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VERSATILITY AND CUSTOMIZATION OF PORTABLE CMM IN REVERSE ENGINEERING APPLICATIONS

by

AMAR RAJA THIRAVIAM
B.S. University of Madras, 2002

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in the Department of Industrial Engineering and Management Systems in the College of Engineering and Computer Science at the University of Central Florida Orlando, Florida

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2004
ABSTRACT

Reverse engineering is the technique of gathering scientific knowledge about a part by physically examining it. In the computer aided manufacturing world this is referred to as *Part to CAD* conversion, where the geometry of physical objects are being captured as Digital 3-D CAD Data. This is vital not only to produce drawing of parts for which no CAD data exists, but also is frequently being used to produce better designs. The industry professionals to achieve this are frequently using Coordinate Measuring Machine [CMM] among other tools. The purpose of this thesis is to demonstrate the versatility of portable CMM as a Reverse Engineering Tool through application experiments aimed at industrial and non-industrial solutions. The thesis also researches into the feasibility of customization options through experimentations focused on reverse engineering. Focusing further on Reverse Engineering applications, some of the interesting digitizing and CAD techniques are demonstrated and compared.
This work is dedicated to my parents Palmani and Thiraviam for their endless love and support.
ACKNOWLEDGMENTS

First I would like to thank my advisor Dr. Yasser Hosni for his guidance and support throughout my thesis. I would also like to thank the rest of my committee Dr. Jamal Nayfeh, Mr. David Feist and Dr. Sandra Furterer. I would also like to pass special thanks to Mr. Greg Pettengil for his input into my research. Further I thank Mr. Allen Sajedi and Mr. Shaun Mymudes of FARO Technologies, Inc for their help and support. Last but not the least I would like to thank all my family and friends who supported me during the course of the thesis.
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<th>Full Form</th>
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<tbody>
<tr>
<td>2D</td>
<td>2(Two) Dimensional</td>
</tr>
<tr>
<td>3D</td>
<td>3(Three) Dimensional</td>
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<td>Computer Aided Design</td>
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<td>CCD</td>
<td>Charge Coupled Device</td>
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<td>CMM</td>
<td>Coordinate Measuring Machine</td>
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<td>CNC</td>
<td>Computer Numeric Control</td>
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<td>CT</td>
<td>Computed Topography</td>
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<tr>
<td>MRI</td>
<td>Magnetic Resonance Imaging</td>
</tr>
<tr>
<td>PCMM</td>
<td>Portable Coordinate Measuring Machine</td>
</tr>
<tr>
<td>RE</td>
<td>Reverse Engineering</td>
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<tr>
<td>RP</td>
<td>Rapid Prototyping</td>
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<td>SALSS</td>
<td>Stand Alone Laser Scanning System</td>
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<tr>
<td>SPC</td>
<td>Statistical Process Control</td>
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<td>STL</td>
<td>Standard Triangulated Language</td>
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CHAPTER ONE: INTRODUCTION

1.1 Reverse Engineering

Reverse Engineering has been defined in many different ways by many authors; the aim of reverse engineering is *to use a physical part to gather complete knowledge* about the part, which enables its replication. This knowledge can be anything from general appearance and physical dimensions to working methodology and material properties. In the manufacturing world ‘reverse engineering’ refers to the process of creating engineering design data from existing parts. It recreates or clones the exiting part by acquiring the CAD (Computer Aided Design) of the existing part.

Typical cases where reverse engineering can be beneficial include industrial and non-industrial applications, such as.

- Capturing the geometrical configuration of an old part whose drawing does not exists.
- Design Modification of an existing part.
- Need to produce a CAD data of a clay model (this technique is used widely by the automotive manufacturers in design of chassis).
- Need to produce a scaled down or scaled up version of an existing object.
- Digitizing a historical landmark, which is in danger of deterioration or other threats [e.g. the statue of liberty is already digitized to have a duplicate copy, so that even in an unlikely event of destruction, an exact replica can be produced).
- Need to reproduce existing artistic work into jewellery.
- To capture the deformed area after crash tests or accidents. [This is done to capture the impact of a crash or accident and further analyze it to produce more robust designs, the deformed region is normally of non parametric nature and calls for optical based reverse engineering).

- To graphically depict clay models of movie characters, this is a common practice in the movie industry.

- To obtain digital data of tooth for implantation. [Impression of the tooth is normally made by plaster of pairs].

- To obtain 3D (3 dimensional) data of Internal Human organs for various applications like diagnosis, training, and implants among others, which fall into the field of Biomodeling.

- To Examine the Internal Stresses and Deformation on metal objects. [This would normally require sophisticated equipment like industrial CT (Computed Tomography) scan equipment.

Thus we can see that reverse engineering techniques are being used in a wide range of applications and is not restricted to the industrial world. The type of reverse engineering that will be discussed in this thesis is the technique where the physical dimensions of a part are being captured to produce the detailed drawing of the part. In the computer aided manufacturing (CAM) world this is referred to as Part to CAD conversion, where the geometry of physical objects be captured as Digital 3-D CAD Data.
1.2 Portable CMM (PCMM) as a reverse engineering tool

In Computer Integrated Manufacturing world Reverse Engineering (RE) is seen as the fastest way of translating the dimensions of a physical model or shape into the digital realm so that manufacturing, machining, or repair plans can be developed for it. In concept, it is fairly simple, an object, such as a pump housing, plastic frame, boat hull, or aircraft is measured physically. Then the measurements are transcribed into a digital medium (a CAD-compatible platform) as an image of dots, streaming lines, or wire frames. Subsequently, this image can be enhanced for its end use via one or more software packages such as surfacing, stress analysis, human factors, ergonomics, plant layout, or product flow. There are various tools available which helps us to reverse engineer an object to capture the physical 3D data. Coordinate measuring machine is one of the most heavily used reverse engineering tool [Mymudes, 2004]. In general, a coordinate measuring machine (CMM) is any machine which measures in a three dimensional rectilinear Cartesian coordinate system [Bosh, John A 1995]. One of the disadvantages of the CMM is that it is of a fixed type and has a limited work envelop. Hence posed physical size constraints to parts that can be measured. The limited degree of freedom (mostly 3 or 4) was also considered as a serious limitation in reverse engineering applications.

The birth of the Portable CMM (PCMM) came as a boon to solve this problem. PCMM’s referred to in this thesis are of the Non-Cartesian Articulated Measurement Arm type systems. The power of portability and the six degrees of freedom rapidly popularized PCMM’s as a computer aided measurement tool and they were quickly assimilated into the workplace as a
powerful reverse engineering tool. The objective of this thesis is to demonstrate the versatility of PCMM in RE through a number of experiments conducted through the course of the study.

### 1.3 Thesis Organization

This chapter (Chapter One) introduces the technique of reverse engineering and gives examples of common situations where reverse engineering can be used fruitfully. It also gives a brief introduction of portable coordinate measure machine (PCMM) and its use as a reverse engineering tool. Chapter two researches into the literature and gives a background on CMM’s, their history, components, and the advent of PCMM. Various reverse engineering tools and techniques are also discussed in this chapter. Chapter three talks about the research objectives of this thesis. The Versatility and Customization of PCMM are demonstrated in chapter four through seven reverse engineering experiments. These experiments explain the reverse engineering methodologies that were used to successfully capture the 3D dimensional data of complex objects. The chapter also talks about the suitability of using PCMM of digitizing free form type aesthetic objects. The Conclusion summarizes the findings of the thesis and opens up some avenues for future research. ‘Appendix: A’ has images of others objects reverse engineered, during the course of the research. A very useful appendix (Appendix: B) has been added to the end of this thesis documenting some useful reverse engineering tips and tricks learned through the progress of this research. ‘Appendix: A’ has images of others objects reverse engineered, during the course of the research.
CHAPTER TWO: LITERATURE REVIEW

2.1 Co-ordinate Measuring Machines

2.1.1 Evolution of Co-ordinate Measuring Machines

As the Manufacturing companies are increasingly embracing computer integrated manufacturing (CIM), the need for Computer-Aided-Measurement increased as well. The evolution of the Co-ordinate Measuring Machine (CMM) was a big breakthrough in dimensional metrology as the need for more accurate measuring devices increased. As one of the most powerful metrological instruments co-ordinate measuring machines have been widely used in major manufacturing plants.

Ferranti, Ltd. of Scotland developed the first measuring machine that falls into the category that we commonly call CMM. This CMM was developed as the companion product to their growing family of numerically controlled machines tools. Ferranti developed this machine in response to the need for faster and more flexible measuring when measuring became more automated [J.A.Bosh, 1995].

In 1956, just two years after Harry Ogden joined the Numerical Control Division of Ferranti Ltd, as Chief Mechanical Engineer he invented the Ferranti Inspection Machine. He then conceived that a freely moving mechanical measuring machine with electronic numerical display would facilitate inspection of machined components at a much faster rate. This in effect changed
the whole economic aspect of conventional Inspection methods by reducing inspection, time and skill required for inspection [J.A.Bosh, 1995].

The key elements that made the development of the coordinate measuring machine possible were the availability of a precision and long-range electronically compatible digital measuring system. They were accurate, relatively easy to manufacture and easily reset to reference. Their accuracy was based upon averaging a number of lines and was not dependent upon the accuracy of any one line [J.A.Bosh, 1995].

![Figure 1: Initial Ferranti Co-ordinate Measuring Machine (Courtesy: Ferranti Ltd)](image)

The initial Ferranti development was an inspection machine with X and Y movements of 610mm (24inches) and 381 mm (15inches) respectively and accuracy (closeness to original
value) of 0.025mm (0.001 inch) and a resolution (smallest measurement that can be made) of 0.12mm (0.0005 inch). The machine was equipped with tapered probes.

It is important to highlight the role of software in complimenting the computer aided measurement solutions. The initial CMM’s had only a digital readout and most of the computations were done manually to obtain any meaningful information. Slowly the computations performed frequently were automated with the help of the software. One of the first such applications is the probe compensation, where the compensation accounts for the radius of the probe tip which comes into physical contact with the object when the object is being measured.

Today Computers play a very important role in the CMM industry by making the measurement system user-friendlier by providing a man-machine interface. They make the life of the foreman easy by graphically describing the actions to be done. Part Programming is another important area, which has expedited up the measurement process and reduced measurement lead times. Some new software like Faro’s SPC graph® even provide statistical process control capabilities. Thus we can see that the improvements in computer have also kept pace with the frequent improvements in the CMM hardware and vice versa.

