Application of Reverse Engineering on CAD Modelling Using Least Square Fitting Technique

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ABSTRACT

As computer-aided design has become more popular, reverse engineering has become a viable method to create a 3D virtual model of an existing physical part for use in 3D CAD, CAM, CAE and other software. The reverse engineering process involves measuring an object and then reconstructing it as a 3D model. The physical object can be measured using 3D scanning technologies like CMMs, laser scanners, structured light digitizers or computed tomography. The measured data alone, usually represented as a point cloud, lacks topological information and is therefore often processed and modeled into a more usable format such as a triangular faced mesh, a set of NURBS surfaces or a CAD models. Applications like 3-matic, Imageware, PolyWorks, Rapid form or Geomagic are used to process the point clouds themselves into formats usable in other applications such as 3D CAD, CAM, CAE or visualization. A sincere effort is made to develop algorithms for above mentioned process of reverse engineering. This research work is about using least square fitting technique for geometric profile generation from point cloud data which usually is noisy, to exactly match basic shapes like line, circle, regular polygons etc. with minimized error. Developing C codes for the algorithms. Creating CAD models in suitable package and analyzing experimental and modeled data.

Keywords: reverse engineering, Theoretical analysis, Production techniques, Measurement of Properties

I INTRODUCTION

In today's intensely competitive global market, product enterprises are constantly seeking new ways to shorten lead times for new product developments that meet all customer expectations. In general, product enterprise has invested in CAD\CAM, rapid prototyping, and a range of new technologies that provide business benefits. Reverse engineering (RE) is now considered one of the technologies that provide business benefits in shortening the product development cycle. Figure 1.1 above depicts how RE allows the possibilities of closing the loop between what is "as designed" and what is "actually manufactured" [1]. Engineering is the process of designing, manufacturing, assembling, and maintaining products and systems. There are two types of engineering, forward engineering and reverse engineering. Forward engineering is the traditional process of moving from high-level abstractions and logical designs to the physical implementation of a system. In some situations, there may be a physical part/product without any technique Details, such as drawings, bills-of-material, or without engineering data.

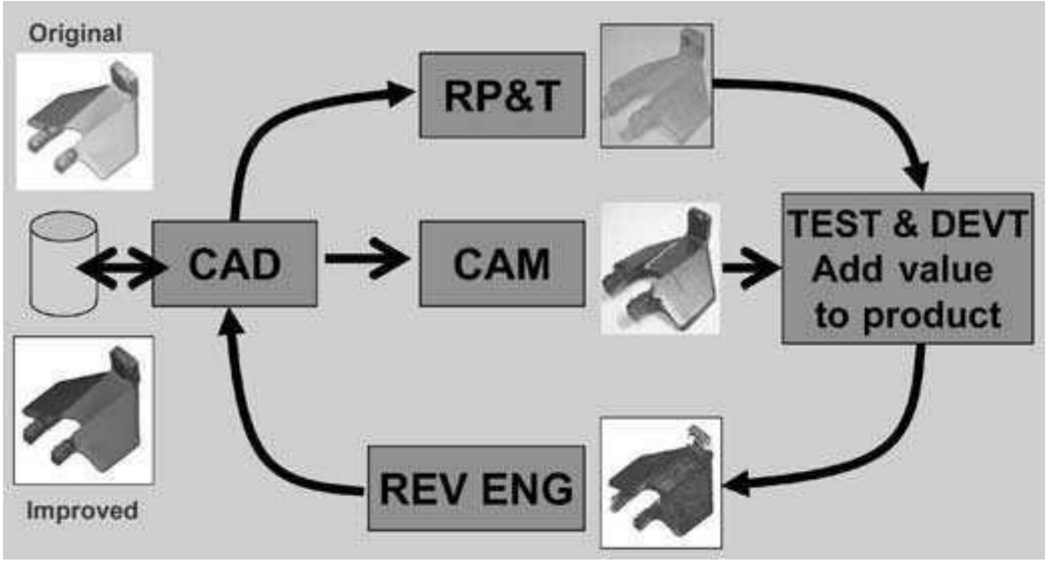

Fig. 1 Product developments cycle [1]

