

**Computer Aided Reverse Engineering with Renishaw Digitizer for Digitization  
and Mazak for Model Fabrication**

by

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Dissertation submitted in partial fulfilment of  
the requirements for the  
Bachelor of Engineering (Hons)  
(Mechanical Engineering)

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## **CERTIFICATION OF APPROVAL**

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A project dissertation submitted to the  
Mechanical Engineering Programme  
Universiti Teknologi PETRONAS  
in partial fulfillment of the requirement for the  
BACHELOR OF ENGINEERING (Hons)  
(MECHANICAL ENGINEERING)

Approved by,

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TRONOH, PERAK

January 2008

## **CERTIFICATION OF ORIGINALITY**

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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AZLAN MOHAMED ADNAN

## **ABSTRACT**

Application of reverse engineering (RE) is gaining its popularity in product design and manufacturing in recent years. It takes whatever methods, manual or computer-aided methods, to duplicate an existing object or system, either hardware or software.

This report discovers about the process of exploring technical challenges to automatically generate computer-aided design (CAD) of an existing part using touch probe imaging techniques. This concept, computer-aided reverse engineering system has a potential for faster model duplication over traditional reverse engineering technologies. RENISHAW 3D Laser Digitizer was used to digitize the object and then the models were saved in IGES file format. CATIA CAD then has been used to create the solid model of the object, and finally the laminated object will be manufactured using MAZAK machine.

In this project, a soccer boot has been reverse engineered. A prototype of the shoe was fabricated using the CNC codes that were obtained from UG NX3. The methodology of this process was presented, and this case study illustrated the RE approach. Technical challenges and future research directions in computer aided reverse engineering were identified.

This approach has proved that, CAD Reverse Engineering increased the effectiveness in remodeling a product. These benefits include to reduce the time consume when generating the coordinates and also to get an accurate dimension of the object. It means that, complex contours of the shoe can be machined accurately by using this approach.

## **ACKNOWLEDGEMENT**

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## **ABBREVIATIONS AND NOMENCLATURES**

RE	Reverse Engineering
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CNC	Computer Numerical Control
DXF	Drawing Interchange Format
EDM	Electrical Discharge Machining
IGES	Initial Graphics Exchange Specification
CT	Computer Tomography
LCC	Life-cycle cost
LCS	Life-cycle savings
ROI	Return on investment
QER	Quality Evaluation Report
UTP	Universiti Teknologi Petronas
FYP	Final Year Project

# **CHAPTER 1**

## **INTRODUCTION**

### **1.1 Background Studies**

#### **1.1.1 What is Reverse Engineering?**

Reverse engineering (RE) is the process of discovering the technological principles of a device or object or system through an abductive analysis of its structure, function and operation. It often involves taking something (e.g. a mechanical device, an electronic component, a software program) apart and analyzing its workings in detail, usually to try to make a new device or program that does the same thing without copying anything from the original.

Reverse engineering encompasses a variety of approaches to reproducing a physical object with the aid of drawings, documentation, or computer model data. In the broadest sense, reverse engineering is whatever it takes -- manual or under computer control -- to reproduce something (Wohlers 1998).

In advanced reverse engineering, digitizer usually being used to capture the coordinates of the specimen using a probe or laser and generates Computer Aided Design (CAD) models of the specimen. The part needs to be hold at the digitizer using fixture to make sure accurate scanning. To fabricate the reverse engineered part, the CAD models have to be processed using Computer Aided Manufacturing (CAM) software. The CAM software will produce the CNC machining commands to be used to produce the duplicated part.

### **1.1.2 Application of Reverse Engineering**

According to Chang-Xue (Jack) Feng and Shang (Sam) Xiao (2000), the application and reasons of reverse engineering a certain parts or technologies are as followed:

- (1) Old products for which there are no prints. Products designed before CAD/CAM existed are typical examples. Another example is where molds and/or dies were originally out-sourced due to lack of internal manufacturing capability and where neither blue prints nor electronic data are available in-house. Now with increased in-house capability in CNC machining or EDM processes, there is a need to duplicate the existing molds and/or dies for the purpose of replacement due to wear or other damage.
- (2) Products modified in production without anyone recording the changes.
- (3) Design reuse: To design a new product, the manufacturer incorporates some old CAD data, not in the form of solid models, into a new design. Reverse engineering is used in order to take advantage of information on existing parts or part elements, including cost, geometry, calculations, assembly steps, and CNC codes to create a new part in minimal time and cost.
- (4) Overseas products that have no documentation, or the information.
- (5) Benchmarking: For centuries, reverse engineer-ing has been practiced by companies with products competing in the same market. By reverse engineering competitor's products, one expects to understand the manufacturing knowledge. Reverse engineering is practiced by all the military powers on whatever equipment of their antagonists that they can get their hands on.
- (6) Automated inspection where CMM automatic-ally inspects a manufactured part after a successful prototype is produced.
- (7) Implants of human body parts (Puttre 1993) where reverse engineering is practiced the same way as in mechanical engineering, but with design ideas usually coming from computer tomography (CT), X-ray, and sketches provided by surgeons.
- (8) Ergonomic and esthetic design of engineered parts. E.g. handles and paddles.

(9) Video and movie production experts use 3D digitizers to capture organic objects, such as human body and animal parts with smooth flowing surfaces, to create shapes for TV commercials and special effects.

## **1.2 Problem Statement**

Reverse engineering in this project has been applied on to a soccer boot. The boot has been digitized to get the computer aided design. This project only focused on touch-based imaging of computer-aided reverse engineering. This approach is using touch probe to digitize the shoe and obtain the 3D model.

It is difficult to apply traditional reverse engineering to the boot because of the shape which is uneven, complex and not easily can be measured. Traditional reverse engineering means that, to remodel an existing object by using standard engineering design process - beginning from sketching the part using AutoCAD or other engineering CAD software till fabricating the part using standard procedures. As we know, some of the CAD softwares have limited features in remodeling an existing part. Complex surfaces on the part will not be able to be drawn by them and gave inaccurate results which differ from CAD Reverse Engineering.

Besides, by using Computer Aided Reverse Engineering process, some early processes in traditional RE can be eliminated such as to measure the dimension of the part and also part remodeling. These processes are taking a lot of time and quite complicated. Engineers could save their time when eliminating those stages which by letting the digitizer runs and generates the coordinates of the object automatically. The digitizer machine moved and at the end of the digitization process, a CAD model of the part was generated as accurate as the original part.

This project also discovered the process of converting the model from points of clouds to surface. Points of clouds means that a set of vertices in a three dimensional coordinate system, X, Y and Z. Usually these point clouds are created by 3D

digitizer/scanner. It represents the visible surface of the object that has been scanned or digitized. There are some cases where the researchers faced difficulties in converting point clouds to surface.

*“Actually, even top-level researchers don't know how to do this well. Researchers are trying to come up with computer programs that can take any point cloud and turn it into a picture with nice smooth surfaces. They also want these programs to run quickly. This problem of making smooth surfaces from a point cloud is known as surface reconstruction.”*

Quote from <http://www.stanford.edu/~ctj/pc.html>

### **1.3 Objective & Scope of Study**

Following are the objectives that have been achieved from this project:

- A soccer boot has been reverse engineered by using the facilities and technologies available in university such as RENISHAW Digitizer for digitization.
- The generated CAD model was manipulated in CATIA CAD to convert the point clouds to solid surfaced model, and then it was saved in .prt file format to make it available in Unigraphics NX3.
- The UG NX3 generated the CNC codes and they were used by MAZAK machine to fabricate the shoe.
- Technical challenges and problems along the way completing the project were explored and shared for future use in reverse engineering.

The scope of study of this project covers a wide range of engineering scope as follow:

- Reverse engineering
- Renishaw - Cyclone Series 2 Digitizer operation
- CAD model manipulation
- CAM software programming
- Fabrication
- Engineering documentation



## **CHAPTER 2**

### **LITERATURE REVIEW**

There are various numbers of researches and studies that have been carried out which is related to reverse engineering. Each books and journals that have been referred have different work scopes depending on the objectives. Some related points and topics are discussed below.

#### **2.1 Traditional versus Reverse Engineering Process**

According to Kathryn A. Ingle (1994), reverse engineering has four stages of process in the development of technical data to support the efficient use of capital resources and to increase productivity. The stages are conducted after a rigorous prescreening of potential candidates, consist of data evaluation, data generation, design verification, and design implementation [15]. Some projects are not considered as reverse engineering if they do not meet prescreening criteria, because success in reverse engineering is generally measured by return on investment. Success in reverse engineering is also measured by overall effectiveness to both long and short term objectives, not merely a singular bottom line.

Forward engineering is the traditional process of moving from high level concept and abstractions to the logical, implementation-independent design needed in a physical system, then reverse engineering is the design analysis of the system components and their relationship within the high level discrete system [15]. **Table 2-1** illustrates the differences between the traditional design process and the reverse engineering process.

Traditional Design Process	Reverse Engineering Process
Need → Design data → Prototype & Test → Product	Product → Disassembly → Measure & Test → Design Recovery → Prototype & Test → RE Product

**Table 2-1:** Traditional versus reverse engineering design process. Source from: Kathryn A. Ingle, 1994, *Reverse Engineering*, New York, McGraw Hill Inc.

## 2.2 The Benefits of Reverse Engineering

With a structured methodology in place to develop technical data to support hardware systems, some tangible and intangible benefits may be derived from reverse engineering process. Reverse engineering could increase ability to maintain a manufacturing capability at its peak performance rate [15]. It takes place in stage 2 (technical data generation) of reverse engineering process when the improved documentation has been developed for logistically unsupported equipment and systems [15]. Once a system is maintainable, output of that system can be enhanced and improved on through future value engineering efforts. Hence, these two factors tend to drive the potential to realize actual life-cycle savings through the use of the improved product documentation. Any real savings from the achievement then can be used to increase the probability of the system, and the potential profits can be pumped back into the system upgrades as newer technology becomes both available and affordable [15]. Besides that, reverse engineering can function as stopgap measure to increase system productivity until enough savings and/or profit become available to conduct full system modernization which is too costly and capital intensive.

Reverse engineering is different with system modernization which involves entire system to be upgraded and eliminate many portions of a current technology. Then it will be replaced with more sophisticated equipments.

## **2.3 Legal Issues**

Engineers should concern about certain legal issues in reverse engineering project. Few of these issues have been fully challenged in either domestic or international courts of law, and there are some areas in which the laws are changing. This section is not intended as a full discourse on these issues, but some are discussed below.

### **2.3.1 Patent Infringement and Theft**

Reverse engineering, in and of itself, is not patent theft. If a system component proposed for reverse engineering is patented in any country, then all reverse engineering efforts for that components must be discontinued [6]. If a portion of a component is patented, its use within the assembly should continue. Continued use of patented part is virtually inviolable. The rights and restrictions vary from country to country. Any unpatented design can be reverse engineered, although guidelines for trademarks, tradenames, and copyright are less clear [6]. In many cases reverse engineering is impractical and unjustifiable unless it is economical to complete the reverse engineering process and then remanufacture a part which is significantly less costly. To do reverse engineering in order to steal another's design is neither ethical nor professional. Since much of international law regarding technical design and ownership issues is changing, it is best to consult a corporate attorney specializing in patent and/or international law if any questions arise during the design evaluation phase.

### **2.3.2 Proprietary and Restricted Data**

Another potential legal issue can be the use of proprietary or restricted technical information. Usually restricted data means that, the reverse engineer cannot access or in any way use this information in the reverse engineering or value engineering process [6]. Again, when these types of information arise during the reverse engineering process, they should be addressed on a case-by-case basis and may require the need for legal counsel.

### **2.3.3 Substandard Part**

There is another danger in reverse engineering: a substandard part such as a bolt or fastener made below required quality standards. To reverse engineer, not value engineer, and promulgate the replication of a substandard part could be disastrous in systems which cannot withstand the large tolerances and lack of safety factors common in substandard [6].