Advancements in CMM in just the last couple of decades have been enormous and unprecedented. The introduction of portable CMM can be considered as the next major breakthrough after the advent of CMM almost five decades ago.
2.1.2 CMM – Components

A typical CMM system consists of the following elements.

1. The Measuring Element (The Machine itself)
2. The Probes
3. The Computer and software.
4. Any Accessories needed to customize the system

The Major Components in a CMM are shown in the Figure 2.

Figure 2: Components of a CMM (Starrett CMM Hand Book, 2001)

1. Surface Plate: This is usually made of granite and is machined to a very highly accurate flatness. Advantages of choosing granite being high resistance to wear, rigidity, vibration isolation and temperature stability.
2. Digital Readout with Cabinet – to display the measured values.
3. Bridge Design – which incorporated the physical design.
4. Probes – to manually contact the object to be digitized.
5. Bearings – to aid in movement among axis.
6. Computer – to process the data captured.

2.1.3 Basic CMM Configurations

Configurations of CMM play a very important role in meeting measurement requirements like accuracy, flexibility, and size of the workpiece.

CMM’s can be basically divided into two categories based on their configuration, they are

- Cartesian type e.g.- gantry type CMM
- Non-Cartesian type – Articulated Measurement Arms.

Articulated Measuring arms are commonly referred to as portable CMM because of their portability.

2.1.3.1 Cartesian Type CMM’s

Different categories in the Cartesian type CMM are:

2.1.3.1.1 Moving Bridge

It has a stationary table to support the work piece to be measured and a moving bridge. With this design, the phenomenon of yawing can occur e-g the two columns or legs move at different angles causing the bridge to twist and causing inaccuracy [J.A.Bosh, 1995].
2.1.3.1.2 Fixed Bridge

In this type the bridge is rigidly attached to the machine bed. The table upon which the workpiece is mounted provides one axis of motion. This type is more accurate than the others but the operating speed is very low.

2.1.3.1.3 Cantilever

This design has a moving cantilever arm that supports a carrier to move in and out. A probe arm is supported by the carrier for the vertical movement. The part to be measured is fixed in the table.

2.1.3.1.4 Gantry Type

A stable base provides the reference surface for items to be measured. Two vertical columns extend up from the base to support a horizontal bridge. The measuring ram is attached to the bridge with the measuring probe attached to the ram. This is the most widely used CMM.

Figure 3: Bridge Type CMM (Courtesy: www.allmeasure.com)
2.1.3.2 Non Cartesian Type CMM’s

The Most widely used of the non-Cartesian type CMM is the articulated measurement arm systems.

2.1.1.2.1 Articulated Measurement Arms (PCMM)

Articulated Measurement Arms use a series of counterbalanced six degree of freedom linkage arms. Precision Rotary Transducers are mounted at each of the six joints and are used to calculate the probe position in three-dimensional space relative to the base of the arm. The measuring envelope is spherical with radius equal to maximum reach of the arm. These systems are portable making them suitable for field use. Figure 4 shows a typical Articulated Measurement Arm system.

Figure 4: Articulated Measurement Arm [Courtesy: Faro Technologies Inc.]
2.1.4 CMM – Reverse Engineering Technique

The basic function of a CMM constitutes of measurement of the actual shape of the work piece by probing the surface at discrete points. Every point measured is expressed in terms of its measured coordinates (X, Y, Z). Parameters like length, diameter among others are computed from these individual points with the help of an appropriate best-fit geometric algorithm. Such software is either embedded into the CMM or available separately.

Reverse Engineering is a method of capturing 3D Data from a physical object to create a 3D CAD drawing of the object. This can be performed with the help of hand tools to cutting edge CMM’s. Due to their high accuracy CMM’s are preferred for most of the industrial reverse engineering applications; however it also has a few limitations.

A typical Reverse Engineering Project using a CMM would follow the following steps.

- Selection of Probe head.
- Calibration of Probe head.
- Positioning and Clamping of the part.
- Measurements of features required for initial alignment / realignment.
- Measurement of simple features.
- Measurement of Complex features.
- Change Alignment and Probes wherever Necessary.
- Complete measurement of required features.
- Export to a file format readable by CAD software.
- Post process to create features and surfaces to produce a final solid model.
2.2 Portable CMM

2.2.1 Background of portable CMM

As more and more companies started using coordinate measuring machines for their inspection tasks, more versatility was needed in the CMM. The major difficulties encountered were:

- Some parts where bigger than the working envelope of the CMM.
- Complex shapes which the standard 3-axis gantry type CMM could not measure.
- Need for in process inspection where there was difficulty in taking the parts to the CMM and bringing the parts back to the line.

The CMM manufacturers partially solved this problem by manufacturing bigger CMM’s and adding an extra axis to increase the ability of the CMM to reach more intricate parts. Lets us look at these developments in greater detail.

2.2.1.1 Need for Bigger CMM’s

As more companies started employing CMM for their measurement needs the versatility of the part increased. One of the restrictions faced in traditional gantry type CMM was the inability to handle bigger size parts, which cannot be accommodated in the table of the CMM measuring envelope. The CMM manufacturers partially solved the problem by building bigger CMM’s. But beyond a point this became impossible as the industries such as aerospace manufacturers felt the need of CMM measurement.
Beyond a point the CMM Manufacturers could not match the size of objects in industries like aerospace and shipbuilding, which required inspections with a high accuracy and precision. Today we have CMM’s that can even a fit a car inside their work envelop but such CMM’s are prohibitively expensive and a need for less expensive equipment was needed. The advent of the portable CMM elegantly solved this seemingly unsolvable problem.

2.2.1.2 Complexity of Parts

Another problem faced by the manufacturers was the need for CMM, which could measure more complex parts. Normal CMM has three axes as shown in Figure 5.

![Figure 5: Three Axes of a CMM](www.optodyne.com)

This made the measurement of the complex parts with undercuts and non-parametric features difficult. Consider the following two cases in Figure 6 and Figure 7.
An extra axis is inevitable in the above two cases. This solved the problem of complex shapes to an extent but as the parts became more complex, the CMM manufacturers could not add extra axes to the normal Cartesian configuration and also each time an axis is added there was a loss in accuracy. So a new configuration was needed which could measure complex parts and also match the accuracy of the rigid three-axes CMM.
In the current manufacturing environment, ‘reducing defects’ is a key concern of the manufacturers and to achieve that the part has to be measured at each stage of the production process rather than the old way of measuring the part at the end of the production line. In a high-volume manufacturing environment transporting the parts back and forth to the CMM that was always housed in a special temperature controlled room became a tedious exercise. Also transporting the parts back and forth increased the production lead-time. Transportation of parts also caused accidental damage during the transit. So there was a need for a device which could be installed on the floor and measure the parts on line without the need of having to move the parts.

### 2.2.1.3 Portability

Portability was another key feature, which the CMM users sought, but the CMM could not be modified to this need. The high accuracy of the CMM’s demanded a very rigid and bulky configuration, special foundations and a controlled environment in which they operated. So the CMM in most cases could not be moved from the place it was installed. Even in cases where it was possible, the setup and breakdown costs were prohibitively high. So this highly needed feature of portability was not satisfied by the CMM and the need for a new configuration, which would offer both the portability and high accuracy, was evident. This need was realized once portable CMM’s came into the computer aided measurement industry.

The difficulties faced by the Industry in using CMM in their Computer aided inspection needs paved the way to the development of a new type of configuration which could measure a three dimensional point on space with matching accuracy (the initial PCMM’s could not match the CMM accuracy but the modern age arm is becoming highly competitive) and be portable and
reach more complex shapes – The articulated arm type configuration of the portable CMM satisfied these characteristics.

Some of the popular models of portable CMM’s available in the market today are shown in the following pages [Figure 8 – Figure 12].

Figure 8: A CimCore PCMM [Courtesy: Cimcore Romer Inc]

Figure 9: Faro Arm [Courtesy: FARO Technologies, Inc.]
Figure 10: Microscribe arm [Courtesy: Microscribe Inc]

Figure 11: Polar Portable CMM [Courtesy: Polar Inc]
A PCMM determines the coordinates of a point in 3D space using an algorithm, which uses the lengths of the each sections of the arm and the angles of rotations ($\theta_1, \theta_2,...$) of all joints. The angles are measured by rotary encoders present at each of the joints in the arm. A probe present at the end of the device (equivalent to the end-effector of a robot configuration) reports on its position in space in from of ($x$, $y$, $z$) $P1$ relative to ($0$, $0$, $0$) $P0$ origin at the base of the arm.
As we can see from the above figure there are at least six axes of rotation (the seventh axis is optional). The origin of the arm is the point \( P_0 \). The angles of rotations are computed by the rotary encoders that are located in each of the six joints. The linkages are of length \( L_1, L_2, L_3 \) and \( L_4 \) respectively. All these lengths are fixed except for the final linkage \( L_4 \). This length is constantly updated with the probe calibration, this includes longer probes. The seventh axis is very important when a curved probe or a laser probe is used. This gives an additional angle of rotation for the probe and hence can maintain the required orientation. Thus the point \( P_1 \) on space is measured with the help of a PCMM.

The main difference between the traditional gantry type CMM’s and the PCMM configuration is that PCMM models have more joints and hence more degrees of freedom. The PCMM has at least six joints and hence the working envelop of portable CMM is much wider and they can reach the same point in space through many configurations.

The configuration of the articulated arm robot lends itself to the configuration of the portable CMM. The motors at each of the joints where replaced by rotary transducers (incremental encoders) which precisely determine the angle of rotation at each of the joints. The embedded software in the portable CMM runs an algorithm, which computes the location of the tip of the probe by making use of the angles computed by each of the rotary encoders and the length the arm section. The calibration procedure adjusts the small inaccuracies in the arm sections due to manufacturing and achieves high precision and accuracy.

The tip of the portable CMM has a probe holder, which has the capability to attach many types of probes; each time the probe is changed the probe must be calibrated to adjust the length of the last arm section and thus ensure maximum accuracy.
These articulated measurement systems provide portable measurement solution to the industry. It can be moved to the part rather than moving the part to the CMM. Another key advantage is that they can be used to measure much larger parts by extending their working volume through referencing with the help of some features (this feature is popularly known as the leap frog technique).

![Figure 14: Leap Frog technique](image)

As shown in Figure 15 the arm position can be extended from position A to positions B and C by measuring at least three features common to both features. Other benefits of this technique include realignment of parts when its moved and aligning additional devices to an existing CAD file.
2.3 Reverse Engineering – Tools & Techniques

2.3.1 Tools Used in Reverse Engineering

There are various tools used in Reverse Engineering. This section explores some of the most common tools.