1.1 Applications of Reverse Engineering

The process of duplicating an existing part, subassembly, or product, without drawings, documentation, or a computer model is known as reverse engineering. Reverse engineering is also defined as the process of obtaining a geometric CAD model from 3-D points acquired by scanning/digitizing existing parts/products. The process of digitally capturing the physical entities of a component, referred to as reverse engineering (RE), is often defined by researchers with respect to their specific task.[1,2]

Abella *et al.* [2] described RE as, "the basic concept of producing a part based on an original or physical model without the use of an engineering drawing". Yau *et al.* [3] define RE, as the "process of retrieving new geometry from a manufactured part by digitizing and modifying an existing CAD model". Reverse engineering is now widely used in numerous applications, such as manufacturing, industrial design, and jewelry design and reproduction For example, when a new car is launched on the market, competing manufacturers may buy one and disassemble it to learn how it was built and how it works. In software engineering, good source code is often a variation of other good source code. In some situations, such as automotive styling, designers give shape to their ideas by using clay, plaster, wood, or foam rubber, but a CAD model is needed to manufacture the Part As products become more organic in shape, designing in CAD becomes more challenging and there is no guarantee that the CAD representation will replicate the sculpted model exactly. Reverse engineering provides a solution to this problem because the physical model is the source of information for the CAD model. This is also referred to as the physical-to-digital process depicted in Figure 1.2. Another reason for reverse engineering is to compress product development cycle times. In the intensely competitive global market, manufacturers are constantly seeking new ways to shorten lead times to market a new product. Rapid product development (RPD) refers to recently developed technologies and techniques that assist manufacturers and designers in meeting the demands of shortened product development time.

Following are some of the reasons for using reverse engineering [1][4]:

- The original manufacturer no longer exists, but a customer needs the product, *e.g.*, aircraft spares required typically after an aircraft has been in service for several years.
- The original manufacturer of a product no longer produces the product, *e.g.*
- The original product has become obsolete.
- The original product design documentation has been lost or never existed.
- Creating data to refurbish or manufacture a part for which there are no CAD
- Data, or for which the data have become obsolete or lost.
- Inspection and/or Quality Control–Comparing a fabricated part to its CAD
- Description or to a standard item.
- Some bad features of a product need to be eliminated *e.g.*, excessive wear might indicate where a product should be improved.
- Strengthening the good features of a product based on long-term usage.
- Analyzing the good and bad features of competitors' products.
- Creating 3-D data from a model or sculpture for animation in games and movies.
- Creating 3-D data from an individual, model or sculpture to create, scale, or reproduce artwork.
- Architectural and construction documentation and measurement.
- Fitting clothing or footwear to individuals and determining the anthropometry of a population.
- Generating data to create dental or surgical prosthetics, tissue engineered body parts, or for surgical planning.
- Documentation and reproduction of crime scenes.

The above list is not exhaustive and there are many more reasons for using reverse engineering, than documented above.

1.2 Reverse Engineering–The Generic Process

The generic process of reverse engineering is a three-phase process. The three phases are scanning, point processing, and application specific geometric model development. Reverse engineering strategy must consider the following:

- Reason for reverse engineering a part
- Number of parts to be scanned–single or multiple
- Part size–large or small

- Part complexity–simple or complex
- Part material–hard or soft
- Part finish–shiny or dull
- Part geometry–organic or prismatic and internal or external
- Accuracy required–linear or volumetric

II LITERATURE REVIEW

Various sources of literature in the field of Reverse Engineering exhibit tremendous work has been done and is being done. A lot of research work is found to be available on various areas of Reverse Engineering like point acquisition, point cloud processing, edge detection, surface reconstruction, 3D Modeling, application and integration of Reverse Engineering. This chapter exhibits attempts towards collection of publications in the related area.