### **2.3.4 Restrictive Contractual Clauses**

There may also be restrictive contractual clauses in the procurement of special items which prohibit any practices such as reverse engineering [6]. Warranties can be voided by the use of reverse engineered parts in some cases. Foreign licensing may also be involved. There are sometimes potential health and safety hazards. There are legal statutes involved or other factors which would be unwise to ignore. There are patent and licensing rights to observe, also. Reverse engineering is not advocated in cases where another's rights or laws are being violated [6]. All unethical practices are to be avoided along with explicitly illegal actions.

## **CHAPTER 3**

### **METHODOLOGY**

#### **3.1 Data Evaluation for Prescreening**

The raw data assembled before continuing the reverse engineering process should be processed in order to make the best decisions.

##### **3.1.1 Economic and Logistics Calculations**

Certain necessary calculations are made in reverse engineering process before beginning the next stage. Following are the definitions that involved in economic and logistics calculation of reverse engineering process.

**Unit cost:** The current price for this item. Unit pricing varies widely according to market price and the quantity purchased over time.

**Target unit cost:** The projected cost to obtain the part after reverse engineering. The standard goal is a 25% decrease in the unit price.

**Annual usage:** The number of parts used pr year for both maintenance and failure requirements. It should be averaged over as many years worth of data as can be found.

**Annual cost:** The unit price multiplied times the annual usage rate. This equals the monetary outlay for the procurement of this component for one year, preferably one good representative year based on normalized usage, not the year of highest usage.

**Remaining service life:** the remaining service life of the operating equipment can be determined by approximating the length of time until a planned replacement system is to be installed.

**Available assets:** The total numbers of parts in inventory at the same time these prescreen calculation are made.

**Life cycle usage:** the annual usage multiplied by the projected remaining service life minus the available assets, including those on back order. This represents the total number of parts which must be obtained to maintain the system through its lifetime.

**Part population:** the total number of parts in the entire system, not merely the singular subsystem being studied for reverse engineering.

**Replacement rate** (also failure rate): the ratio of annual usage divided by the part population times 100 to express in percentage.

**Life-cycle cost (LCC):** equal to the life cycle usage multiplied by the unit cost or the annual cost multiplied by remaining service life if there are no assets in back orders.

**Life-cycle savings (LCS):** computed by multiplying the LCC by 25 percent. The 25 percent represents the 25 percent target decrease in unit cost. This equals the predetermined decrease of the procurement cost, which is the desired result by reverse engineering.

**Projected cost to reverse engineer (RE cost):** an estimate, best guess, often costing many thousands of dollars based loosely on the technical complexity of the part and the amount of available data. The prescreen estimate is necessary to make an initial recommendation.

**Return on investment (ROI):** the ratio of the projected LCS minus the projected cost to reverse engineer divided by the projected cost to reverse engineer. This results in the ratio of the net savings to the reverse engineering cost and is the cost-effective measure of reverse engineering an item. Prescreened component are not recommended to enter stage 1 without a stage ratio of **25:1** [15]. Reverse engineering project below that value presents risk. Calculation of ROI will be simply expressed as:

$$\text{ROI} = \frac{\text{LCS} - \text{RE cost}}{\text{RE cost}}$$

Source from: Kathryn A. Ingle, 1994,  
*Reverse Engineering*, New York,  
McGraw Hill Inc.

Example of the data evaluation is shown in **Appendix 3-1**.

### 3.2 Four Stages in Reverse Engineering Process

In order to reverse engineer a product or a component of a system, the engineers and researchers generally follow the following four stages [15] [14]:

- Stage 1: Identify the product or component to be reverse engineered.
- Stage 2: Observe or disassemble the product/component to understand how the original product/component works.
- Stage 3: Implement the technical data generated by reverse engineering in a modified version of original.
- Stage 4: Create a new product/component.

The first stage is often called as “prescreening”. During this stage, the reverse engineers determine the candidate product for their project. Potential candidates for the reverse engineering project may be a single item, part, component, unit, or subassemblies, which may contain many smaller parts which work together as a single entity. The standard primary steps in stage 1 are as follows:

- Visual and dimensional inspection
- Discrepancy review versus available data
- Failure analysis
- Quality evaluation report
- Stage 1 report
- Go/no-go decision

In standard industry practices, stage 1 entails the complete characterization of part using visual and dimensional inspection, material analysis, and identification [14]. Comparisons to available must be made. A failure analysis is conducted if failed sample parts have been obtained [14]. Then, quality evaluation report (QER) must also be generated. A stage 1 report must also be generated complete with the projected reverse engineering cost estimates. A final go/no-go decision must be reached by both the project leader and the approval body on the basis of the available information [15].

The second stage of reverse engineering is disassembly or decomposition of the original product, is the most time-consuming phase of the entire project. In this stage, reverse engineers attempt to construct a characterization of the system by accumulating all of the technical data and instructions of how the product works [15]. The engineering drawings will define the configuration of the component, and the technical data package will contain all additional inspection and quality assurance requirements to manufacture a like part [15]. The technical data develops throughout many iterative phases in the four stages of reverse engineering process. Tools are often used in aiding the reverse engineers in this stage. One of the many tools used is digitizer, which will be the main concern of this research project.

Next, in the third stage, the reverse engineers will try to verify that the data generated by disassembly or decomposition is an accurate reconstruction the original system. Engineers verify the accuracy and validity of their designs by testing the system, creating prototypes, and experimenting with the results [15].

The final stage of the reverse engineering process is the creation of a new product to the market. The new products of reverse engineering projects are often innovations of the original product with competitive designs, features or capabilities. These products may also be adaptations of the original product.



## **CHAPTER 4**

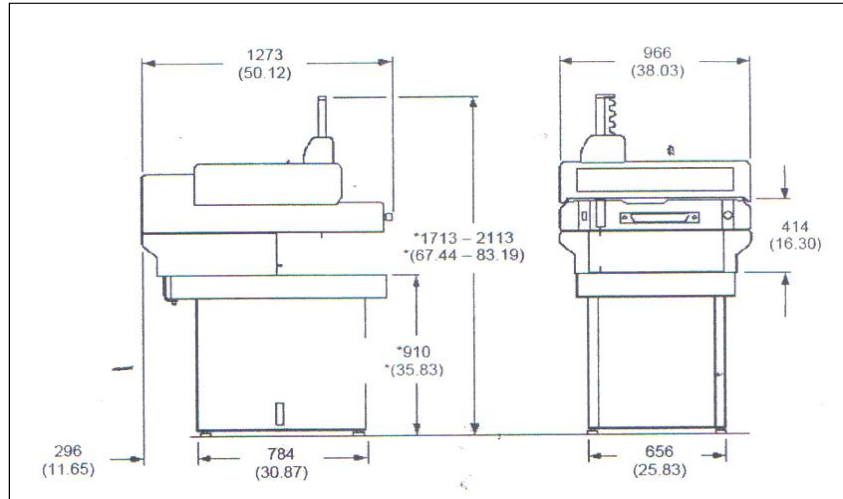
### **FINDINGS**

During the project execution, there are numerous findings that have been discovered. These are included gaining new knowledge and skills such as the way to operate the RENISHAW Digitizer and familiarization with engineering software such as Tracecut, CATIA V5 and Unigraphics NX3. Those experiences gained from this project are very useful and beneficial for reverse engineers.

#### **4.1 Familiarization with RENISHAW Series 2 Digitizer**

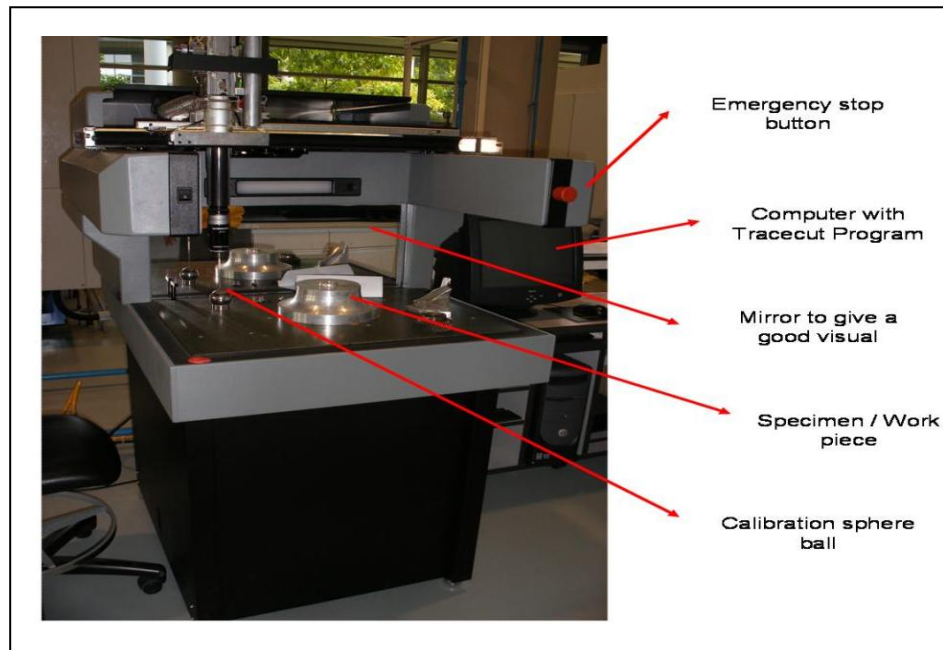
Digitizer is a mechanical machine used in this project for on-machine dimensional measurement of components and cutting tools for process set up, control and verification. It is capable to transfer physical data into digital data. A scanning probe is used to scan the coordinate of the points at the surfaces of the work piece. Digital image of the specimen is then generated using these scanned coordinates.

The project focuses on the REINSHAW – Cyclone Series 2 Digitizer which is available in the Manufacturing Laboratory, Block 16 of Universiti Teknologi Petronas. There are two options available for scanning purposes whether to use laser technique or touch probe. This project undergoes the scanning process by using touch probe technique.



**Figure 4-1:** Dimension of RENISHAW – Cyclone Series 2 Digitizer

The dimension of the RENISHAW – Cyclone Series 2 Digitizer is 1273 mm (L) x 966 mm (W) x 1713 mm to 2113 mm (H) as shown in Figure 4.1 above. The axis travel of the digitizer is 600 mm x 500 mm x 400 mm. the digitizer is capable of scanning at a speed of 6 meters per minute. To operate the digitizer, electrical power supply at 90 – 265 VAC, 47 – 60 Hz, and compressed air supply at 5.5 to 10 bars are required.



**Figure 4-2:** RENISHAW – Cyclone Series 2 Digitizer

**Figure 4-2** above shows the picture of the RENISHAW – Cyclone Series 2 Digitizer with label of important parts. For safety purpose, an emergency stop button is located at the top right corner of the machine. For ease to the operator, the digitizer is equipped with a light for clearer view of the digitizing process. A mirror at the far end of the digitizer makes the scanning of the work piece at the back side visible to the operator. The table of the digitizer is made of composite granite tile with grid of M8 holes. These holes are for the fitting of fixtures.

There are two techniques for measuring the dimensional of component in REINSHAW Digitizer machine which are laser range technique and touch probe technique. For laser range technique, work piece will be scanned by the laser and reflect the data. Those data will be read automatically by the Tracecut software and a 3D drawing of the specimen will be obtained. It differs from touch probe technique which is using probe to touch the work piece. Then the date will be directly transfer to the software and 3D drawing will be obtained line by line or point by point.

The digitizer has to be calibrated every time when it is used. For calibration process, the calibration sphere ball is used. The probe, as shown in **Figure 4-3**, will be calibrated automatically at the calibration sphere ball during calibration process to determine the diameter of the touch probe.



**Figure 4-3:** Calibration process

In this project, touch probe technique has been used to measure the figure of the work piece.