2.3.1.1 Hand Tools

Reverse Engineering can be done by many of the traditional measuring tools that are used in metrology. Figure 15 shows some of the commonly used tools.

- Vernier Calipers.
- Micrometers
- Height gauges
- Steel rule
- Depth gauges
- Protractors.
- Screw Gauge
- Measuring tape
2.3.1.2 CMM

We have already seen the evolution, components and configurations of coordinate measuring machine. It would be appropriate to stress the importance of the CMM as a Reverse Engineering tool, even after the advent of various other tools. CMM remains to be one of the key reverse engineering tools.
Some of the disadvantages of using a CMM for Reverse Engineering include the restricted motion of the probe head in three axes. This is partially overcome by providing and additional degree of freedom but certain complex features still cannot be digitized with a conventional CMM.

2.3.1.3 PCMM:

With portability and increased degree of freedom added to the armory; portable CMM’s emerged as a much better choice for reverse engineering applications. Refer to Section 2.2 for more elaboration on PCMM.

Figure 17: Faro Arm [Courtesy – Faro Technologies]
2.3.1.4 Laser Scanners

Laser Scanners are increasingly getting assimilated to the group of RE tools in the industry, because of their non-contact measurement technique. They are able to handle any type of material (when coated with reflective coating) and the point-by-point digitizing breaks the barriers regarding shape as it can capture any free form and non-parametric shapes. Frequently Laser probes are being attached to CMM’s and portable CMM’s to perform non-contact scanning. One of the noted disadvantages of RE using laser scanners is the extensive post processing required and the requirement for a reflective surface. Figure 18 is that of a Desktop Laser Scanner being used for a reverse engineering application where the laser point source moves vertically capturing the 3D CAD data of the object as the table rotates. The resultant is a point cloud that is imported into a point cloud-software to obtain a surface model. This is achieved by post processing, which is explained in detail in Experiment 4.2.2 and Appendix: B.

Figure 18: Laser Scanner [Courtesy – Roland DGA Inc]
2.3.1.5 Computed Tomography (CT) Scan

CT first was an inner-health analysis tool for industrials. From 2D slices of the examined part, information about porosity and cracks could be extracted. So, CT systems provide non-destructively the result expected by imaging a part in a particular plane pixel by pixel. By stacking CT numeric slices of a part in many parallel planes, we can obtain a 3D numerical representation of that part. Therefore, CT can be a very powerful digitalization tool, because it images internal features as well as external surfaces. A special image processing software converts the set of slices output by a CT scan into a meaningful CAD model. Industrial CT scanners use the same theory however uses a more powerful X-ray source. Figure 19 shows the working of a CT scan as X-ray beam is projected into a metallic object. It gives a representation in the form of “degrees of grayness” for every pixel along with its co-ordinates are stored in the form of slices. This set of slices is then transformed in to a one CAD file by arranging on top of each other.

Figure 19: Working of a CT scanner [Courtesy: CMS Tech Inc].
2.3.2 Reverse Engineering Techniques

Reverse Engineering Techniques can be broadly classified into contact and non-contact methods. Some of the popular techniques in both categories will be discussed in this thesis.

![Diagram showing Reverse Engineering Techniques with Contact and Non-Contact Methods]

**Figure 20: Reverse Engineering Techniques**

### 2.3.2.1 Contact Methods

Most of the conventional reverse engineering techniques fall into this category. The 3D data is mostly captured by contact through a hard probe attached to a CMM or a portable CMM. This can also be achieved by manually measuring the critical dimensions using any of the traditional measuring tools. More than one RE tool can be used in a project to achieve a reduced cycle time.
Some of the shortcoming of this category of reverse engineering is that the surfaced may be marred or damaged by contact. It may be fragile; which would not accommodate any contact methods and in some cases it may be too complex (undercuts, freeform features among others) that it is not feasible to capture all the features.

### 2.3.2.2 Non-Contact Methods

Industry professionals are increasingly seeking non-contact reverse engineering techniques because of their capability to scan complex geometry and in some cases like Bio-RE, detecting subsurface geometry the only known way is to reverse engineer the part by non-contact methods. The following are the some of the situations when non-contact reverse engineering is well suited.

- The object is complex and has many non-parametric and organic shapes.
- The object can be damaged or deformed by physical methods.
- Contact measurement tools are not reachable in certain parts of the object.
Figure 22 is a demonstration of non-contact scanning used for capturing the geometry of a free form object.
2.3.3 Reverse Engineering Using Portable CMM

PCMM has tremendous potential to be an effective reverse engineering tool. The following are some of the advantages of using PCMMs for reverse engineering applications.

- Increased degrees of freedom provide reach into complex part geometry.
- Laser scanner attachment makes it versatile for contact and non-contact reverse engineering.
- Different options of probes help increase their versatility.
- Portability enables capturing data from extremely large objects. [Alignments, commonly known as leap frog should be used whenever the part/machine orientation is changed.
- Portability enables field use.

Fig 23 shows the process of scanning a part using PCMM (with laser probe); the reverse engineering methodology to be followed is detailed experimentations in chapter three.

Figure 23: Reverse Engineering Using Portable CMM [Courtesy: Faro technologies Inc.]
CHAPTER THREE: RESEARCH OBJECTIVES

Reverse Engineering is widely used in the manufacturing arena, and the need for better tools to accomplish reverse engineering with versatility and precision is evident. One of the underused tools for Reverse Engineering is the portable CMM. The wide spread use of PCMM as a measurement tool has probably made the industry professionals underestimate the reverse engineering potential of this neat equipment. Some of the challenges involved in reverse engineering projects include.

- Size of the object
- Complexity of the Object – unreachable features.
- Complexity of Object – nonparametric free form shapes.

To overcome the challenges mentioned above we propose the use of PCMM as the RE tool. The research objectives of this thesis is to demonstrate the potential of PCMM as a reverse engineering tool and also to research on customization options available which would enhance the versatility of PCMM.

The methodology followed in this research is the use of demonstrative application experiments (Chapter: Four). These experiments will proceed from simple objects, which can be reverse engineered in a few minutes to produce a virtual replica of complex objects, which require multiple orientations and software to accomplish the RE.

The lists of experiments are given below.

- Experiment 4.1.1: Reverse Engineering of a parametric object.
- Experiment 4.1.2: Reverse Engineering of symmetrical non-parametric (free form) object.
- Experiment 4.1.3: Reverse Engineering of complex symmetrical free form object.
- Experiment 4.1.4: Reverse Engineering of complex non-symmetric free form object.
- Experiment 4.1.5: Reverse Engineering of complex parametric object requiring multiple set ups.

Extending beyond these typical applications we research on the type of applications that need minor change/addition to the equipment to perform more complex projects. The experiments conducted to demonstrate this capability are.

- Experiment 4.2.2: Use of non-standard probes for reverse engineering applications.
- Experiment 4.2.3: Use of Laser Probe for non-contact reverse engineering applications.

Further a comparative study (Experiment 4.3.4) was conducted on Aesthetic Engineering applications to show the advantages of using portable CMM for artistic applications. The digitizing and post processing times involved will be analyzed and recommendations to made to serve as guidelines to select the appropriate tool based on the application at hand. We also explore the methodology of creating 3D CAD models from 2D images in the future research section. Other CAD models developed through these reverse engineering experiments are tabled in Appendix: A. Appendix: B provided helpful reverse engineering tips for a PCMM user based on the lessons learned in the course of the study.
CHAPTER FOUR: DEMONSTRATIVE EXPERIMENTS

4.1 Versatility of Portable CMM

4.1.1 Reverse Engineering of a parametric object.

4.1.1.1 Introduction

The objective of this exercise is to demonstrate the basic steps of reverse engineering. The part used in this experiment is simple parametric object; We will proceed to more complex parts in the further exercises.

![Figure 24: The Flange in the assembly](image)

The part chosen in this experiment is a flange in a boat engine subassembly. The part was chosen because of its simple nature and parametric shape.
This is a good example for reverse engineering using portable CMM because the PCMM can be taken to the object rather than bringing the object to the CMM. One important thing about the part is that because of the position of the flange in the assembly, it would be impossible for a three axis CMM to digitize this part to recreate it as CAD model.

4.1.1.2 Methods and Materials

_Hardware:_ Faro 8 ft Sterling Arm.

_Software used:_ Cam2Design®, Rhinoceros®, Flamingo®

_Probes:_ Standard Point Probe

The part was mounted on the table and fixed with clamps to prevent any movement. The point probe was calibrated and checked for accuracy using the documented procedure [FARO Technologies, Inc.].
The point probe was selected for this object because of the smaller size of the holes in the object. Detailed guidelines on probe selection and calibration are given in Appendix: B. The first step in the reverse engineering process is to define a plane. [It is important to define the term digitizing at this stage. Digitizing is the ‘digital capturing’ of a point or feature in 3D space using the PCMM.] The plane is defined by digitizing at least four points the part that we measure. Then we can create an alignment with our selected features this helps a great deal in complex parts but for this simple part this step is skipped. The next step is to digitize the outer diameter of the flange. This is done using the circle command, which fits the digitized points in the circle. At least three points are required to define the circle, the more points we measure the more accurate the representation of the circle is. Then we measure all the smaller circles. The thickness of the flange was manually measured using calipers to expedite the reverse engineering exercise. Fig 27 shows the measured features of the flange.
The file was then exported to Rhinoceros software and modeled as 3D object (Figure 28).

Figure 27: Measurements in CAM2Measure

Figure 28: Solid modeling using Rhino
4.1.1.3 Results

The CAD file was exported into CNC software and a replica built using a CNC machine.

Figure 30: Reverse Engineered Flange to work as a plug.
4.1.1.4 Discussion

From this simple exercise we can understand the process of reverse engineering and the use of PCMM in achieving this. As seen in the experiment the flange need not be disassembled and to perform the reverse engineering exercise such versatility if rare in other RE tools. We have gone through the reverse engineering cycle of going from object to CAD using limited digitizing and then replicating back to modified object. We will keep increasing the complexity of parts as we go through the exercises. Based on the part the tools and techniques will vary but the basic process followed is the same.
4.1.2 Reverse Engineering of Symmetric Non Parametric Object.

4.1.2.1 Introduction

The objective of this exercise is to demonstrate the process of reverse engineering of a non-parametric object i.e., with no geometric features like circles, cones among others. The following exercise will demonstrate this by reverse engineering ceramic parts, which are used as pottery. The parts chosen for this are relatively simple, but are non-parametric in nature.