2.1Data Acquisition (Techniques And Equipments)

J. Chow, T. Xu, S.-M. Lee and K. Kengskool [5] evaluate the feasibility of using Reverse Engineering and concurrent engineering methods with data obtained from state-of-the-art laser scanning to remanufacture complex geometric parts. They demonstrate that laser scanning and CAD model reconstruction can duplicate aircraft structure components accurately and efficiently, within the tolerances of ±0.127mm.

In applying a CMM with a touch trigger probe to digitize mechanical objects, five parameters tend to impact the accuracy of digitizing the most: probe size, part orientation (probe orientation), pitch value (Sampling points), travel speed, feature size. C X Feng and Xianfeng Wang [6] applies and compares the non linear regressions analysis and neural network modeling methods in developing empirical models for estimating the digitizing uncertainty. Above five digitizing parameters have been considered simultaneously.

E. Vezzetti [7] proposes a methodology for defining a selective sampling plan, whose grid dimensions are related to the complexity of the analyzed local surface regions. The proposed method aims at identifying a selective sampling plan with an adaptive pitch, which locally varies depending on the surface complexity of the analyzed region (Fig. 2). In order to reach this goal, first of all, it has been necessary to implement a segmentation strategy and to divide the entire object surface into different complexity regions. The Gaussian curvature K (Fig. 2) has been employed as a morphological descriptor with the following formulation

$$K = 2\pi - \sum_i v_i \quad \text{......} (1)$$

Where, v_i indicates each of the angles, which share the same central node of a discrete neighbourhood.

2.2Point Data Processing

J P Kruth and A Kerstens [8] report on the incorporation of geometric boundary conditions in the CAD modeling of freeform surfaces from cloud of points with non uniform rational B-splines (NURBS). CAD modeling of a free-form surface from a point cloud with NURBS can be formulated as the creation of a NURBS surface in Eq. (1) that approximates a cloud of *m* measured points within a given tolerance.

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$$p(u,v) = \frac{\sum_{i=1}^{n_u}\sum_{j=1}^{n_v} B_{ui}(u).B_{vj}(v).w_{ij}.C_{ij}}{\sum_{i=1}^{n_u}\sum_{j=1}^{n_v} B_{ui}(u).B_{vj}(v)w_{ij}} \quad \text{......} (2)$$

The surface parameters to be determined from the points are the B-spline functions B_u and B_V, uniquely defined by their order k_u and k_V and knots t_u and t_V respectively, The $n = n_u x n_V$ control points c_{ij} and their weights wij.

H C Kim, S M Hur and S H Lee [9] proposed and compared the solution of the segmentation of noise-free data and noisy data based on triangulated data. The solution for noise-free data is relatively simple having a small number of user-defined criteria. However, the solution for noisy data requires more criteria to produce a reasonable result when noise is globally distributed on the measured data. For noise- free data triangular net can be formed by repeated connection of a point of one polyline to a point of another polyline by use of the max–min angle criterion.

2.3 Edge Detection, Feature Recognition, Modeling From Point Cloud

C X FENG and Xianfeng Geng [9] apply and compare the nonlinear regression analysis and neural network 463odelling methods in developing empirical models for estimating the digitizing uncertainty. The models developed in this research can aid error prediction, accuracy improvement, and operation parameter selection in computer aided Reverse Engineering and automatic inspection. Both prediction models appear to provide a satisfactory prediction with the regression model providing a slightly better performance in both model construction and model verification.

Jafar Jamshidi, Antony R. Mileham and Geraint W. Owen [10] introduce the automation of several algorithms for 463odelling process into a unique CAD 463odelling system. The system user can create a complete CAD model by integration and minimum manipulation of the high resolution scanned data, obtained using a high accuracy Coordinate Measurement Machine with touch probe, and low resolution scanned data obtained using a high speed Laser Scanner, rapidly and accurately. By using this automated system, the user does not require extensive expertise for CAD 463odelling. This system is most suitable for parts which have sensitive machined features and also complex but non-sensitive geometry on their casting surfaces.