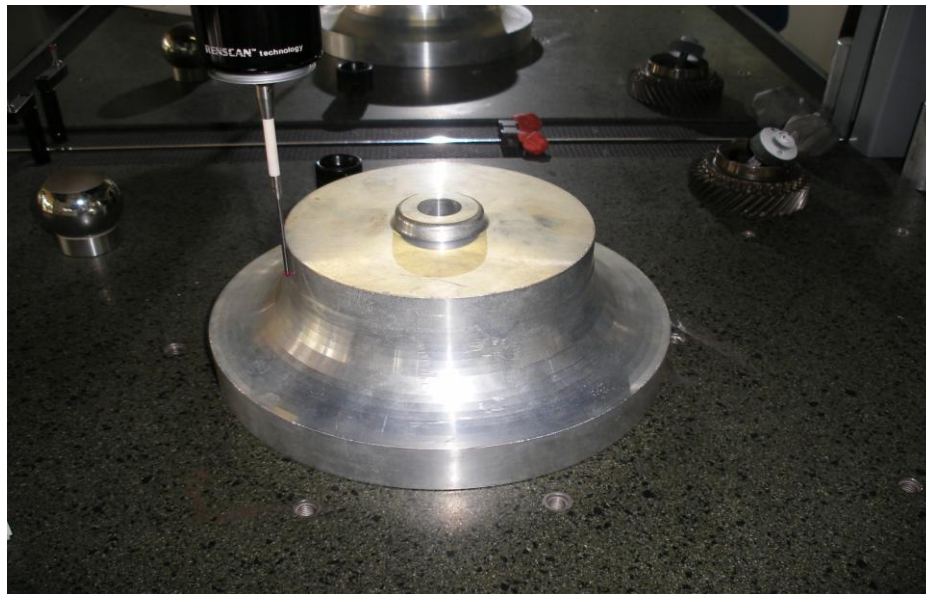
## 4.2 Digitizer Operation Familiarization

RENISHAW – Cyclone Series 2 Digitizer operation training was carried out. This is for familiarization with the digitizer's operation system, as well as to understand the technical requirement of the fixture design. Also, from the training session, a lot of brilliant ideas for further progress were generated.

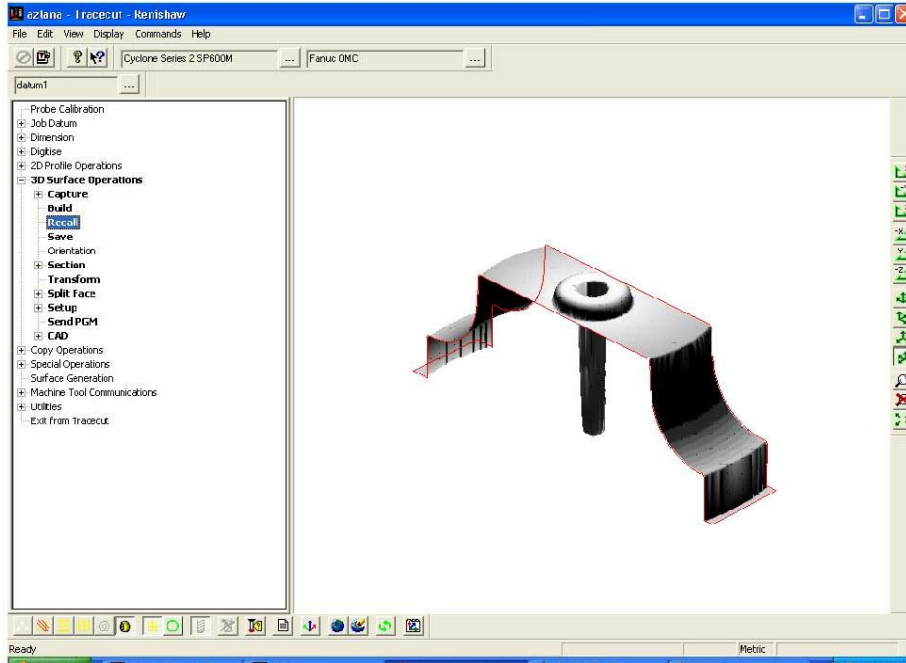
### 4.2.1 Training and Practices

Before beginning the real project, several practices have been done on how to operate the machine in the Mechanical Laboratory, Block 16. The training and practices that assisted by UTP Lab Technician, Mr Hafiz Safian has helped me to gain a better understanding about REINSHAW Digitizer. Besides that, REINSHAW Operating Manual Books and Help Topic from the Tracecut software also have been referred as the guidance.

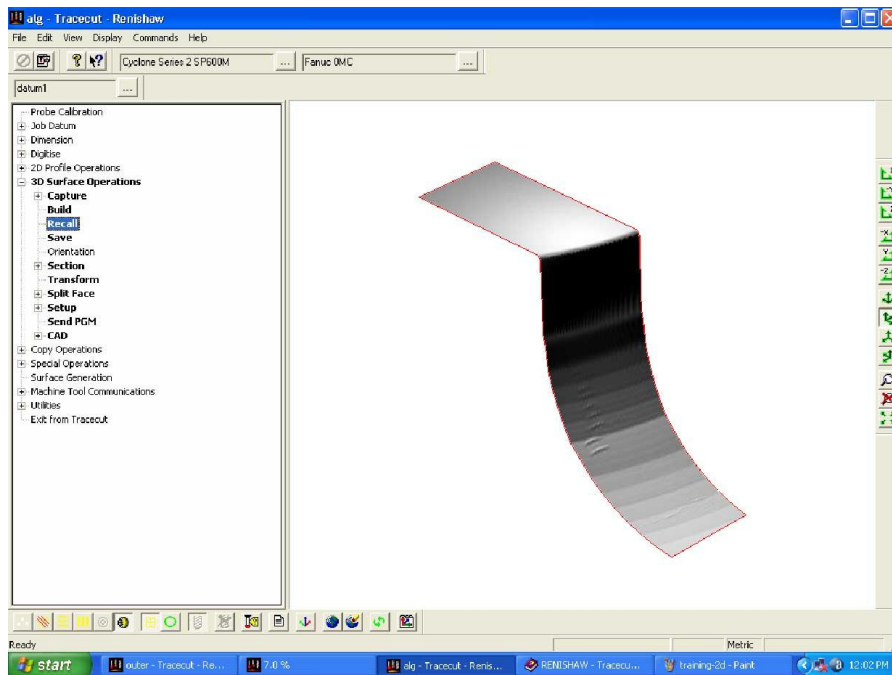
An impeller block has been used as a work piece sample during the practices. Following are the pictures taken during the training session:



**Figure 4-4:** Touch probe is scanning the impeller block during the practice session



**Figure 4-5:** A 3D drawing obtained from the impeller block that has been scanned by the touch probe. The data has been automatically generated into the software.



**Figure 4-6:** The other part of the impeller block. Picture above showed the accuracy of the touch probe technique which can detect scratches on the work piece.

### 4.3 Soccer Boot

Following is the soccer boot with its dimension that was used in this project:



Figure 4-7: Side view



Figure 4-8: Top view



Figure 4-9: Expected output

#### 4.4 Work Piece Digitization

The shoe was ready to be digitized. I decided to use a touch probe with small diameter of 8mm to ensure smooth running during the digitization process. Before proceeding with the scanning process, the empty hole in the shoe has been filled with old news paper to make it compact. This is to ensure no obstruction during the touch scanning because the ball probe will be touching the surface of the shoe, so rigid body is needed.

**Figure 4-10** shows the right axes on the capture device of the machine.



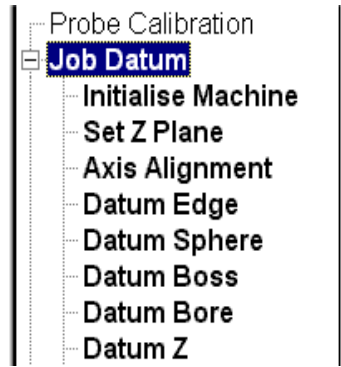
**Figure 4-10:** Three axes on the capture device

Following are the details command on how to digitize the shoe using Renishaw Digitizer.

##### 4.4.1 Machine Initialization

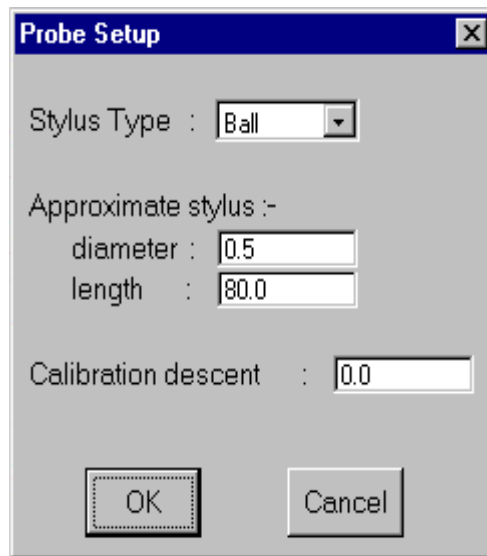
To begin any work on the machine, firstly the machine must be initialized. Following are the full step by step commands used to initialize the machine.

1. The required stylus diameter in the Cyclone has been set accordingly.
2. From the main tree menu **Job Datum** option was selected. The Job Datum menu will be expanded to show all the options available as shown in **Figure 4-11**.



**Figure 4-11:** Job Datum Tree Menu

3. **Initialise Machine** was selected followed by **OK** command. The Cyclone then has been booted after few minutes.
4. After done booting, the following box appeared.



**Figure 4-12:** Probe Setup box

Filled out the fields for approximate **Stylus Diameter** and **Length** and then clicked on **OK**.



When this dialogue was completed and OK was chosen the Cyclone moved above its calibration position and automatically carried out measuring cycles to establish the absolute datum position of the machine and also the diameter of the chosen probe.

5. At the completion of the procedure, a dialogue appeared showing the measured value. If the reported stylus ball diameter is different to that entered in the **Probe Setup** dialogue, change it to the exact whole number value and then click on **OK**.

#### 4.4.2 2D Data Capture

Then, after completed with the machine initialization, I proceeded to the second stage which is work piece 2D data capture. First of all, the shoe was set up on the capture device and has been mounted as shown in **Figure 4-13**, so that the location of shoe is fixed. It is to ensure the shoe will not move during scanning process. The machine was ready to do the job after ensured that an 8mm probe stylus is mounted on the machine and has been calibrated.



**Figure 4-13:** Mounted shoe using plasticine

Following are the full step by step commands used to capture the 2D data of the shoe:

1. From the Tracecut, the option **Job Datum** was selected by clicking on the plus sign. All available options were showed for job datum operations. **Datum Z** option was clicked and moved the probe 10mm away from the floor of the capture device.

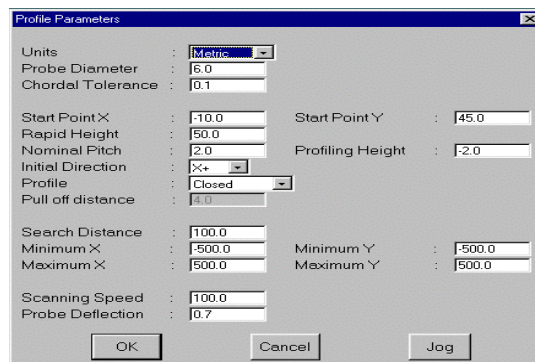
- From the **Job Datum** menu, the option **Set Z-Plane** was selected. Then the probe was used to position the machine to take the three measurements on the top of the part as shown in **Figure 4-14**. **OK** button was clicked at each position.



**Figure 4-14:** Three measurements on the shoe were selected to set Z-Plane

At the end of the cycle, a dialogue appeared showing the real Z-position and the **Z-datum** as **0.00**. I accepted the setting by clicking on **OK** button.