As shown above, seven parts are chosen for reverse engineering with the objective to get CAD file of these parts. The parts will not be recreated physically again in this experiment.
4.1.2.2 Methods and Materials

*Hardware*: Faro 8 ft Sterling Arm.

*Software used*: Rhinoceros®, Flamingo®

*Probes*: Standard Point Probe

The Rhinoceros® Software is chosen for this exercise as it gives a better visual aid for the objects and since the object does not require a ball probe (Third party software like Rhino® does account for the probe compensation). If a ball probe is chosen for digitizing through Rhinoceros® software the probe is to be compensated by offsetting the digitized feature.

The basic technique that will be followed will be to trace the profile of the cross section curve and then revolve the closed curve to get a solid object. In this case an alignment will be needed because for most of the parts we have to flip the part to obtain the full cross section curve.

To make the process of digitizing easier a profile curve was drawn manually on the object using a marker and then the digitizing using the curve as the reference. Since the parts used in this exercise need realignment during the reverse engineering process, we have to first measure alignment features, any inbuilt features available in the part should be preferred first. In the event that no particular features exist, we can mark three points and use them as alignment features. The three features must be farther apart to get a accurate realignment. It is better to have them in an approximate triangular orientation. Rhinoceros® software only accepts three alignment features, so it is not necessary to have more than three features, in the event of using other software like CAM2Design®, more than three features may be used.
The following figures 32, 33 show the setup of the exercise.

Figure 32: Set up for Reverse Engineering

Figure 33: Digitizing of Ceramic part
Figure 34: Digitizing the profile curve

Figure 35 shows the points taken in the curve drawn on the part. The spacing between successive digitized points is based on the complexity of the part. Once the profile curve is digitized it can be revolved either using a circular feature that the object has or by drawing a separate curve. Two setups were needed to complete the digitization. The Figure 36 shows the profile curve and the circle. At the post processing stage the curve is swept along the circle as the rail curve, the resultant CAD model is shown in Figure 36. It is important for the profile curve to extend till the center of the circle, failure to do so will require additional digitization or extending the curve being ‘extend curve’ command in the software.
Figure 35: Profile Curve of a Ceramic part.

Figure 36: CAD model after sweep command.
4.1.2.3 Results

Thus the CAD model of the ceramic part was created. The rendered model of the above part is show in Figure 37.

![Figure 37: Rendered Image of the Ceramic Part](image)

4.1.2.4 Discussion

The seven ceramic parts were reverse engineered to produce CAD drawings using a simple reverse engineering technique. Only the critical profile curve was digitized and the CAD model created by using the ‘sweep command’ of the CAD software. The difference between the experiment 4.1.1 and 4.1.2 was that the object defined in 4.1.2 does not have geometrically defined structure. Reverse engineering of such object using typical hand tools could be difficult task, but the versatility of the PCMM combined with the symmetrical nature of the project reduced the reverse engineering cycle time considerably.
4.1.3 Reverse Engineering of Complex Non Parametric Object.

4.1.3.1 Introduction

The objective of this experiment is to reverse engineer a complex non-parametric model. In this case the object chosen was a model of a rooster shown in Figure 38. This object is a free form complex non-parametric shape. It has symmetrical features and cannot be reverse engineered by simply digitizing some of the features like we did in experiment 4.1.2, but each feature should be digitized and hence the digitizing time is going to more than that of the previous experiment.

Figure 38: Rooster Model
4.1.3.2 Methods and Materials

**Hardware:** Faro 8 ft Sterling Arm

**Software used:** Rhinoceros®, Flamingo®

**Probes:** Standard Point Probe

The point probe is being used in this experiment to trace the sharp edges present in the object. Rhinoceros software was selected because of the ease of use when digitizing non-parametric objects. Each of the critical curves necessary to replicate the general shape of the object was digitized. Some of features like the eyes were directly drawn on CAD since reproducing the small feature was found to be a difficult task for a PCMM; since this is an object of aesthetic nature these deviations are allowable. The command used to digitize the curves was ‘interpolate points’ command from the Rhinoceros software.

After all the curves have been digitized (Figure 39) the next step was to create the surfaces. Since there are no planar features, surfaces were created using the edge curves. In many cases some of the curves needed were digitized again based on the need for post processing. ‘Sweep rails’ command was heavily used in creating the surfaces on the body of the rooster. Different surfaces were merged to create a closed polysurface as shown in Figure 40.
Figure 39: Rooster Model – Digitized Curves

Figure 40: Rooster Model – Surfaces
4.1.3.3 Results

Thus the rooster model was reverse engineered using the PCMM and Rhinoceros® software. The eyes and the base were directly created during post processing. This is one of the advantages of reverse engineering that the user is able to make changes to the original object. The file was then verified for any incomplete surfaces with holes and then rendered using the flamingo® plug in of the Rhinoceros software. The Figure 41 below shows a rendered image.

![Figure 41: Rooster Model – Rendered View](image-url)
4.1.3.4 Discussion

The object in this experiment was a fairly complicated part. But even though the features were non-parametric the intricacies in the part were less than the object used in experiment 4.1.2. The smoothness of the surface and the accuracy cannot be verified since there is no CAD drawing, however the virtual replica is believed to be aesthetically acceptable. We will select a more intricate aesthetic model and proceed with our experimentation in demonstrating the versatility of reverse engineering application of PCMM.
4.1.4 Reverse Engineering of complex non-parametric object –II.

4.1.4.1 Introduction

The objective of this experiment is to reverse engineer a complex aesthetic model using manual digitizing with portable CMM. The object selected is shown in Figure 42.

As we can see the part shown is very complex with lot of non-parametric curves, which do not follow particular form or function. Hence the reverse engineering technique needs to be compatible with the level of complexity of the part. Arguably this object can be reverse engineered more efficiently using non-contact methods, but the objective of this experiment is to demonstrate the versatility of PCMM in such complex applications.
4.1.4.2 Methods and Materials

Hardware: Faro 8 ft Sterling Arm, Vernier Calipers

Software used: Rhinoceros®, Flamingo®

Probes: Standard Point Probe

The standard point probe is used in this case as well; to avoid issues with probe compensation moreover the thin edges in the part can be effectively digitized only with the help of a point probe. All the edges, which are to be digitized, were marked with a thin blue marker in this case for easy digitizing. Figure 43 shows the part being digitized.

![Aesthetic model being reverse digitized.](image)

Figure 43: Aesthetic model being reverse digitized.

It is important for individual curves that the points digitized to be as close of possible, otherwise these will be approximated during the post processing stage and can lead to
inaccuracies. This object cannot be digitized by capturing just one curve like we did with the other. But since the object is symmetrical we can only digitize half of the model and replicate the other half using mirror command.

![Figure 44: One-Half of the Curves digitized](image)

As we can see in Figure 44 only one half of the curves were digitized and the rest of the curves will be replicated using the mirror command. Planning the Reverse Engineering Project based on the needs can yield timesavings like this one. A temporary line was drawn at the center of the drawing to aid mirroring. Thus all the critical curves in the object are being reverse engineered.

The Figure 45 shows the drawing after mirroring of one half of the curves. The figure also shows the three alignment (used to realign the part/device in different orientations) points
used. Note that the orientation of the three points is in the shape of an approximate triangle. Even though the part does not need a realignment, alignment features where measured because of the complex nature of the part, since any accidental movement of part or object could result in the situation of having to start with the project again from ground zero.

Figure 45: Mirrored Curves with alignment points

The next step in the experiment will be to create the surfaces. This was mostly done using ‘rail revolve’ commands of the CAD software. The control points in the curves were adjusted wherever necessary to obtain a smooth curve. Since the outer rectangular envelope is not a
critical part of the object in hand, this was manually measured and recreated in CAD. After all the surfaces were created the resultant CAD model shown in Figure 46

![Figure 46: Surfaces created from curves](image)

Thus we can see that we have created all the surfaces necessary to reproduce the object, since the object is very complex the post processing time taken was much higher than the previous experiments. The ‘drape command’ was used to make a smooth surface over the top of this surface model. This command will also produce a flat base on which these surfaces are present. This would expedite the process of post processing. The outer envelope was created and
extruded to meet with the current draped surface. Thus a final CAD model of the object was obtained. Figure 47 below shows the CAD model of the object.

![Figure 47: Aesthetic Model – CAD model](image)

One of the benefits of reverse engineering is that the object can be manipulated and modified after we have a CAD file. This is now a solid surface, which can be physically recreated using any prototyping or manufacturing techniques.

**4.1.4.3 Results**

Thus the aesthetic model was reverse engineered using the PCMM; this was a fairly complex object and was reverse engineered in a single set up without moving the position of the
part or the PCMM. Some of the popular CAD techniques like “mirror” command and array command were used to make the digitizing and the post processing process faster. Figure 49 shows the rendered image of the object.

![Rendered Image of the aesthetic model](image)

**Figure 48: Rendered Image of the aesthetic model**

### 4.1.4.4 Discussion

One of the things that made the project easier or not so complex is the fact that the entire set up was completed in one set up and we did not have to move the part from one setting. Also in this experiment we saw that the entire digitizing was done in one software. But there are some cases where we might have to do the digitizing in more than one software. We will see this case in the next experiment. We have to remember that the change in software will also require realignment.
4.1.5 Reverse Engineering of a Complex Parametric Object.

4.1.5.1 Introduction

The objective of this experiment is to demonstrate the most widely used application of reverse engineering – Industrial Reverse Engineering. Its common practice in the industry to reverse engineering parts that do not have a drawing using tools like CMM and hence obtaining a CAD drawing. The object selected for this exercise is an automobile compressor clutch which has a lot of intricate features. Figure 49 shows rendered images of the clutch showing the complexity of the parts.

Figure 49: A/C Compressor Clutch.


4.1.5.2 Methods and Materials

**Hardware:** Faro 8 ft Sterling Arm.

**Software used:** Rhinoceros®, Flamingo®

**Probes:** Standard Point Probe, 0.25” Ball Probe

The various steps involved in the reverse engineering of the part are

- The part was clamped in the table in the upright position. It is important to clamp the part in such a way that the position of the clamps does not interfere with the digitizing of the part.

- This part requires at least two orientations; the next orientation will need the part to be clamped in the upside down position with the spiral part faced up.

- The alignment features are marked with a marker; geometric features present in the object are to be preferred against markings made. In this case since the geometric features are not accessible from both orientations, so markings were made using a permanent marker. Care was taken to make the points small and precise, the center of the point will be considered as a reference point. The center of the point was marked with the help of the dot punch (marking tool). Hence we would digitize the exact same point each time we digitize it from different orientations.