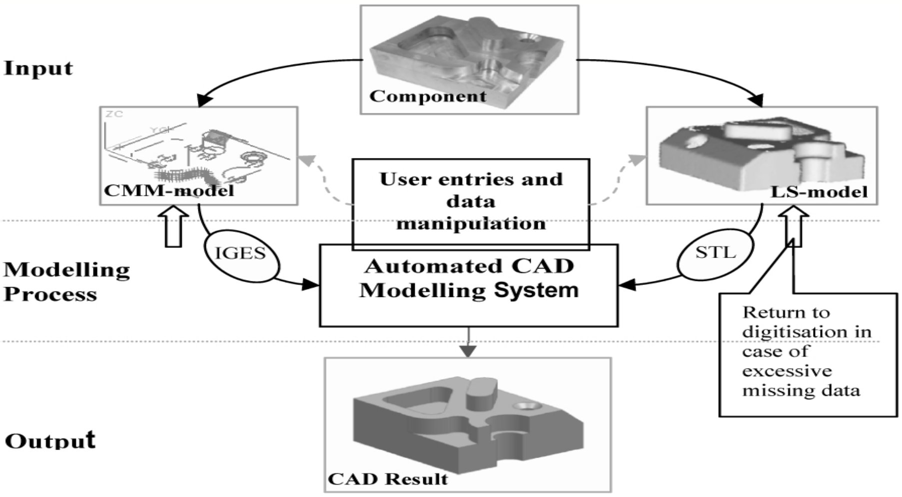

Fig. 2 Overview of the CAD 464modelling process in the system [10]

III EXPERIMENTATION

This chapter mentions casting and preparation of the specimens by using Lathe machine. It also highlights the procedure and steps involved for obtaining the point cloud data files which are further used in the subsequent steps for obtaining final results.

3.1Fabrication and Preparation of Specimen

The specimens used are made of Zinc Metal. Great efforts are made to maintain accuracy of the shape. Basic primitive shapes are developed like cone, frustum of cone and cylinder. Zinc Metal models developed are finished to acquire smooth surfaces. Then they are painted white to have much better finish and to aid in better acquisition of point cloud data from 3d white light scanner. The dimensions of specimens are listed in Table 1 along with the total volume and the total surface area. The dimensions are measured with the Vernier Caliper with least count of 0.02mm.

Fig .3 Snap of Zinc Metal Specimen used

Table 1 Dimensions Measured by Vernier Caliper, Area and Volume of Specimens

Parameters	Dimension(mm)		Volume (mm^3)	Surface Area (mm^2)
	Diameter or Edge Length	Height		
Base Cylinder	27.57	40.63	24255.50024	3519.1150
Middle Cylinder	23.22	37.47	15867.116310	2703.4447
Cone Frustum	9.43	37.07	2588.3242512	1097.91060

IV ACQUISITION OF POINT CLOUD DATA

White light 3D scanner is incorporated along with Scanning Software for data acquisition. The point cloud is obtained in three simple steps, mounting the object on work table of scanner, preview the time required and pressing scan button to start scanning.

There are two options available to the user regarding the mode of scanning i.e. rotational and planner. Generally rotational option is used for obtaining point cloud data of circular surfaces and planner for flat surfaces.

Though Scanner has minimum pitch of 0.02mm, keeping in view the size and the time consumption 2mm pitch is used for all the specimens using planner and 1 degree for all specimen using rotary method.