- From the tree menu, **2D Profile Operations** was selected followed by **Capture** and then **Create**.
- A box appeared. **Current Job Name** was set to **boot** and the **Current Profile Name** to **boot\_outside**. After done, **OK** button was clicked.
- Then, the start point of the profile should be selected. Again **2D Profile Operations** was selected and followed by **Create**. Previous file, **boot\_outside** was opened. The following box in **Figure 4-15** appeared.



**Figure 4-15:** Profile Parameters for 2D data capture

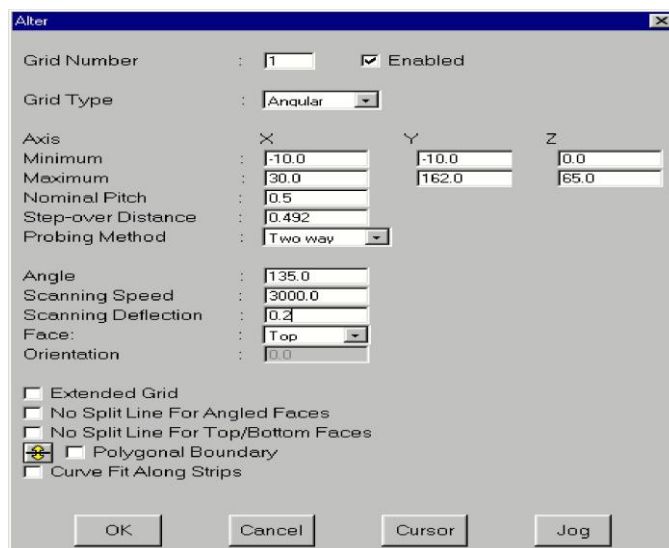
Jog button was clicked to select the start point. Then, used the probe to position the start point and ensured that the initial direction box was filled with the right direction. **OK** button was clicked after all.

6. Last step in 2D data capture was to click the **Receive** button, and then the probe went around the sample to capture the 2D data.

### 4.4.3 3D Data Capture

Following are the full step by step commands used to capture the 3D data of the shoe.

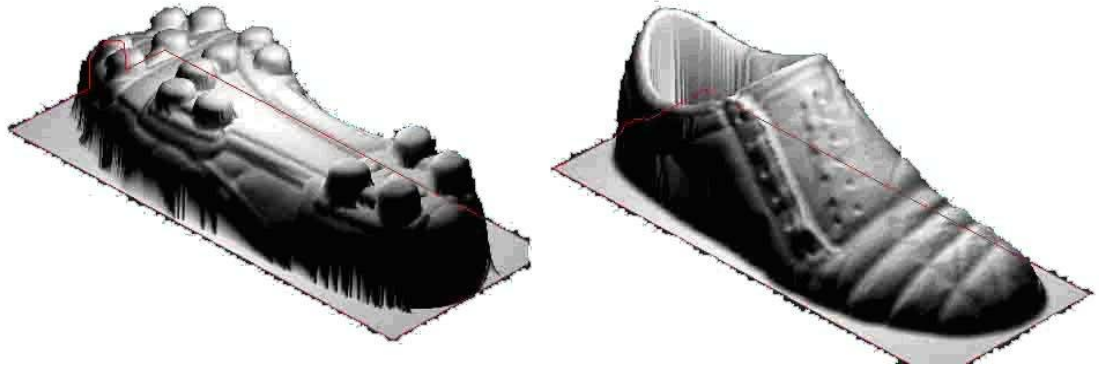
1. From the main tree menu, **3D Surface Operations** was selected and followed by **Capture** and then **Create**. A box displayed. File name was set to **boot\_new**.
2. Then **Profile** option was selected from the main tree menu, clicked OK button after opening the **boot\_outside** file.
3. To alter the scanning process, **Alter** option from main tree menu was selected. The following box in **Figure 4-16** appeared. **Grid Type** box was changed to angular and followed by changing the **Angle** box to 90°.



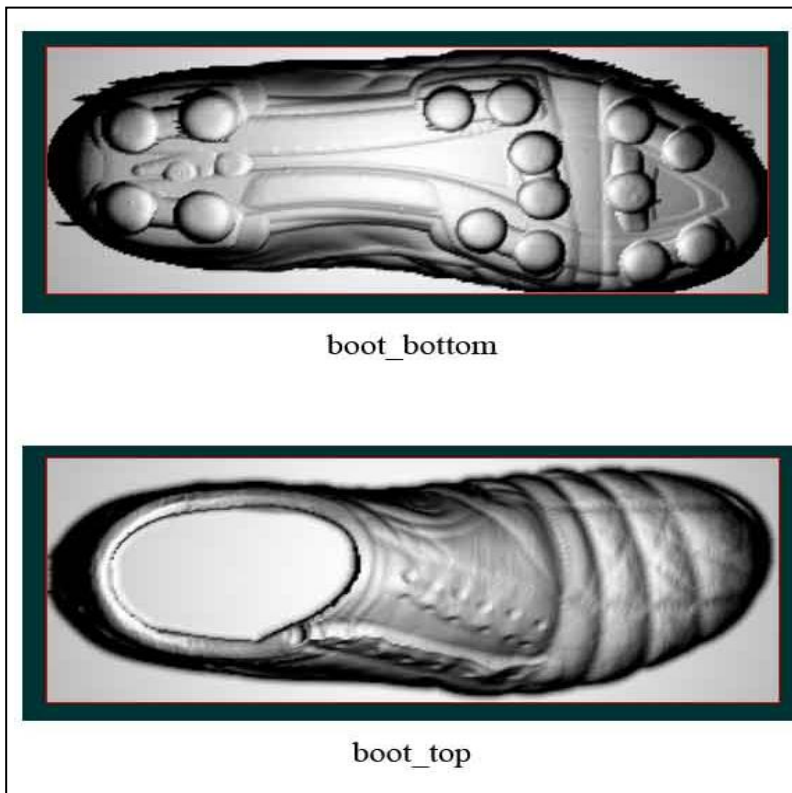
**Figure 4-16:**  
Alter box is used  
to set up the  
scanning process

4. Finally, from the main tree menu, **Receive** option was selected to start scanning. The scanning process of 3D data took about 3 hours and 30 minutes for top part and 4 hours 05 minutes for bottom part.

#### 4.4.4 Result



**Figure 4-17:** Isometric view of the shoe model shows the result from the digitization



**Figure 4-18:** 3D data captured after scanning process. Pictures above represent top and bottom parts of the shoe in plan view.

## 4.5 File Conversion

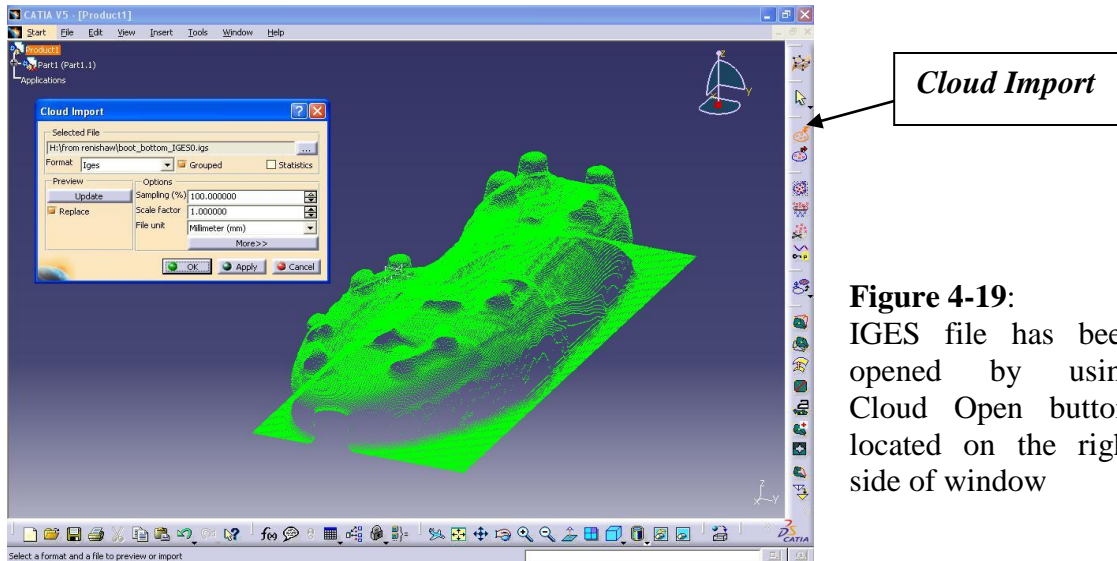
The CAD model of the shoe have been saved in several files format, including IGES, DXF poly, DXF lines, STL and Mastercam. This is to ensure that the engineering software such as CATIA CAD, Unigraphics NX3 and Mastercam8.1 could support those files when exporting them. Modifications would be made to combine both parts become one and also to find other alternatives to convert those files which are in lines and points of clouds to solid surfaced model. Solid surfaced model is a need for CAM software in order to create the CNC codes for fabrication. MAZAK machine in UTP laboratory only supports CNC codes from Unigraphics NX3 or Mastercam8.1 for fabrication process.

### 4.5.1 Export to Catia

The IGES files of the shoe have been successfully exported to CATIA CAD P3 V5R14 and appeared in points of clouds. I have modified them into solid meshed model and saved them in various files format such as cat.part, cat product and IGES. Unfortunately, both top and bottom parts did not combine perfectly although the result looks like one. The locations of both parts were adjusted and aligned closely to get a full picture as shown in **Figure 4-22**.

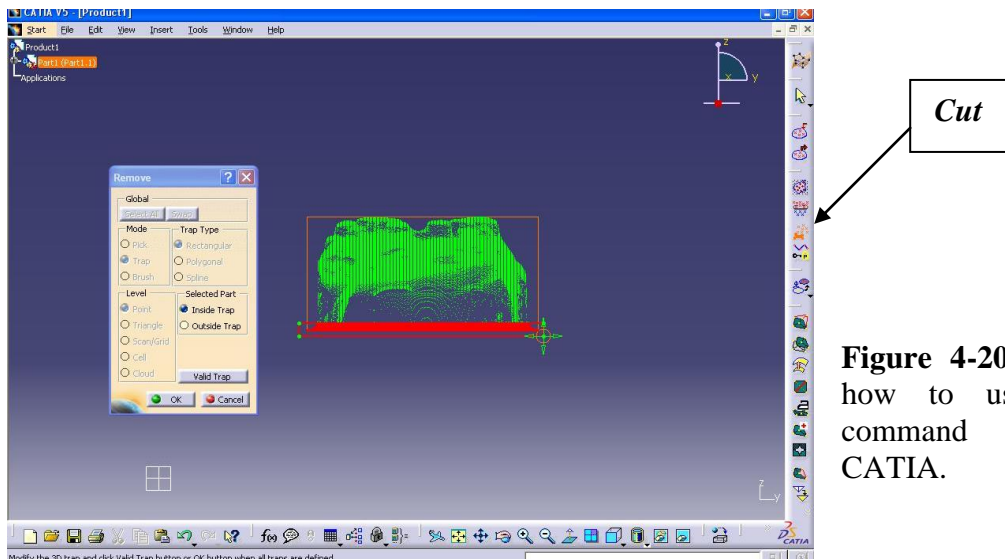
Following are full step by step commands used to convert the point clouds to solid meshed model in CATIA CAD.

1. IGES models have been exported to CATIA P3 V5R14. In CATIA, they were opened by **Digitized Shape Editor** which is located under **Shape** tree menu.
2. **Cloud Import** button was selected and a box appeared. Browsed the previous IGES file and clicked **Apply** button, followed by **OK**. Details shown in **Figure 4-19**.