- The Cam2Design® software is invoked. The first step after opening the software is to check for the probe selection. It must be confirmed each time before digitizing that the actual probe present is the one selected in the software. The probe is secured well and
then calibrated. The calibration error must be verified to be below the recommended specification (0.006).

- First step will be to measure the alignment features to be used in realignment. The realignment in Cam2Design® software is called the Leapfrog® technique. It is important to label the three alignment features, as they will be measured again.

- Start by measuring all the necessary planes. Each Plane is measured by taking at least three points. Measure all circles and their respective planes. Figure 50 shows the digitized circles and planes.

Figure 50: Digitized Planes and Circles
The next step will be to digitize the top portion. This is done with the help of the ball probe. The setting in the probe dialogue is changed to and the ball probe calibrated to specification. This is done using 3D freehand scan commands. The ball probe is chosen against the point probe because it can easily slide around the boss of the object with contact to the probe such would not be possible using the point probe. Digitized curves will be compensated for the radius of the probe at the post processing stage. Figure 51 shows the digitized curve.

![Figure 51: The Curve digitized without compensation.](image)

Figure 51 also shows the alignment points being highlighted. The three alignment features are in approximate triangular orientation to give a better realignment.
The next step will be to realign the part and trace the spiral part of the object. The object is flipped and clamped in the reverse position. The leapfrog command is now used; the software prompts us to measure the same features in the same order. Once the leapfrog is completed, the software gives the error associated with the alignment. It was verified to be an acceptable error (0.0003).

Now any circles or other parametric features that can be measured using the point probe are measured first.

The point probe is replaced by the ball probe, calibrated and used to digitize the spiral portion. Digitization is done using the same technique by sliding the ball probe on the object.

Figure 52: The Digitized Spiral Curve
- Next the slot in the spiral part was digitized using the point probe. (the ball probe cannot reach it).
- The bottom plane of the slot was measured as a reference for the depth of the slot.
- Now there are some parts, which cannot be digitized by sliding. These can be either digitized as points in Cam2Design® or as a curve using the interpolate points command in Rhino®.
- The CAD file was opened in Rhino®. It is important to realign the features now. When we use connect digitizer command the software prompts us to measure three reference points as the origin, x-axis and y-axis, the three alignment points must be measured during this prompts. Then upon prompt we select the three points in the same order to facilitate realignment.
- Any required features, which can be easily measured by hand tools, are measured at this point. The post processing stage now starts by creating the necessary features. One of the first steps involved in post processing of this part is to compensate for the curves digitized using the ball probe. The offset curve command is used to achieve this. The Value of offset is equal to the radius of the ball probe (.125”).
- Surfaces are created and then extruded to form polysurfaces wherever necessary. The Boolean difference command was used to create slots and holes in this project. The completed surface model is shown in the Figure 53.
Figure 53: Surface model of the Compressor Clutch

The actual uncompensated curve can also be seen in Figure 54. Once the post processing is completed the integrity of the file must be verified. This step is more important when the file is going to be prototyped using a rapid prototyping machine. In this case we must ensure that we have a “watertight” model. Going back to the experiment 4.1.4 the drape command would possible have removed any holes in the object. But in this case it has to be done by verifying that each polysurface is a closed polysurface and not an open polysurface; these methods are explained in the Appendix B as well. The next step would be to do the dimensioning of the
model. This can be done using the software. The Three views with dimensioning are shown below in Figure 54, 55 and 56.

![Figure 54: Dimensions of the Clutch – Top View](image)

![Figure 55: Dimensions of the Clutch – Front View](image)
Figure 56: Dimensions of the Clutch – Side View

Figure 57: Clutch – Rendered View
4.1.5.3 Results

Thus the Clutches were reverse engineered to obtain accurate CAD data. This can now be used to recreate them physically either by using prototyping or manufacturing techniques. With the CAD file now in hand any modifications desired can also be done. Figure 58 shows rendered image of a similar reverse engineered clutch.

![Clutch 2– Rendered View](image)

*Figure 58: Clutch 2– Rendered View*

The rendering of the CAD drawing is done using the Flamingo® module of the Rhinoceros® software. There is an extensive library of materials available for us to choose from; lighting and animation options are also available.
4.1.5.4 Discussion

In this experiment we have seen a much more complicated case of reverse engineering than the above experiments. Even though the features were mostly parametric the orientation and complexity of the features made this exercise of reverse engineering a challenging effort. This was a real case of project done for a local manufacturing company. The accuracy of the CAD files was assessed by the company and was acknowledged as excellent. The actual numerical data was not provided. Now that we have seen the reverse engineering experiments let us move on to other complex cases, where the current set up of hardware was found insufficient. Is another hardware supposed to be used? Or is it necessary to make changes to the equipment, in this case PCMM to make the machine versatile? We will discuss these issues in the forthcoming section.

4.2 Customization of Portable CMM

4.2.1 Need for Customization

Portable CMM’s were evolved as a result of difficulties faced in measuring certain complex and large parts using normal gantry type CMM. The single biggest advantage of these CMM’s is that they are portable. They also come with at least six joints and hence it can handle more complex objects than the fixed CMM, which has mostly 3 axes.

However the widespread use of the portable CMM started exposing need for improvements for situations like.
- Unreachable complex parts where the hard probe cannot reach.
- Complex non-parametric shapes where large number of points needs to be digitized and where manual digitizing became tedious or infeasible.

Only a small change or addition to the equipment was needed to overcome such challenges. We will look at two such modifications that were made and their contribution to the reverse engineering applications. The two cases of customizations that will be researched in this section are

- Custom probes which are designed for specific objects, which would reach the complex features of objects.
- Optical probes that work using the optical triangulation principle, made both dimensional measurements and reverse engineering applications much easier.

For both these customizations, the original six axes PCMM was considered insufficient. Because of the following reasons.

- For probes, which were curved or angled, with the six axes it was not possible to orient the probe in a particular direction from different directions.
- The laser probe required a perpendicular orientation from the object scanned always this could not be maintained when scanning from different directions.

To solve these problems a seven axes portable CMM was used and customizations became much easier. Both non-standard probes and laser probes are compatible only with a 7 axis FARO PCMM. The figure below shows a 7 axis Faro Arm.
Some of the existing non-standard probes are shown below

- Shown below is a curved probe, it has a ball end and this can be used to digitize the tight areas, which cannot be digitized with a normal probe.
• This is a long probe, which can reach depths that cannot be reached by the normal probe. Since there are no angles and curves this can be used in a six axis PCMM.

![Long Probe](image1)

**Figure 61: Long Probe [Courtesy: Faro Technologies Inc]**

• The head of this probe is in the form of a swivel edge and this probe enables measuring of sharp and thin edges.

![Swivel Edge Probe](image2)

**Figure 62: Swivel Edge Probe [Courtesy: Faro Technologies Inc]**

• This probe is custom made for measuring 1/2" spheres. The tip is in the form of a cone instead of sphere.
Figure 63: ½”Cone Probe [Courtesy: Faro Technologies Inc]

This probe is designed to capture dimensional data in places too small for a probe extension; this 50 mm long probe features a small 6.35 mm shaft with a 3mm diameter ruby probe at a 90-degree angle. [www.faro.com].

Figure 64: 90 deg angle Probe [Courtesy: Faro Technologies Inc]

- This probe can measure regions, which are not reached because of the angular location. It has a carbide steel point probe with a solid 4" extension and a 60-degree bend.
• This probe is used to make marks for drilling at exact locations. It has a center punch located at its end, which is spring activated.

• This touch probe is widely used in three axes CMM’s. It digitizes points as soon as soon as it comes into contact with the object, this is helpful in digitizing flexible objects.
Figure 67: Touch trigger Probe [Courtesy: Faro Technologies Inc].

- Figure 68 shows a Laser point probe and is used in taking points where the surface is soft and can be deformed by physical touch. This works by the principle of laser triangulation.

Figure 68: Laser Point Probe [Courtesy: Romer Inc].
• Figure 69 shows a laser line probe, which is now being used widely for reverse engineering applications.

![Laser Line Probe](image)

**Figure 69: Laser Line Probe [Courtesy: Faro Technologies Inc].**

### 4.2.1.1 Customization of PCMM for Reverse Engineering

The different types of nonstandard and optical probes used were discussed in the previous section. The use of such customizations in reverse engineering applications will be discussed now. The experiments to demonstrate this will be focused on the use of a long straight probe to digitize a complex part which cannot be reached by a normal probe and an aesthetic model free form model which cannot be effectively digitized with a contact probe.
4.2.2 Reverse Engineering of a complex object using a long non standard probe

4.2.2.1 Introduction

In this experiment we will research the feasibility of reverse engineering a complex turbine blade using the PCMM. The reason for choosing this object is that a standard probe will not reach into the blades of the turbine and hence a longer non-standard probe was used during the experiment. The use of an angled probe was not considered since the experiments were performed on a six axes PCMM, such probes could be easily used with a seven axis PCMM. [Appendix: A explains the reasons for incompatibility of laser and curved probes with the six-axis arm configuration]. Figure 70 shows the turbine blade selected for the experiment.

Figure 70: Turbine Blade
4.2.2.2 Methods and Materials

*Hardware:* Faro 8 ft Sterling Arm.

*Software used:* Rhinoceros®, Flamingo®, Cam2Design®

*Probes:* Standard Point Probe, 0.25” Ball Probe, 4” extension straight probe

![Probes](image)

**Figure 71: Probes used for reverse engineering turbine blade**

Figure 71 shows the set up for the experiment. Once again since this is being a parametric object; many CAD techniques can be used to expedite the reverse engineering process. In this case, only one of the blades can be reverse engineered and the rest can be replicated through the circular array command.

- As with the other experiments the first step is to calibrate the probe that is to be used and hence the ball probe was calibrated first. One of the advantages of ball probe is that it makes the use measurement of lower surfaces easier.
The Cam2® software was used for the entire digitizing cycle since the other third party software does not support the calibration process.

The nonstandard longer probe was then calibrated. The calibration process is the same as that of the other probes.

![Image: Digitizing of the turbine wheel using non-standard probe](image)

**Figure 72: digitizing of the turbine wheel using non-standard probe**

The three realignment features were measured as this part requires four different orientations due to the complexity of the part. Figure 72 and 73 shows the part being measured with the non-standard probe.

The important planes were measured and the circles on the each of the planes were measured as well. The boundaries of the turbine blades were measured as lines and the blade itself is to be measured as points. In the post processing stage these points will be made into a spline.
Figure 73: Reverse Engineering the blade

Figure 74: The Captured Digital CAD Data of the turbine
First a single curve was digitized using the 3D Scan command in the CAM2 Software. Figure 74 shows the digitized curve.