4.1Least Square Fitting Of Line

The least-squares line uses a straight line

$$y = a + bx \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

To approximate the given set of data, (x_1, y_1), (x_2, y_2), ..., (X_n, y_n), where $n \geq 1$. The best fitting curve $f(x)$ has the least square error, i.e

$$\Pi = \sum_{i=1}^{n}[y_i - f(x_i)].^2 = \sum_{i=1}^{n}[y_i - (a + bx_i].^2 = \text{min} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

To obtain the least square error, the unknown coefficients *a* and *b* must yield zero first derivatives.

$$\begin{cases} \dfrac{\partial \Pi}{\partial a} = 2\sum_{i=1}^{n}[y_i \ - (a + bx_i] \\ \dfrac{\partial \Pi}{\partial b} = 2\sum_{i=1}^{n}x_i[y_i \ - (a + bx_i] \end{cases} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Expanding the above equations, we have [44]:

$$\begin{cases} \sum_{i=1}^{n} y_i = a\sum_{i=1}^{n} 1 + b\sum_{i=1}^{n} x_i \\ \sum_{i=1}^{n} x_i\, y_i = a\sum_{i=1}^{n} x_i + b\sum_{i=1}^{n} x^2{}_i \end{cases} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(6)$$

The unknown coefficients *a* and *b* can therefore be obtained:

$$\begin{cases} a = \frac{(\sum y)(\sum x^2)-(\sum x)(\sum xy)}{n\sum x^2-(\sum x).^2} \\ b = \frac{n(\sum xy)-(\sum x)(\sum y)}{n\sum x^2-(\sum x).^2} \end{cases} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

4.2Model Generation with Reverse Engineering

Developing models from point cloud data is one of the necessities and important step in reverse engineering. The accuracy of developed models of course depends on the skill and experience of the user. This chapter explains basic procedure of developing

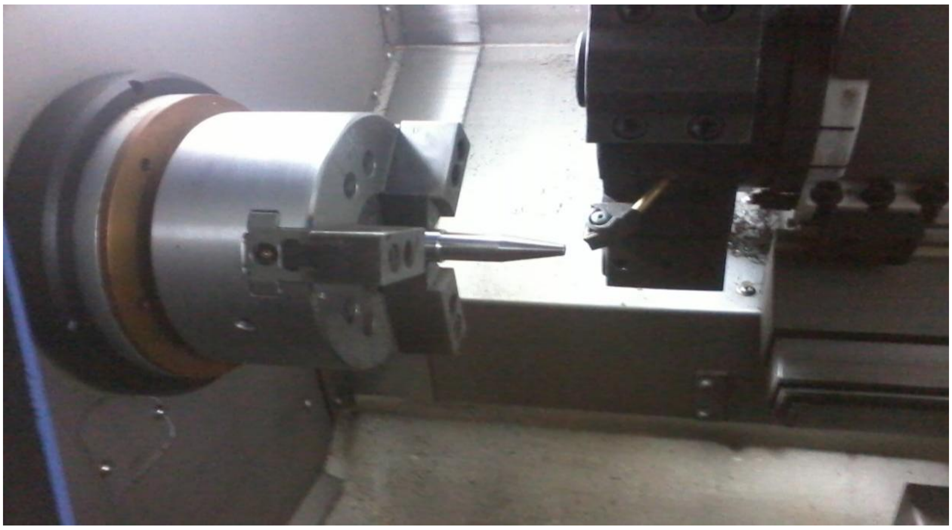

Fig .4 Machining of Zinc Metal Specimen used

V RESULTS AND DISCUSSION

The aim of this dissertation work is to analyze how accurately least square fitting method can be implemented in order to trace the accurate profile generated from available point cloud data. The following sections review and discuss the results obtained by implementing the proposed algorithms as discussed in chapter 4 and source codes for CNC program.

5.1Fitting of Data as Circle

The output of Kasa method gives the centre coordinates and radius of the circle such that sum of the radial distances is minimized. The equation of the circle can be easily obtained from the centre point and the radius of the circle.