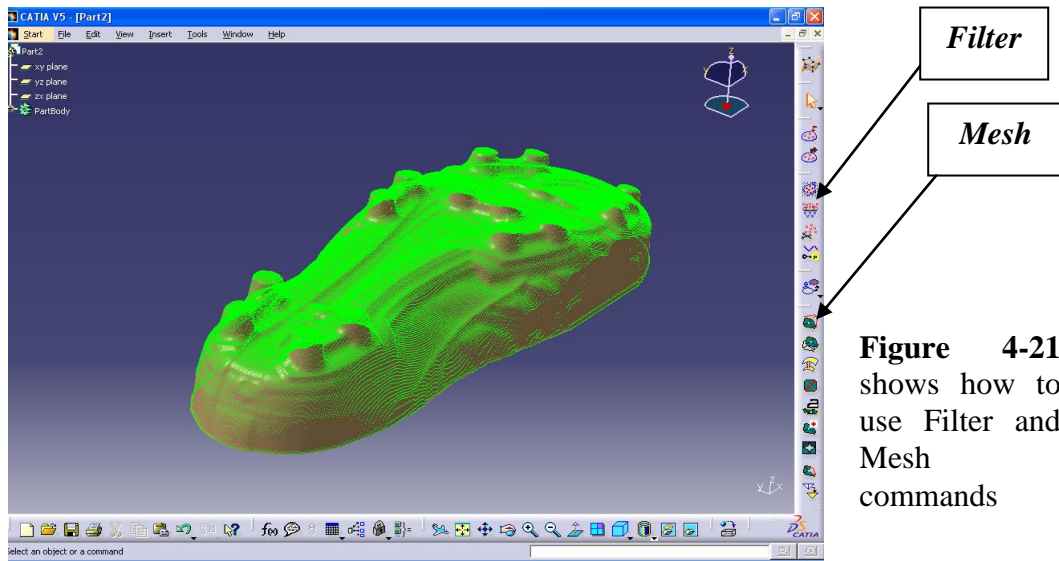
**Figure 4-19:**  
IGES file has been opened by using Cloud Open button, located on the right side of window

3. Extra clouds from both models (top and bottom) have been cut by using **Remove** command located on the right side of the window. **Remove** box appeared. Then I clicked on the model and clicked again while moved the cursor to the area where to be cut away. The area became red and **OK** button was clicked after confirmed with the area to be removed. Details are shown in **Figure 4-20**.



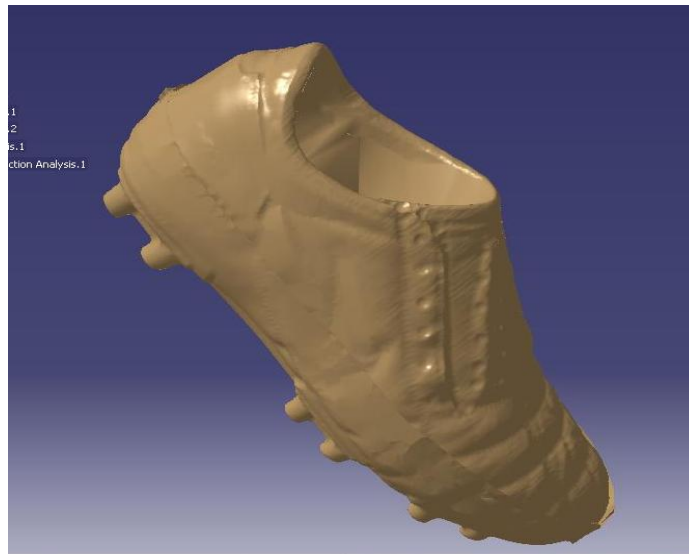
**Figure 4-20** shows how to use Cut command in CATIA.

4. **Mesh** command was used to mesh the cloud and obtain solid surfaced model. Then again followed by **Cut** command to remove the green lines. The whole figure was selected to remove all the green lines. Details are shown in **Figure 4-21**.



**Figure 4-21** shows how to use Filter and Mesh commands

5. The locations of top and bottom parts were adjusted and aligned closely to get the full model of shoe. Below are the results.

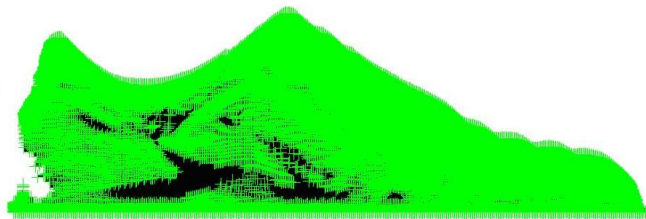


**Figure 4-22:** Result after meshing and filtering the model.

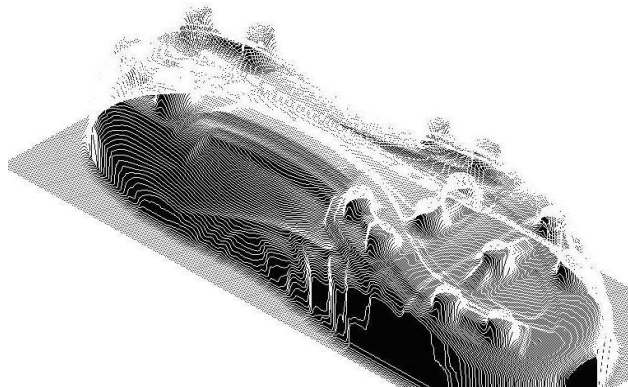
The modified model has been transferred from CATIA CAD to Mastercam8.1 and UG NX3 but it still appeared in point clouds. This is because the Mesh command used in this section just only gave an illustration surface of the shoe, which means that, the shoe is still in point clouds and totally not in surface. Other command should be used.

#### 4.5.2 Export to Mastercam and Unigraphics

In Mastercam8.1, IGES and DXF files have been transferred successfully. While for UG NX3, I only succeed to open DXF files. But those models appeared in point clouds and lines. Features and options in both software have been explored and studied but had no solution to turn the model into solid surface. Hence, those CAM software failed to generate the CNC codes .Below are the results for direct transfer of DXF and IGES files from the Tracecut program to Mastercam8.1 and UG NX3 software.



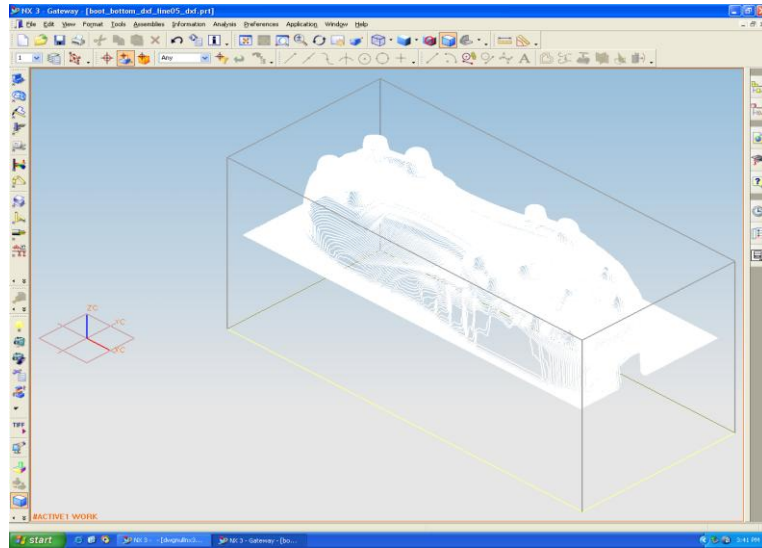
**Figure 4-23:** IGES file to Mastercam8.1, the model appeared in points of clouds and failed to generate codes.



**Figure 4-24:** DXF file to Mastercam8.1, the model appeared as lines

Points of clouds means that a set of vertices in a three dimensional coordinate system, X, Y and Z. Usually these point clouds are created by 3D digitizer/scanner. It represents the visible surface of the object that has been scanned or digitized.





**Figure 4-25** shows DXF file in UG NX3

Table below shows the result when the files were transferred directly from the digitizer to Mastercam8.1 and UG NX3.

Software	IGES	DXF
Mastercam8.1	Success	Success
UG NX3	Error	Success

**Table 4-1:** Result for files transfer directly from digitizer

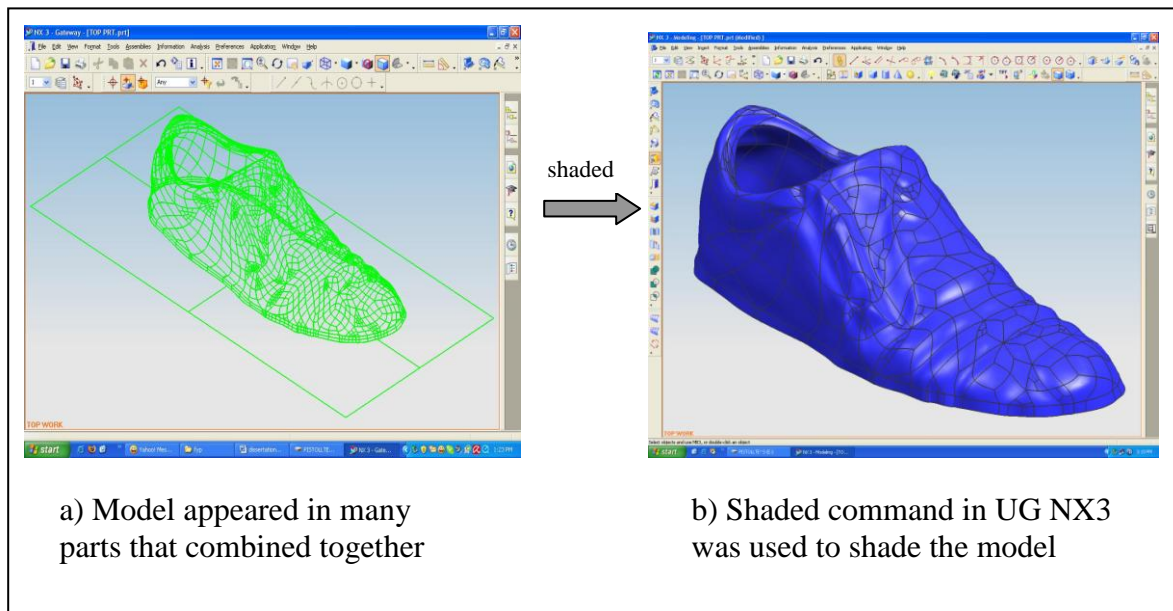
#### 4.6 Model Fabrication

Even though the files can be transferred directly from the digitizer to the Mastercam8.1 and UG NX3, but none of them existed in solid surfaced model included the one in the CATIA (**Figure 4-22**). The shoe model was still in points of clouds. Hence, both software, Mastercam8.1 and UG NX3 were not able to generate the CNC codes for the points of clouds. This matter then was referred to Mr Rao, CAD/CAM consultant from IME Technology Sdn. Bhd. According to him, although the shoe model can be opened by Mastercam8.1, but it is not able to generate the CNC codes. This is because of the model that appeared in points of clouds and not in solid surface.

Mastercam8.1 needs a solid surface in order to generate the CNC codes. Those files were sent to him, and he successfully converted those files into solid surface. He used **CATIA V5 > Digital Mock Up > RE Work Bench** commands to mesh the points of clouds to solid surface. Those modified files were saved in MC8 format and were sent back to me after few weeks. By using Mastercam8.1, the models again were converted into prt. file format in order to open it by using UG NX3. CNC coding and simulation for the shoe model were created by UG NX3. They will be used for product fabrication.