The CAD file was then imported to Rhino® software where the post processing step begins.

The first step in the post processing is to come up with one complete blade; this is done by rotating a single blade curve till the blade boundary line.

Once a complete blade was formed the other six blades were replicated using the circular array command.

The surfaces of the blades were created using the two rail sweep command.
The other planar surfaces were formed from surface from planar curve command.

### 4.2.2.3 Results

Thus a completed CAD file was produced after the post processing stage; the Figure 76 shows the four views of the completed drawing.

![Figure 76: Reverse Engineered virtual replicate of the turbine blade](image)

### 4.2.2.4 Discussion

In this experiment one of the possible customization options was used to reverse engineer a complex object, which could not be digitized using the standard PCMM set up. There are a lot of non-standard probes available; moreover a probe can be designed for customized use for the
particular object as well. If a custom probe was designed for a PCMM, the accuracy of the measurement depends on the end effector’s design and material used. If the tip is not a point or ball, it cannot be calibrated using any of the standard calibration techniques, and a compensation length is to be entered in the software. This adjustment length will be the difference between a standard ball probe and the current custom probe.

In certain situations the object may call for non-contact measurement techniques like the laser scanning technique. In those situations the PCMM can be augmented with a laser scanner attachment to effectively digitize parts. One such case will be demonstrated in the next experiment.

4.2.3 Reverse Engineering of a plaster angel model using a Laser Scanner attachment

4.2.3.1 Introduction

In this experiment the model shown in Figure 78 is to be reverse engineered and reproduced using rapid prototyping technique. This experiment will show us the strong relationship between rapid prototyping techniques and reverse engineering techniques. The use of point cloud manipulation software will also be discussed in this experiment.
As shown in the above picture the model has many freeform non-parametric shapes which make the selection of a laser attachment appropriate. Also since the surface of the object is light colored it easily reflects the laser light and aids the data capture process. If the surface is dark colored it must be sprayed with a dissolvable reflective coating.

4.2.3.2 Methods and Materials

Hardware: Faro 8 ft platinum faro arm, 3Dsystems Thermojet Solid Object printer

Software used: Geomagic Qualify®, Rapid Form®, Pixform

Probes: Faro Laser Scanner Probe.
As with the other experiments the first step would be to calibrate the probe. The hard probe is first calibrated with a standard technique. The laser probe calibration is different from the calibration of a hard probe. The laser scanner scans a white sphere from different orientations to calibrate the laser scanner probe. The calibration determines the position of the laser plane in the CCD (Charge Coupled Device) camera; It is important for us to calibrate the hard probe first because the position of the laser scanner itself is dependent on the hard probe calibration values.
and hence any error in the arm configuration is multiplied into the accuracy of the point cloud data scanned by the laser scanner. The following pictures (Figure 79 and 80) illustrate the laser scanner probe calibration. As the next step the laser exposure is set; this feature assigns a particular exposure based on the object that is being scanned.

Figure 79: Laser Scanner Probe Calibration
The first step in the laser scanning experiment is to decide on the part orientation. A proper orientation from which most of the prominent features can be digitized is selected first. In this case more than one scan is probably not needed. In this experiment another scan is still made to demonstrate the merging of multiple point clouds. The second scan will have an overlapping region over the first scan, as this is required to merge the two scans. However it is important not to have a more than necessary overlap as each merge will account for a certain loss in accuracy and in this case as the overlap increases the loss of accuracy increases. Figure 82 shows the object being scanned using the faro arm.

Figure 80: Different orientations of laser probe during scanning
After scanning the part in the top orientation, the part is flipped and scanned in the other side. In this case the outer square envelope acts as a common overlap between the two scans. We will see how the two scans are being aligned in the post processing stage. Due to the nature of the part it could also be partially scanned in just one orientation since the bottom surface is just a flat surface with no specific features. This can be later filled in with a ‘flat hole fill’ command. The figures on the following page show the point clouds that were captured. These two point clouds will then be imported to the Rapidform Software where they will be merged. It is important to note that the scanner also picked up the surface of the object in which the model was placed. However the quality of the scans in those regions is not as good, since the laser exposure has been set to the object material type.
Figure 82: Scanned Point Cloud in the first orientation

Figure 83: Scanned Point Cloud in the second orientation
The post processing step begins when the two point clouds are imported to Rapidform® software. Three common points are chosen from the two point clouds to merge the point clouds. This is done through the help of the register command. The following figure shows the point clouds after registering. The holes are filled using curved or flat methods. The holes, which cannot be filled automatically, are smoothened by cleaning the boundary and filled in after that. Smoothing is done to make the surfaces smoother.

![Point cloud – angel model](image)

**Figure 84: Point cloud – angel model**

Even though the figure above looks like a nice rendered image it is just a ‘cloud’ of points. The surfaces are made from the model using the auto surface command. This follows the methods of adaptive triangulation, where more surfaces are created in complex regions and flat
single surfaces in flat regions. In this case the back face of the model will have fewer surfaces and the more complicated front surface will have more surfaces.

The point cloud with the surfaces superimposed on it is shown in the Figure 85. The number of surfaces can be adjusted based on the complexity of the part. In our experiment 200 surfaces were used to create the CAD model. This surface model has discrete surfaces; these are then merged to one surface in the CAD package. This file was then imported as a STL (Standard Triangulated Language) file and was built in a rapid prototyping machine. The machine used was Thermo jet 3D printer with wax as the build material. One of the advantages of using wax in such applications is that the object can further be replicated in metal using the investment casting or the lost wax technique.

Figure 85: Surfaces Superimposed on point clouds
4.2.3.3 Results

Thus we can see that the complex angel model was reverse engineered using the laser scanner attachment of the portable CMM. Two different software were used in this experiment Geomagic® Qualify which acted as an interface for the digitizing stage and Rapidform® which was used to perform the post processing. A STL file was used to create the rapid prototyped model. The rapid prototyping was done using Thermojet - a Solid Object Printer. The Figure 86 shows the actual and the rapid prototyped model.

![Figure 86: The actual and rapid prototyped models.](image-url)
4.2.3.4 Discussion

This experiment was different from the other experiments in the sense that the reverse engineering was done without physical contact with the part and that large amount of points were digitized to create the object. This may seem to be a highly accurate method but nevertheless has shortcomings like

- Position of the scanner with respect to object (it must be perpendicular to achieve greater accuracy.
- Material needs to be reflective.
- Merging of two different point clouds also contributes to the inaccuracy.

Even with these challenges the laser scanning technique is being widely used by the industry especially for non-parametric shapes.

4.3 Aesthetic Engineering

4.3.1 Background of Aesthetic Engineering

Industry professionals for new product development and other technical applications typically use reverse Engineering techniques. Other applications of reverse engineering have been largely left unexplored. One such area is the use of reverse engineering in architectural ornamentation and jewelry design, or ‘Aesthetic engineering’ [Thiraviam, 2004].
There are varieties of techniques used for 3D reverse engineering, however for the purpose of this thesis the discussion is limited to the two major technologies that can be used for digitizing of free form designs, namely:

- Portable Coordinate Measuring Machine (PCMM)
- Stand Alone Laser Scanning Systems (SALSS)

In this section we will overview the technologies that make aesthetic engineering (AE) feasible and discuss the relative advantages and disadvantages of PCMM and SALSS. In addition we will also create a framework for aesthetic engineering.

### 4.3.2 Aesthetic Engineering through the use of PCMM

The integration of computers and the Coordinate Measurement Machines (CMM) made it feasible for us to accurately represent objects in 3D by digitizing points using touch probe. However, typical gantry type CMM’s are constrained by their degrees of freedom which is limited to three axes. Also the size of the object, which can be measured, was limited to the work envelope of the CMM. The portable CMM came as a boon to the industry by solving these limitations. Portable CMM’s that we refer to it here are of the articulated measurement arm type.

These machines resemble a robotic arm. Typically it has 6 – 7 axes and thus can “move” freely in space in a way that would enable reaching and capturing point coordinates of complex surfaces, which are normally difficult or impossible to obtain from normal CMM’s. Since it is portable the size of the object that can be measured is unlimited.
The technique of reverse engineering was already discussed in detail in the previous section. The aesthetic models reverse engineered are reviewed here. [Table 1, 2 & 3]

**Table 1: Aesthetic Engineering of a jewellery model**

<table>
<thead>
<tr>
<th>Plaster Mold</th>
<th>Digitizing</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Plaster Mold" /></td>
<td><img src="image2.png" alt="Digitizing" /></td>
</tr>
<tr>
<td><img src="image3.png" alt="CAD data" /></td>
<td><img src="image4.png" alt="Rendered Image" /></td>
</tr>
</tbody>
</table>

Table 1 shows that aesthetic engineering can be performed even with a standard touch probe when sophisticated non-contact scanners are unavailable or where the cost is not justifiable. The model was digitized with ease with the faro arm, imported to Rhino Software and
then post processed to produce a CAD file. Also the model was scaled down and represented as a ring.

Table 2: Aesthetic Engineering – Rooster Model

<table>
<thead>
<tr>
<th>Plaster model</th>
<th>CAD data</th>
</tr>
</thead>
<tbody>
<tr>
<td>NURBS surfaces</td>
<td>Rendered Image</td>
</tr>
</tbody>
</table>

Table 2 shows a similar object with aesthetic features and was reverse engineered with a contact point probe.
In this experiment the model was scanned using the laser scanner attachment of the PCMM. This method brought into light the advantages of the non-contact measuring technique. Two point clouds were obtained after digitizing. An extensive post-processing followed this, creating a surface model from the point cloud. This could then be imported into any of the compatible formats for rapid prototyping or computer integrated manufacturing.
4.3.3 Aesthetic Engineering through the use of Stand Alone Laser Scanning systems.

Laser Scanning is another technology that is used to capture the digital shape of the objects by non-contact methods. It is based on the principle of Laser triangulation.

Figure 87: Laser Triangulation –(NDT Handbook, 2003)

In this method the laser from the laser source is focused by help of a focusing lens and hits the target surface and is reflected back to a imaging lens and then to a photo detector. Charge coupled devices are typically used as photo detectors. Thus the laser scanning systems employ laser triangulation to accurately capture data points from any complex surface.

In some cases the laser light after being focused is converted into a line by the help of light sectioning. Cylindrical lenses are typically used for this purpose. The data obtained from the laser scanner is in the form of ‘point cloud’. This has to be now exported in to any point
cloud manipulating software to create the surfaces. Typically we would require multiple scans to cover the entire geometry of the object to be scanned.

