J. Zawora. 1998. Identification and Geometrical Modelling and Complex shape surfaces using Coordinate Measuring Machine and CAD/CAM systems. *Journal of Materials Processing Technology.* 76: 49-55.

[11] Hsieh, Y. C., S. H. Drake, and R. F. Riesenfeld. 1993. Reconstruction of Sculptured Surfaces using Coordinate Measuring Machines. *Advances in design Automation, ASME.* 2: 35-46.

[12] Huang, X., and P. Gu. 1998. CAD-model based Inspection of Sculptured Surfaces with Datums. Int. *J. Prod. Res.*. 36(5): 1351-1367.

[13] Yau, H-T., and C-H. Menq. 1995. Automated CMM Path Planning for Dimensional Inspection of Dies and Moulds having Complex Surfaces. *Int. J. Tech. Manuf.*. 35(6): 861-876.

[14] Kim, S., and S. Chang. 1996. The Development of the Off-Line Measurement Planning System for Inspection Automation. *Computers Ind. Engng.*. 30(3): 531-542.

[15] Hsi, Y.F., Y. Liu, F. Xi. 2001. Analysis of Digitizing Errors of a Laser Scanning System. Precision Engineering *Journal of the International Societies for Precision Engineering and Nanotechnology.* 25 (2001) 185-191.* Main author

2003 IEEE Workshop on Applications of Signal Processing to Audio and Acoustics, October 19-22, 2003, New Paltz, NY