#### 4.6.1 Simulation and Coding in UG NX3

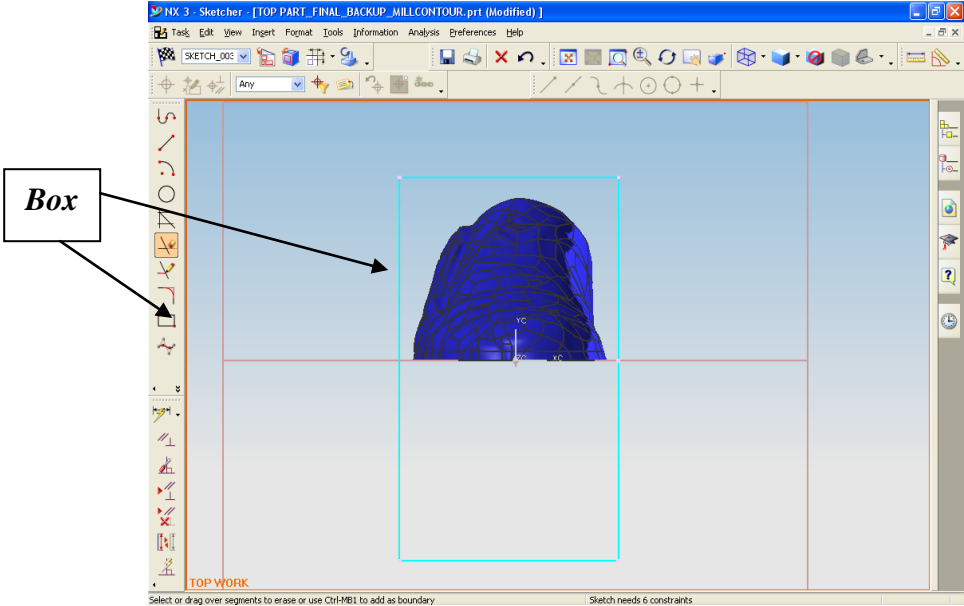
After opening the prt. file in UG NX3, it appeared in many parts that were combined together as shown in **Figure 4-26(a)**. Then the **Shaded** command was used to shade the model.



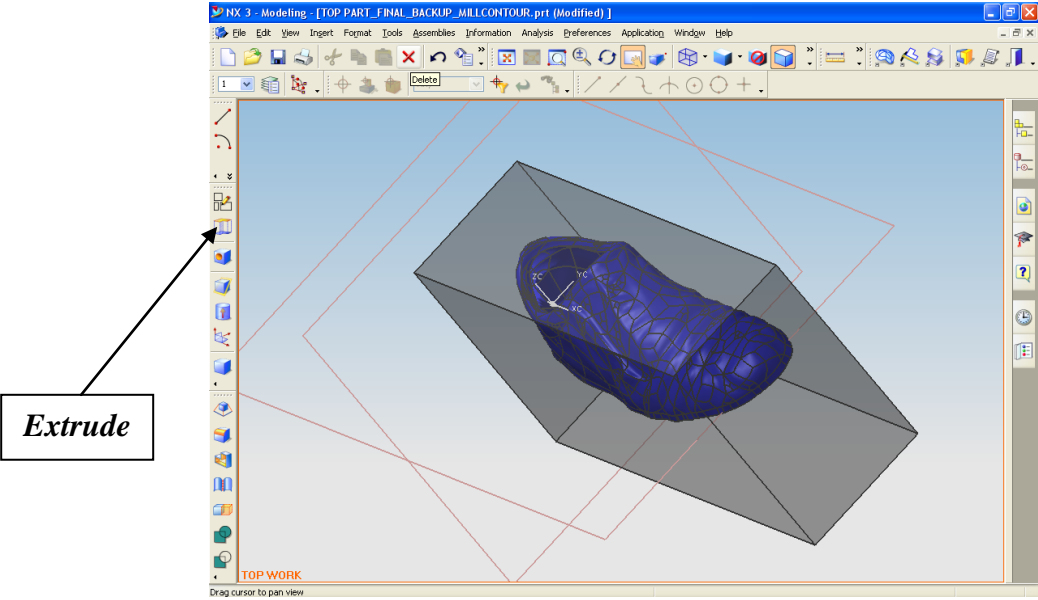
**Figure 4-26:** Model transformation from lines to shaded model

In the ZC-YC axes **Sketch** application, a box was sketched covering around the shoe and followed by **Extrude** command in modeling application to build a square box piece covering the entire shoe figure. Then, by clicking on the **Edit** tab command on the

upper right side of the window, and followed by **Object Display**, the **Translucency** controlled bar was adjusted to the appropriate range to make the box transparent and the shoe can be seen through it. Outputs of these processes are shown in the **Figure 4-27** and **4-28** below. The dimension of the square box was set up similarly with the dimension of the raw material that is going to be machined. The square box acts as the blank material while the shoe is the work piece.







**Figure 4-27:** A box was sketched covering around the shoe in ZC-YC sketch application



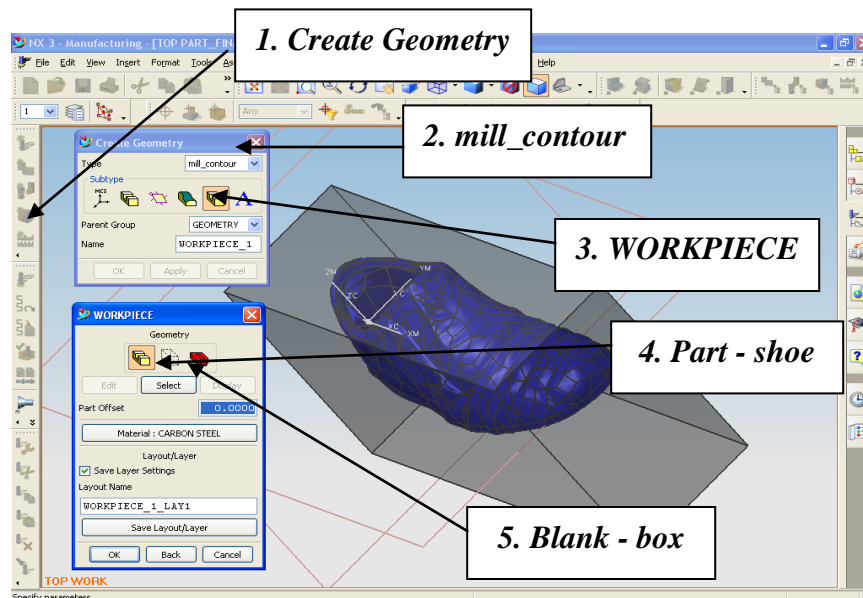
**Figure 4-28:** Extruded transparent box with a dimension of 77mm (width) x 252.25mm (length) x 125.83mm (height)

Next stage is model manufacturing which is to generate the CNC codes for machining process. This stage began by clicking the **Application>Modeling** tab on the upper side of the window and after completed with the sketch and modeling applications. There were four important commands that always being used at this stage as followed:

Commands	Symbols
1. Create Geometry	
2. Create Tool	
3. Create Operation	
4. Create Program	

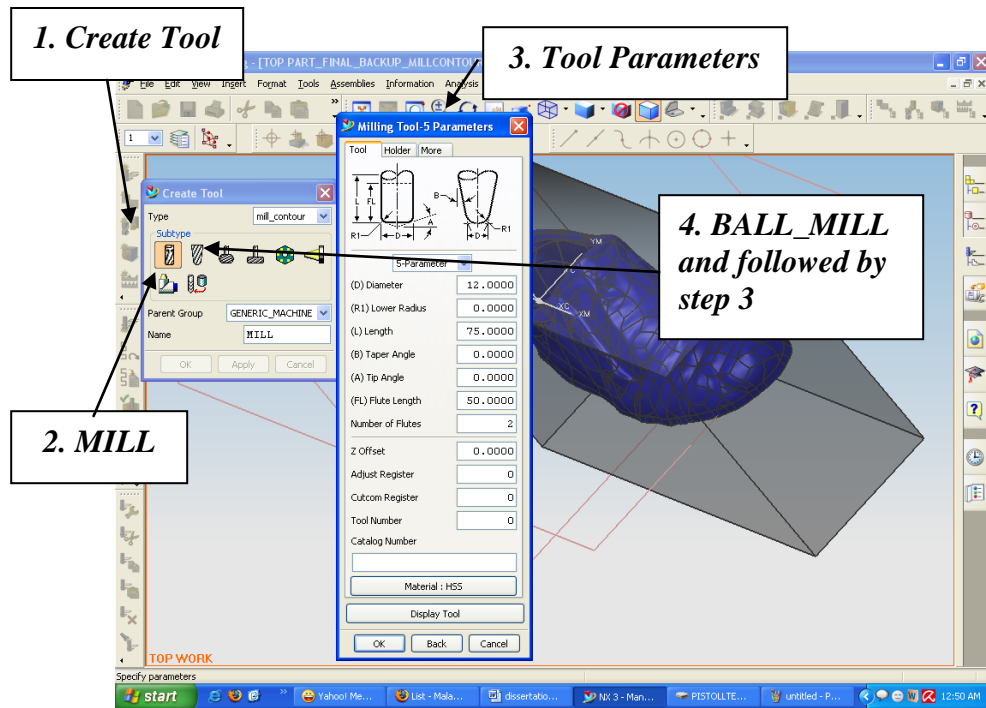
**Table 4-2:** Four basic steps in manufacturing application

Firstly is to set the geometry for the completed drawing that came with a square box and a shoe. **Create Geometry** symbol was clicked and followed by **WORKPIECE** symbol in order to select the part and blank for the operation. Shoe was selected as the part and box as the blank. Steps are shown below in **Figure 4-29**. **Blank** and **Unblank** commands from Edit tab were used to help in selecting the part and blank of the geometry.



**Figure 4-29:** Create Geometry methods

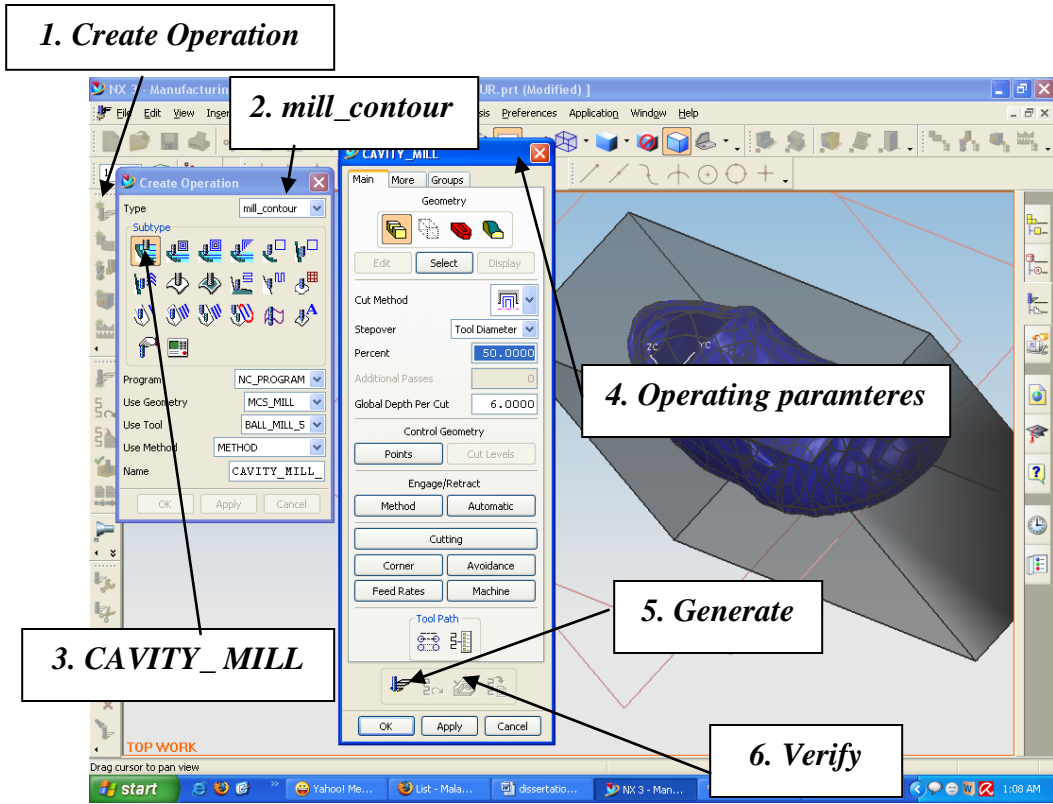
Then, tools were selected for this operation by selecting the **Create Tool** symbol. **MILL** and **BALL\_MILL** symbols then were selected individually from mill\_contour option. Tool parameters were set for both tools. There are two mill tools being used in this operation, milling tool with the diameter of 12mm for roughing and ball milling tool with the diameter of 12mm for finishing. Steps are shown in **Figure 4-30**.