The radius and the centre coordinate of the circle obtained by implementing Kasa method is shown in Table 2. Comparison between the coordinates of point cloud data and the coordinates obtained from the circle equation is shown in Table 2 and 3 are in close vicinity to each other as can be seen. The mean absolute percentage error (MAPE) for x, y coordinates and radius is 0.5077%, 0.5167% and 1.2725% respectively

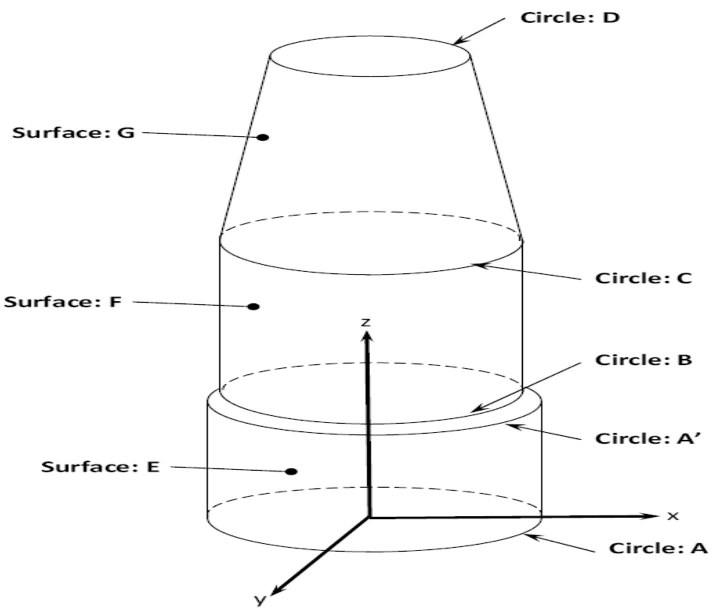

Fig. 5 Figure depicting various details on specimen

Table 2: Result from Kasa Method and its error analysis

S.no.	Circles	actual radius	radius by kasa method
1.	circle A	27.57	27.43
2.	circle B	23.22	23.10
3.	circle C	9.43	9.31

Table 3: Mean Absolute percentage error

Circles	Mean Absolute percentage error
Circle A	0.577983
Circle B	0.5617958
Circle C	1.272534

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5.2CNC Programe for the Specimen

N10 G0G53DX0.Z-200

N20 T0101M16

N30 G96S200M3LIMS=1800

N40 G0G64X38.0Z10.0

N50 G0Z2.0M8

N60 G0Z1.50

N70 G1X-1SF.15

N80 G0X38.0Z2.0N90

N90 G0Z1

N100 G1X-1.5

N110 G0X32.Z3

N120 G01Z-45.F.2

N130 G0X35.0Z2

N140 X30.0

N150 G01Z-45.0

N160 G0X35.0Z2.0

N170 X29

N180 G12-45.0

M190 G0X35.Z0.0

N200 GO/X-1.5

N210 G0X24.4Z1

N220 G01Z0

N230 G01X27.45Z-1.25

N240 G01X5Z-45Z-1.25

N250 G01X35.0

N260 G0Z2.0M9

N270 G0Z10.M5

N280 G0G53D0X0.0Z-200

N290 T04D1M16

N300 G97S400M42IMS=1200

N310 G0G64X86.0Z10.0

N320 G0X1.0Z2.0M8

N330 G01Z0.0F.1

N340 G1Z-12.0F.0

VI CONCLUSIONS

A sincere effort is made to extract exact shape from noisy point cloud data which is acceptable and within tolerances. The algorithms were developed keeping a common user in view with average knowledge of the subject. Now instead of manually fitting the shape which is more error prone the user can automatically do it by given programs. The results obtained by implementation of algorithms are well within acceptable tolerances. The mean absolute percentage error is less than 2% for almost all implemented algorithms.

Through the above work a procedure is made to fit line, circle and regular polygons into noisy point cloud data obtained from 3D scanners with the concept of least square fitting techniques. The algorithms are implemented in C-language. The results obtained are used to model shapes in Auto-Cad/NX6 and programme for CNC machine.

The correctness of the algorithms can be verified by comparing the results obtained while developing their source codes with actual point cloud data and with the results of Kasa. It is observed that the results are very close to actual values hence these algorithms can be well implemented for shape generation from noisy data obtained from 3D scanners.

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