Sometimes simultaneous digitizing with laser scanning systems and contact methods need to employed to get the efficient results. Surfaces can then be created and exported to any required form for manufacturing or prototyping.

There are several stand-alone laser scanner systems available in industry, and equipments is selected based on the nature of application. An experiment was conducted to reverse engineer the aesthetic angel model using a stand-alone laser scanner. A Roland Picza 3D Laser Scanner was selected. Section 4.3.4 details the experimentation, which scanned the angel model previously used in experiment 4.17.

Figure 88: Stand Alone Laser Scanner [Courtesy: www.rolanddga.com]
4.3.4 Reverse Engineering of a plaster angel model using a Stand Alone Laser Scanner

4.3.4.1 Introduction

In this experiment the angel-model will be reverse engineered using the Roland Picza scanner. This is a stand-alone type scanner and works based on the principle of laser triangulation. The figure below shows the operation. The ultimate objective of this experiment is to compare the relative advantages and disadvantages of using PCMM versus Stand-alone Laser Scanner like the picza scanner.

![Laser Scanning Using Picza Scanner](image)

**Figure 89: Laser Scanning Using Picza Scanner [Courtesy: Roland DGA Inc].**

As shown in Figure 89 the object is placed on the rotating table in the scanning chamber. The laser beam is fixed and the rotating table helps maintain the perpendicularity between the laser beam and the object. Unlike the Laser Scanner attachment of the PCMM the laser source is a point light. Since the laser is fixed the object requires more extensive preprocessing to prepare the object.
4.3.4.2 Methods and Materials

*Hardware*: Roland Picza Laser Scanner – LPX 250

*Software used*: Dr.Picza®, Pixform®

As mentioned earlier, reverse engineering using stand alone laser scanning systems require more extensive preprocessing where the object is prepared for scanning, frequently the object is painted with a dissolvable white coating to aid reflectivity. The angel model being made of a white plaster material does not need such preparation. The next step would be to mount the object on the rotating table using modeling clay. Clamping the part with supports prevents the object from moving during the rotational motion of the table. The modeling clay is also scanned in the process, but later this is removed from the original scan at the post processing stage. Figure 91 shows the model mounted on the rotary table.

*Figure 90: Picza Scanner with the Angel – Model*
There are various settings to be specified in the Dr.Picza Software before the scanning begins they are shown in the Figure 92. This part was scanned in ‘plane scanning mode’ with 4
different scans since the entire geometry cannot be scanned in one scan. There are four different point clouds produced as a result. But they are automatically registered since they are scanned from the same orientation. Figure 96 shows the point cloud of the scanned object.

![Figure 93: Point Cloud of angel model](image)

As shown in Figure 93 the clay model used to mount the model was also scanned. These parts are to be removed in post processing. The post processing starts as the point cloud is imported to the pixform software. First the noise is filtered based on the value of 0.01 inch. Any point which is more than 0.01 inch from the nearest adjacent point will be removed. The regions needing more scans will be evident after this step. The part is set up on the rotating table again for making another scan. The new scan is then imported to pixform, it is important that these two point clouds have overlapping areas. The two point clouds are registered into one shell by picking three of points in the overlapping area. After the holes are filled using a hole fill
command the surfaces are created using ‘auto surfacing’ command, which is available in pixform.

**4.3.4.3 Results**

Thus the angel model was reverse engineered successfully using the picza scanner. The resultant surface model is shown in Figure 94.

![Figure 94: Angel – Surface model](image)
4.3.4.4 Discussion

In this experiment we have seen the process of reverse engineering using a stand-alone laser scanner. There were some additional steps involved in this like the preprocessing. This is common in other scanning techniques including the PCMM however due to the nature of the part used preprocessing was minimum during the experimentation in PCMM. Thus we have demonstrated the aesthetic engineering using a desktop laser scanner. In the next section we will compare the two methods and highlight the advantages and disadvantages.

4.3.5 Comparison of PCMM and SALSS for Aesthetic Engineering Applications

The technique of aesthetic engineering was demonstrated in the previous section. The relative advantages of PCMM and SALSS in aesthetic engineering will be discussed in this section. The comparisons are made between both systems. Some of the important criteria, which will be used in the study, are

- Preprocessing
- Digitizing Time
- Post Processing
- Accuracy of the models.

4.3.5.1 Preprocessing

Preprocessing is the step before the actual digitizing begins; all activities that help us prepare the part and the equipment falls under this category. This includes mounting the part, probe calibration among others.
Pre-Processing in PCMM with laser probe constitutes of the following steps:

1. Calibrating the touch probe
2. Calibration the laser probe.
3. Orienting the object.
4. Spray painting with dissolvable white coating if necessary.
5. Setting the exposure to the material.

The total time taken for the preprocessing stage of the angel model was approximately 13 minutes.

The preprocessing in the SALSS includes the following steps.

1. Spray painting the part with white coating
2. Mounting the part in rotary table with modeling clay in the proper orientation.
3. Specifying the scan envelop and other scan setting and previewing to make sure the settings are correct.

The total time taken for this step for the angel model was approximately 22 minutes.

4.3.5.2 Digitizing

Digitizing is the actual data capture that takes place during the reverse engineering. The digitizing process in PCMM and SALSS are explained below.

The digitizing process for a PCMM is a manual process and could cause fatigue for the operator on large parts. Keeping the scanner always perpendicular to the scanned surface is also necessary; maintaining the scanner in the midrange can also be a challenge for someone new in operating the system. The scanning time varies based on the size of the object. One good thing
about scanning with this system is that the person can see the points being gathered as the
digitizing takes place and vary the digitizing based on the quality of the captured data. The
approximate scanning time taken for the angel model in two orientations is 25 minutes.

The digitizing stage in SALSS is mostly automatic, with manual preprocessing between
successive orientations. The total digitizing time taken for our experiment was 139 minutes. This
varies slightly based on the specifications of the computer used, but since the same thing applies
to PCMM as well we ignore this factor.

4.3.5.3 Post processing

Post processing is the most difficult step in the reverse engineering process and the
variation in this step is very large as well. Causes of variation can be factors like type of software
used, CAD proficiency of the person among others.

The post processing stage in PCMM includes filtering for noise, merging the point
clouds, filling the holes in the point clouds, smoothing among others. The approximate time to
produce an STL file from the point cloud was 71 minutes.

The post processing stage in SALSS follows the same course as that of the PCMM, but is
a little more complicated because of the modeling clay which is digitized also these regions are
to be removed manually using shell select command. The approximate time taken for this step
was 128 minutes.

4.3.5.4 Accuracy of the models

The accuracy of the model refers to the dimensional accuracy of the CAD model.

The accuracy of the laser scanner used for the experiment is 0.015 inches. This can be
multiplied by the inaccuracy of the arm itself.
The accuracy of the Picza scanner used was 0.08 inches. The final accuracy of the model can vary based on the inaccuracies added during post processing. This accuracy of Picza cannot be taken as a representative value of all stand alone laser scanners because there are other more expensive scanners with a better accuracy than the Roland Picza. The following table summarizes the information:

**Table 4: Comparison between PCMM and SALSS**

<table>
<thead>
<tr>
<th></th>
<th>Time Taken (in minutes)</th>
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<tbody>
<tr>
<td></td>
<td>PCMM</td>
</tr>
<tr>
<td>Preprocessing</td>
<td>13</td>
</tr>
<tr>
<td>Digitizing</td>
<td>25</td>
</tr>
<tr>
<td>Post Processing</td>
<td>71</td>
</tr>
</tbody>
</table>

Thus it can be seen that the PCMM has advantages over SALSS in all of the important criteria discussed and hence is recommended for the aesthetic engineering applications. One added advantage with PCMM is the possibility of digitizing simultaneously with the hard probe; this can give a tremendous advantage over the other commercially available systems. In certain cases like the ceramic objects, which were discussed in section 4.1.2, hard probe digitizing is more efficient than the laser scanning technique. Now that the advantages of using PCMM for Aesthetic engineering applications are known a framework for aesthetic engineering was created and is Figure 98. Disadvantages of using the PCMM against picza scanner include the high price and the need for seven axes CMM.
Figure 95 shows the methodology and advantages of aesthetic engineering using PCMM.
CHAPTER FIVE: CONCLUSION

5.1 Summary

The methodology of reverse engineering was illustrated and the versatility of PCMM to capture seemingly impossible objects was proved in this research. As it was shown the basic framework involved in reverse engineering remained same whereas the strategies varied based on the object at hand. Seventeen different objects where reverse engineered to obtain accurate CAD models. The relationship between rapid prototyping and reverse engineering was also shown where the virtual replicate (CAD) was produced physically in a 3D printer. Customization options were explored to reverse engineer parts, which could not be digitized with the standard set up either because of their complex structure, which could not be reached by standard touch probe or free form complex shapes, which could require point-by-point digitizing. Solutions were developed for these cases by the use of non-standard touch probe (4.2.2) and Laser Line Probe (4.2.3).

Some of the problems encountered in reverse engineering the models include equipment restrictions to handle customization. For example the curved non-standard probe and the Laser probe, which were developed as customization solutions for solving the aforementioned problems, were not compatible with the standard six axes PCMM. Experiments were modified by using a straight non-standards probe for digitizing the unreachable areas in a standard set up. A seven-axis setup was used to scan the aesthetic model. Such issues brought into light some of
the restrictions of the seemingly unconstrained motion of the portable CMM. Another major challenge was the realignment of complex objects between reverse engineering sessions. Several Setups were used to reverse engineer the turbine (4.2.2). Some of the more complex parts might require design of customized jigs to facilitate easy digitizing of such objects. Similar Jigs might be used to clamp the models to be scanned by the laser scanner attachment. The technique of rotary table used in the stand-alone scanner could be used to clamp the objects to be digitized by the laser probe attachment of the PCMM.

One of the other results of the thesis is a comparative study of the use of PCMM and Stand Alone Laser Scanner Systems for the Aesthetic Engineering applications. It was shown in the study that PCMM is a better Reverse Engineering tool especially for aesthetic engineering application. This thesis could hence serve as a guiding document in the selection of suitable equipment for reverse engineering equipment. Appendices A and B will depict some of the other objects that were reverse engineered and will also give some useful reverse engineering tips gathered during the course of the experimentations in the thesis.