**Figure 4-30:** Create Tool methods

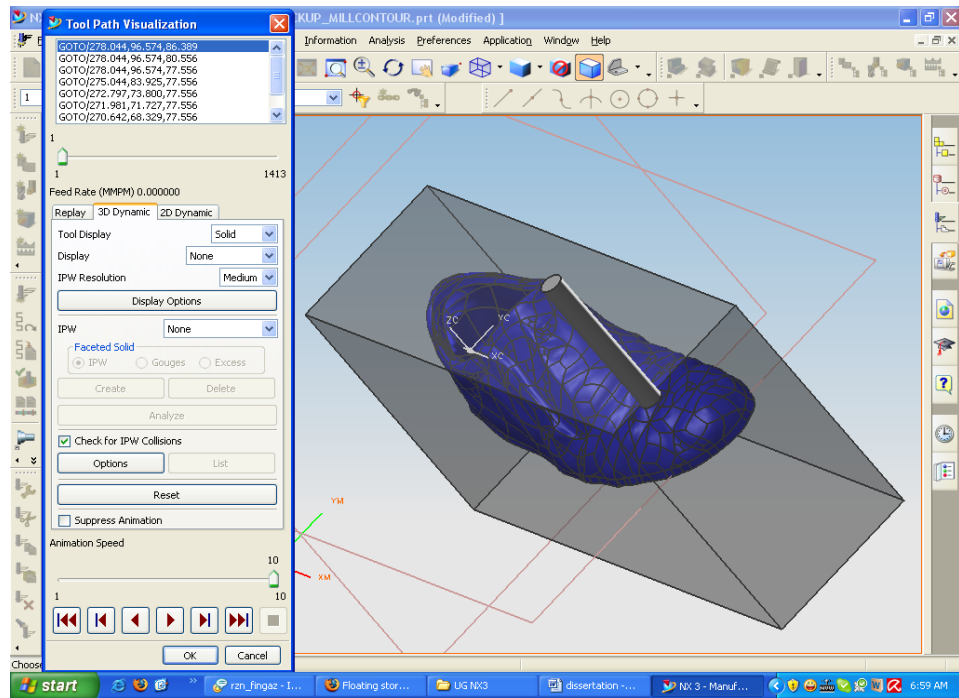
The final stage before creating the program codes is to create operation by selected the **Create Operation** symbol. Two operations have been selected which are cavity mill and fixed contour by selecting **CAVITY\_MILL** and **FIXED CONTOUR** symbols respectively. Roughing was carried out by cavity mill operation while fixed contour operation was used for finishing. 12mm diameter milling tool was used for roughing in cavity mill operation and 12 mm ball milling tool for finishing.

After setting up all the operating parameters, **Generate** symbol at the bottom of the **CAVITY\_MILL** box was clicked and followed by **Verify** button. It took a few minutes to verify the operations. Steps are shown in **Figure 4-31**. Same steps applied for fixed contour operations.



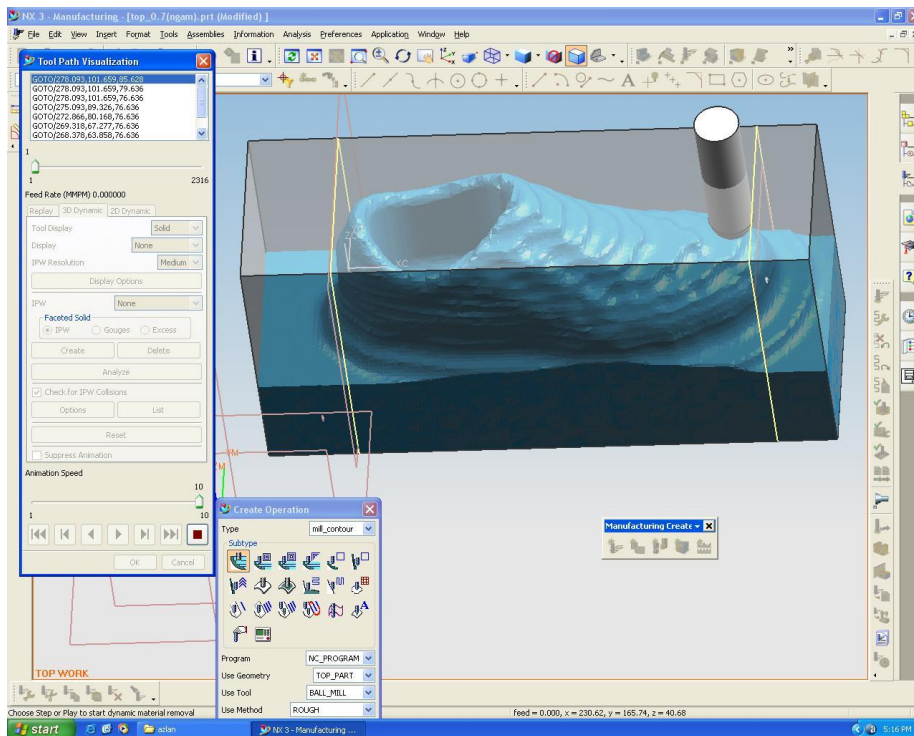
**Figure 4-31: Create Operation methods**

Then the following box appeared,



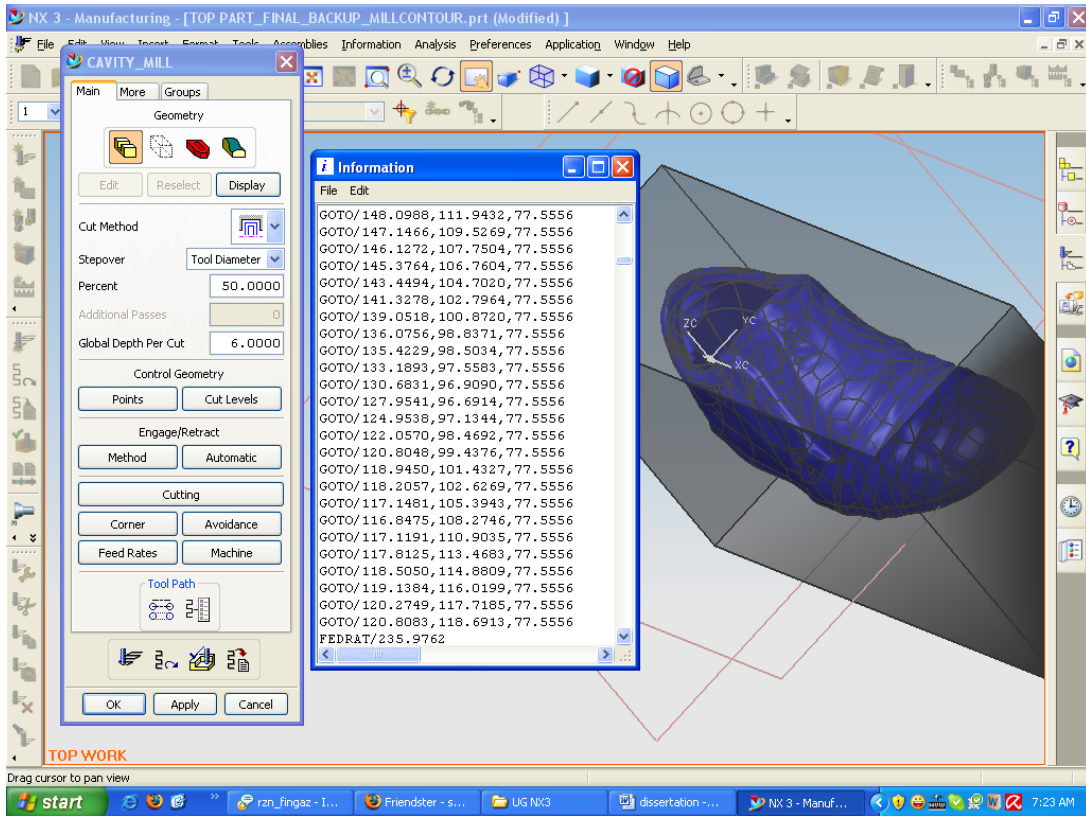
**Figure 4-32: Simulation of the cavity mill operations**

**Figure 4-32** simulated the cavity mill operations that have been set previously. This was the actual movement of the tool in MAZAK machining process. The successive of simulation will give a good end product or output for machining later on. To start the simulation, **Play** button at the bottom of the Tool Path Visualization box was clicked. Before beginning the simulation, the **3D Dynamic** or **2D Dynamic** buttons that are located on the top of the box have to be selected. It gave an option whether to view the simulation in 3D view or 2D view. Same methods applied for fixed contour operations. **OK** button then was clicked after accepted all the operating parameters and assured the simulation processes.



**Figure 4-33:** Simulation in progress

After pressing the OK button, Tool Path Visualization box closed automatically and CAVITY\_MILL box appeared again as shown in **Figure 4-34** below. Then, **Create Program** symbol was clicked to generate the program for the previous operations respectively, cavity mill and fixed contour mill. A box containing CNC codes appeared for each operation and was saved in notepad file format in desired location.



**Figure 4-34:** Create Program button used to generate the CNC codes

## 4.6.2 Machining

Before transferring the CNC codes into MAZAK machine, they have been coded by using IMSpexec to meet MAZAK machine specifications. The machine will not be able to read the programs if failure to convert the codes in EIA file format. Then they were transferred into the machine via wireless connection.

Wax piece is used as the raw material for the fabrication purposes. Following is the figure of the wax piece with its dimension.





**Figure 4-35:** Wax piece is used as the raw material for machining

Wax piece then was clamped properly on the rotary table inside the machine. It was clamped as tight as possible to ensure there is no movement during machining process. The machine has been warmed up for thirty minutes. Then Mr Hafiz initiated the CNC codes and the tool was running as in the simulation.

**Table 4-3** below summarizes the total time taken by MAZAK machine to complete the operation for both parts, top and bottom part of the shoe.

<b>Part</b>	<b>Time Taken for Roughing</b>	<b>Time Taken for Finishing I</b>	<b>Time Taken for Finishing II</b>	<b>Total time taken</b>
Top	16 m 54s	23m 07s	-	40m 01s
Bottom	23m 26s	37m 56s	30m 45s	92m 07s

**Table 4-3:** Total time taken by MAZAK machine to fabricate the shoe

### 4.6.3 End Products

**Figure 4-36** and **4-37** show the final product of top part and bottom part respectively. The size of end products has been reduced to the scale of 0.56 from the actual size by UG NX 3 software.



**Figure 4-36:** End product – top part



**Figure 4-36:** End product – bottom part

## CHAPTER 5

### CONCLUSION AND RECOMMENDATIONS

#### 5.1 Problems Faced and Recommendations

Due to lack of supervision during the practice session, the impeller block has moved and interrupted the scanning process. The machine operator should ensure that nobody disturb the scanning operation to avoid any mistakes in future. Appropriate notice should be placed on the machine as a reminder for all.

During the digitization, I noticed that UTP's Renishaw Digitizer does not have enough devices. Difficulties occurred when digitizing the shoe, the machine moved in three axes only. Since the machine was not provided with indexer, the shoe cannot be rotated 360 degree, because of that I decided to scan it into two parts; top and bottom. According to Renishaw website, [www.renishaw.com](http://www.renishaw.com), to have the best digitization process, the machine must be included with indexer and motorized probe head as shown in **Figure 5-1** below. The motorized probe head drives in 2 axes, enabling the probe configuration to be positioned at almost any angle. It is designed to meet the arduous requirements of 'body-in-white' measurement, where fine angular position and long reach are needed [5]. As a recommendation, UTP management should consider buying these devices for future uses.



**Figure 5-1:** PHS1  
- Motorized probe  
heads [5]

I have involved in online forums discussions with experts to talk about the problem of transferring files from CATIA to Mastercam8.1. Some said that, UTP current Mastercam8.1 does not support files from CATIA V4 and V5A. It is seven to eight years old. To strengthen this statement, I provided the print-screen of the discussion in **Appendix 5-1** for evidence. According to Jay Kramer, Certified Mastercam Instructor from [www.cnczone.com](http://www.cnczone.com) and also a CNC manager for one of the top prototype company's in the United States, "*Newer Mastercam supports Catia 4 & 5 but you are using a product that is about 7 to 8 years old*". I would like to recommend to the management to upgrade our Mastercam8.1 and other software for better uses in future.

UTP also does not have the latest software of Unigraphics NX3. I have practiced to familiarize with the UG using the latest version of NX5. Unfortunately, UTP laboratory is using the old NX3 which made some commands are different with the latest version. As result, more difficulties occurred such as different commands and the old has limited features.

Besides, the Mastercam8.1 software also has not been fully installed. Some features in the Mastercam8.1 software are not available. This is may be because of the price for the full installation is too expensive and UTP cut the budget. So that, the supplier installed the program partially depending on the price that UTP paid them. As result some features are not available to be reached by students and troubled them in their project.

MAZAK machine in UTP laboratory malfunctioned oftenly. It always being put under maintenance and not operating for several times. As scheduled, each student who is using the MAZAK has his own turn to do the fabrication. If the MAZAK machine malfunctioned, the schedule will be delayed and it affected all FYP students who are going to use it. Proper maintenance schedule should be arranged to avoid this matter happen again. Besides management should have enough spare parts for the machine for maintenance purposes.

UTP management is encouraged to spend some money for the development training for staff on how to use the software that available in laboratory. Sometimes FYP students had no idea where should they refer to when getting problem with the software. By hook or by crook they have to find the best way in whatever problems they faced. There are few experts available in UTP for Tracecut, Mastercam and Unigraphics software. According to Mr Rao from IME Technology Sdn Bhd (UTP Mastercam service provider), they do provide training courses for their clients. Management should grab this opportunity and enhance the skills of UTP personnel by sending them to join those courses. Then they might help those students.

Before machining the parts, CNC codes obtained from UG NX3 has to be transferred to the MAZAK machine via wireless connection. Unfortunately, weak wireless connection between desktop and the machine troubled me to transfer the programs. Hence, corrective actions have been taken by ITMS (UTP IT Department) to overcome this situation. As result, it has delayed the progress of the projects and affected the other students who will use the same machine. The wireless connection should be enhanced or use a cable as the other alternative for the connection between the desktop and the machine.

As a reminder, before machining, please ensure the work piece is clamped tightly in the MAZAK machine. As told by the laboratory technician, Mr Hafiz Safian, failure to do so will give a bad machining output especially if the work piece is a metal or aluminum. A few students have experienced this kind of incidents which is wasted the materials.

According to the previous machining plan, the part will be machined in multi axes in order to obtain the best figure of the shoe. Multi axes machining allows the milling tool to access at any different angle on the work piece. This part will be machined in five axes and codes for that process were created. Unfortunately, the machine was not able to read the programs properly and failed to machine after trying for many times. Due to that problem, I decided to just use multi contour program which allows the tool to move in only three axes, X, Y, and Z-axes. Then, the machine successfully did its job.

5.2 Conclusion

Figure 5-2 illustrates the summary of the CAD reverse engineering process flow that has been applied onto the shoe. Both parts went through the same path as followed:

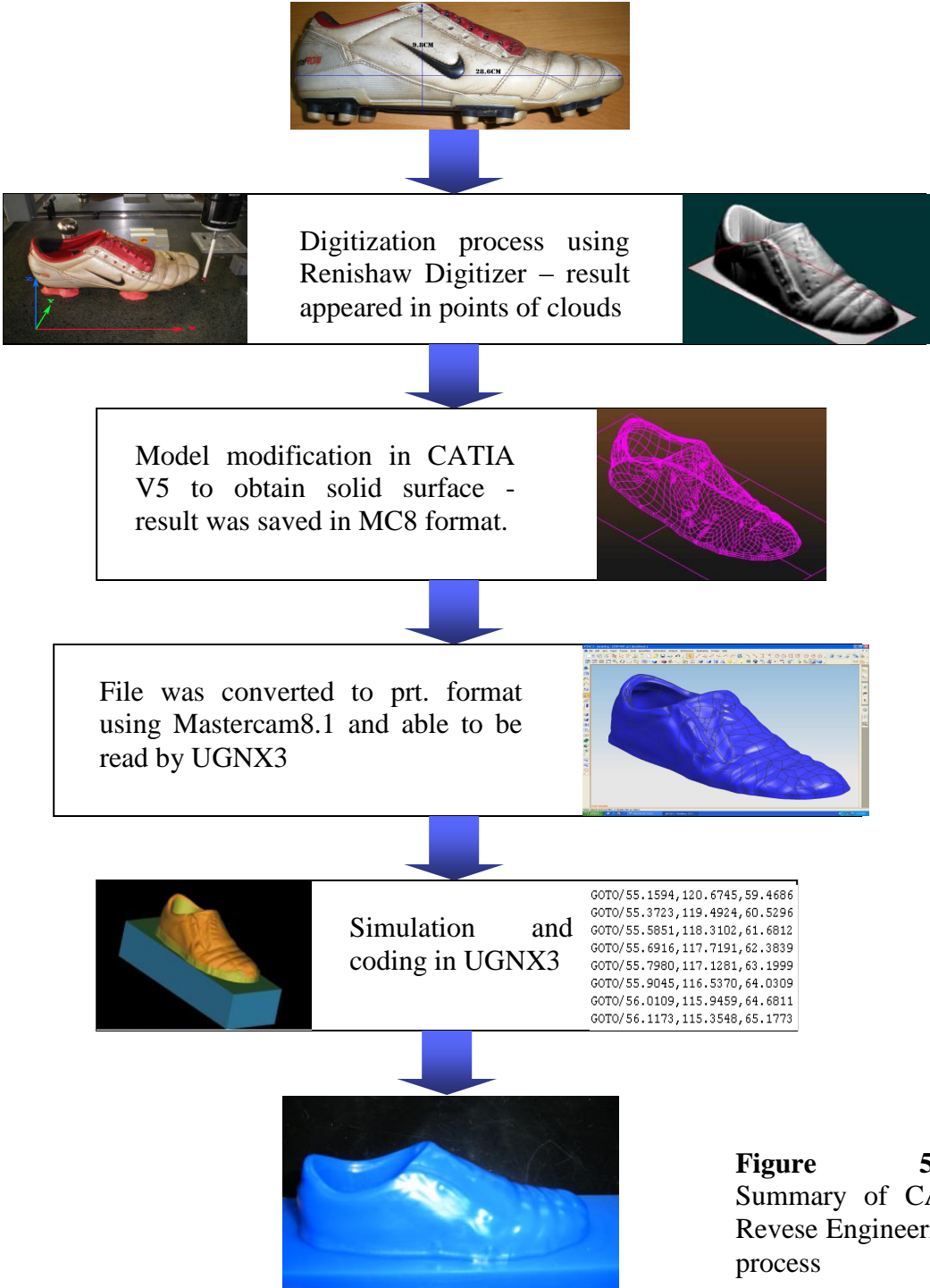


Figure 5-2: Summary of CAD Reverse Engineering process

All objectives of this project were achieved which is include reverse engineered the shoe using RENISHAW Digitizer, file formats modification in CATIA to convert to solid surface, simulation and coding using UGNX3 and product fabrication. A lot of technical challenges have been discovered along the way completing this project.

As the conclusion, Reverse Engineering technology can be used to digitize the shoe by using RENISHAW Digitizer and produce UTP Golden Boot Award.

## REFERENCES

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## **APPENDICES**

## Appendix 4-1 : Example of the data evaluation in Reverse Engineering

**Example.** The whatzit costs \$300. The whatzit is part of a system which needs to be maintained for only 10 more years. Routinely 500 parts are used per year. There are 2000 parts on hand with 1000 on back order.

The following economic information can be determined. The 2000 parts in stock will maintain the system for 4 years at 500 parts per year. With 1000 on back order there is 2 more years of supply. This means that 6 of the remaining 10 years worth of repair parts are available and only 4 years remain in the life cycle for which there are no parts.

The 4 remaining years will require approximately 2000 parts at a usage rate of 500 parts per year. If there are no shelf-life restrictions, these 2000 parts can now be purchased for an investment of \$600,000 (\$300 per part  $\times$  2000 parts). A few considerations are in order before reaching a conclusion to purchase the remaining 4 years of supply now.

If \$300 per whatzit is considered to be a reasonable cost, it makes good economic sense to purchase only 4 years of supply now or later on rather than invest in reverse engineering.

If, by reverse engineering, the whatzit unit price can be reduced by 25 percent (the target unit price reduction) to \$225 each, then the 2000 remaining parts can be purchased for \$450,000 (\$225  $\times$  2000). This would result in a \$150,000 LCS over the remaining life of the part. LCS can also be calculated by multiplying LCC (\$600,000) by 25 percent (0.25), which also accounts for the 25 percent reduction in the unit price. \$600,000  $\times$  0.25 = \$150,000.

From the \$150,000 LCS the cost to reverse engineer would need to be subtracted out. If the cost to reverse engineer is \$30,000 (assume the reverse engineering cost to be 100 times the cost of the item) the return on investment can be calculated also:

$$\text{ROI} = \frac{\text{LCS} - \text{RE cost}}{\text{RE cost}}$$
$$\text{ROI} = \frac{\$150,000 - \$30,000}{\$30,000} = \frac{\$120,000}{\$30,000} = 4:1$$

Return on investment is expressed as a ratio. If you recall the guidelines from Chap. 1 (section on the risk of failure) that prescreened components should not enter stage 1 without a projected ROI of 25:1, then the reverse engineering of the whatzit with a projected ROI of 4:1 presents a risk due to the slim margin for return. At this point it is simply the engineer's and management's judgment call on proceeding further into stage 1.

**Example.** The whatzit again costs \$300 per part. The system has 22 years of remaining service life. There are only 1000 parts on hand. Annually, 500 parts are replaced because of system usage. Is there a significant return on investment sufficient to justify the potential of reverse engineering the whatzit?

Using 500 parts per year, there is a 2-year supply available. There are 20 (22 - 2) years left to maintain the system. The 20 years  $\times$  500 parts per year = 10,000 parts to be supplied over the remaining service life.

LCC = 10,000 parts  $\times$  \$300/part = \$3,000,000. LCS = \$3,000,000  $\times$  25 percent (0.25) = \$750,000. The reverse engineering costs again are estimated to be \$30,000.

$$\text{ROI} = \frac{\text{LCS} - \text{RE cost}}{\text{RE cost}} = \frac{\$750,000 - 30,000}{\$30,000} = \frac{\$720,000}{\$30,000} = 24:1$$

A projected ROI of 24:1 is worth pursuing when the net savings is as large as \$720,000. This leaves plenty of room for error and still points the project to stage 1 for a full and complete evaluation of additional factors which cannot be accounted for in the paper review of the prescreen.

Source: Kathryn A. Ingle, 1994, *Reverse Engineering*, New York, McGraw Hill Inc, pg: 63, 64

## Appendix 5-1: Print-screen of forum discussions in www.cnczone.com