5.2 Future Research

Thus far in the thesis various reverse engineering techniques were used to demonstrate the versatility of PCMM through multiple experiments. But it is important to note that the true value of these reverse engineering tools and techniques is in the successful application of such techniques in practical situations. One important area of future work is to serve the local industry by using the reverse engineering potential of the PCMM and supplemental tools to provide
appropriate solutions to the existing industry problems. Experiments 4.1.2 and 4.1.5 are some of the examples where PCMM was used to solve the typical industry problems in the Central Florida region. Better Reverse Engineering techniques can be subsequently developed based on industry specific needs.

Another area of future research is to develop scientific experimentation/evaluation techniques and standards to compare and quantify the performance of reverse engineering tools or techniques. Such methods would help make decisions on the selection of specific tools and techniques. Operator variability and training are important criteria that must be considered while developing such standards. Such techniques will also help us analyze the performance of specific reverse engineering techniques. It is important to note that the experimentations in this research are demonstrative in nature and should not be used as a basis for choosing specific tools, however Appendix: A provides helpful guidelines to make such decisions.

Apart from developing standards to evaluate current techniques and tools it is also important to pay attention to potential breakthrough improvements, which could change the entire facet of reverse engineering technology. One such technique is the method of obtaining 3D CAD model directly from 2D pictures. This method is still in its infancy and the results obtained are crude however experiments are being conducted to determine its feasibility. The software Rhinoceros® was used for exploring this technique. The command called ‘hieghthfeild from bitmap’ was used in the experimentations. Figure 96 shows the picture taken using a 3.2 mega pixel digital camera.
Various parameters like lighting and orientation of the object can be adjusted to obtain better results. The background of the object is also very important, during the process. The software makes a grayscale image and then grayscale of each of the pixel from the 2D digital...
image and assigns a height proportional to it. The result is similar the object shown in Figure 100. The number of control points and height can be varied in the CAD model. There is a tremendously large amount of post processing of data involved in this method to obtain any meaningful CAD model. So this method can be preferred only if the object is relatively simple and manual digitizing through hard or optical probes is not feasible. This technique can be married with the principle of PCMM if the camera is located at the probe location and picture taken at different orientation. Based on the position of the tip of the arm the different scans can be automatically merged to single point cloud. This area of point cloud manipulation itself is another area open for research. Such research could one day lead into a magical machine which would just take the picture and produce multiple 3D copies of the objects or may be even humans!
APPENDIX: A REVERSE ENGINEERED CAD MODELS
Table 5: Reverse Engineered CAD Models of Experiment 4.1.2

<table>
<thead>
<tr>
<th>Experiment 4.1.2</th>
<th>Reverse Engineered CAD Models</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><img src="image1" alt="Model 1" /></td>
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<tr>
<td></td>
<td><img src="image2" alt="Model 2" /></td>
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<tr>
<td></td>
<td><img src="image3" alt="Model 3" /></td>
</tr>
<tr>
<td></td>
<td><img src="image4" alt="Model 4" /></td>
</tr>
</tbody>
</table>
Table 6: Reverse Engineered CAD Models of Experiments 4.1.2 and 4.1.5
APPENDIX: B REVERSE ENGINEERING TIPS
Selection of PCMM

Even though the manufacturers of PCMM’s are limited, choosing the right PCMM for a particular RE application may be a difficult task. Some of the most important criteria for making such decisions are measuring envelop of the arm, accuracy among others. The information provided may help make such decisions.

Table 7: Comparison of PCMM’s in Market


<table>
<thead>
<tr>
<th></th>
<th>Accuracy (+ / -) in inches</th>
<th>Maximum Measuring Envelope (in foot)</th>
<th>Laser Scanner Compatibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faro®</td>
<td>0.0008</td>
<td>12</td>
<td>Yes</td>
</tr>
<tr>
<td>Cimcore®</td>
<td>0.0012</td>
<td>12</td>
<td>Yes</td>
</tr>
<tr>
<td>Microscribe®</td>
<td>0.006</td>
<td>5</td>
<td>No</td>
</tr>
<tr>
<td>Axila®</td>
<td>0.0013</td>
<td>17</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Other factors in selecting a PCMM are given below; however one has to select the PCMM based on the application at hand.

- PCMM’s with larger measuring envelope usually have a lower accuracy, unless otherwise required a smaller PCMM should be preferred over a larger one.
- Laser Scanner attachments are not compatible with six axes configuration; hence for non-contact laser scanning applications, six axis PCMM should be preferred.

- PCMM’s compatible with other third party software should be preferred to make use of features available in that software.

- The wrist design of Microscribe® is different from the other designs; this configuration could be advantageous for certain RE applications. [http://www.immersion.com/digitizer/products/online_demo.php].

- Bridge type CMM’s and other non-contact CMM’s which are of lighter weight are frequently referred as Portable CMM’s; one must distinguish between these systems and the systems (articulated measurement arms) under discussion.

- Compatibility with various accessories must be given due concern before making the purchase decision.

**Probe Selection & Calibration**

1. Always prefer the use of ball probe against th point probe. Point probe is not always preferred because the accuracy of the measurements are based on how sharp the point tip is and moreover it needs to orient exactly perpendicular to the measurement surface to get accurate measurements. But the measurements made by the ball probe are much more robust against inaccuracies as the point measured is the center of the probe.
2. A disadvantage of a ball probe is that the third party software do not compensate for the probe radius while making measurements. However the CAD model can be offset to a value equivalent to the radius of the ball probe to obtain accurate cad model.

3. When making measurements always make sure that the right probe is selected by the software. It is possible that the probe was physically changed but not the software settings, resulting in incorrect data.

4. Non-standard probes cannot be used with any third party software, as they need a new probe calibration, which can be done only with the PCMM software. Offsetting the surface model by a fixed distance during post processing will not produce the accurate model.

5. Six axes PCMM only supports probes that are symmetrical, this means that curved or angled probes cannot be used. A similar constraint (need to maintain the scanner perpendicular to scanning surface) limits the use of laser probes in six axes configuration. However the seven axes configuration supports the use of non-standard and laser probes, but is less accurate than a similar six axes PCMM.

6. Plug-ins are available to make the third party software compatible with the use of certain nonstandard probes e.g. Geomagic Qualify has a plugin which enables the use of laser probe attachment of the PCMM (Faro Arm).

7. Probe Calibration is a method of specifying the exact location of the probe tip, it is very important to perform a probe calibration at the beginning of each project and also when a probe is changed. This adjusts any wear in the probe or any variations due to fastening of the probe.
8. Non-Standard probes are to be calibrated using the PCMM software, *before calibrating the laser probe the hard probe must be calibrated.*

**Preprocessing**

1. Preprocessing involves all steps before the actual digitizing (data capture). One of the important preprocessing steps is the clamping of the object. This step is very important, as any slight movement will cause inaccurate data to be captured.

2. Clamp the part closer to the arm whenever possible, the accuracy of the PCMM is higher in this region and reduces in the farther region.

3. It is important to decide on the number of orientations required for complete digitization of the object at the preprocessing stage.

4. If the object requires multiple orientations, decide on the alignment features that are needed to realign the object. *All features used for alignment must be accessible from each of the orientations.*

5. Same principles are applied when laser scanning a part using laser probe attachment, where the part must be oriented in such a way that most of the features are captured.

6. A difference between laser scanning and manual scanning is that, a *big overlap (more number of alignment features) is good in manual scanning whereas a big overlap (larger area overlap) reduces the accuracy of the point cloud in non-contact scanning.* This is due to the inherent insufficiencies in point cloud manipulation technique.
7. When using clay to fill up holes before laser scanning it is better to use dark colored clay resulting less number of points from clay being captured during scanning.

8. If digitizing of inner geometry is difficult, modeling clay may be used to produce replica of the male portion. The replica can be digitized and merged at the post processing stage.

Digitizing

1. Digitizing is the process of capturing the 3D CAD data; either by contact of touch /hard or by non-contact methods using optical scanning techniques.

2. Alignment Features should be digitized first, so that even there is an accidental movement of the part, the measurement session can continue after realignment.

3. Knowledge in CAD techniques can be beneficial in any digitizing session. One can digitize selected features and recreate others based on CAD commands.

4. When digitizing complex curves use the ball probe to slide against any supporting surface.

5. Use the laser scanner in the optimum range to obtain more accurate data; far range and near range is not as accurate. Always keep the scanner perpendicular to the object to be scanned to obtain better results.

6. Several software have lock functions, which enable selective digitization in certain areas, these functions should be considered in digitizing complex objects.

7. Do not hesitate to use simpler measuring devices like micrometer, steel rule among others when digitizing with PCMM would take more time.
8. Experiment with other third party software for digitizing even though there are some limitations with respect to the choice of probes among others, there may be other desirable features, which make the use of such software appropriate. Some of the CAD packages which can be interfaced are Solid works®, Rhinoceros® among others.

9. During digitizing session more than a software may be used to continue digitizing, so the use of third party software can be beneficial in certain situations.

10. Certain PCMM’s facilitate the simultaneous use of hard and laser probes. In such cases the hard probe may be used to measure the alignment features as the alignment features created using a hard probe could result in a more accurate alignment.

**Post processing**

1. Post Processing includes all the steps performed after the digitizing session, to produce the complete CAD model of the object.

2. Time taken for post processing heavily depends on the strategies followed during preprocessing & digitizing. Most often there may be a requirement s to go back to further preprocessing and digitization sessions after preprocessing and hence these steps should not be considered to be in sequence.

3. *Do not move any of the features at the preprocessing stage*, movement of these features could result in inaccurate CAD models.

4. Functions like smoothing, changing control points of curves, among others could damage the integrity of the CAD file.
5. Above conditions may be relaxed if the application is purely aesthetic where the accuracy of the model is not as important as the appearance.

6. To build a CAD model using any of the rapid prototyping techniques, the CAD file is exported into a **STL format. A CAD Model in STL format this should be a complete water tight mesh.** This can be verified by the ‘object properties’ command where the surfaces needs to described as closed **polysurfaces and not open polysurfaces.** Failure to verify this aspect could cause the rapid prototyping to fail.

7. Before importing the CAD model in STL format, all curves points and other discrete surfaces must be deleted from the model since this could be interpreted as open surfaces.

8. Plug-ins available to perform rendering functions, which could help us to create a near photographic of the CAD model. [e.g. flamingo® plug-in for Rhinoceros® Software.]

9. Post processing of a point cloud obtained through laser scanning is more intensive than that of manual digitizing. When merging two point clouds, keep the over lapping region minimum and delete unnecessary overlap.

10. Partial rescanning is to be preferred against hole filling whenever possible, this is more critical when the tolerances of the models are more important.

11. When creating surfaces over point cloud, specify the number of surfaces to not accurately represent the point cloud. An improper selection of surface count could result in a inaccurate CAD model.
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