Surface segmentation and reconstruction in reverse engineering

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Abstract. Reverse Engineering (RE) is the process by which the geometry of a physical part is recreated digitally by digitizing and data modification. RE main difficulty is surface reconstruction. This difficulty increases by increasing part complexity. In this research, a developed reverse engineering approach has been adopted to create a 3D CAD model for power stern. The approach begins from the existing and goes through three main steps (scanning, data pre-processing, and part segmentation and surface reconstruction) and finalize to a readable CAD model. A mathematical representation for the NURB curve has been created to formalize the edges of segments then reconstructing plan and tabulated surfaces according to the segment geometry. Algorithms and computer programs using MATLAB programs have been built to implement the proposed approach and save the data.

1. Introduction
Nowadays, Reverse Engineering (RE) is a significant matter while designing products that highlight inverse methods, deduction, and discovery in design. In mechanical engineering, (RE) has developed from capturing technical product information, and introducing manual redesign procedure while empowering efficient concurrency benchmarking to a more elaborated process depending on advanced computational models and modern digitizing technologies [1]. RE utilized 3d scanners to rapidly procure geometric surface data of parts and models. These data are regularly in the form of a dense data called cloud Point. Due to the colossal amount of point cloud, it is necessary to treat them before surface reconstruction. Surface reconstruction refers to segmenting the processed data into sets to create surfaces representing the object form [2]. The reconstructed 3D object can be directly transformed into CAD/CAM and RP (Rapid Prototyping), and afterward can be legitimately utilized in Computer Numerical Control (CNC) [3]. Related articles have been review in this survey.

• Miguel and Kenji (2005) presented a district-growing algorithm to fast and automatically noise processing and segmenting the dense mesh into various shapes attributes regions representing seed regions. Each region vertices were approximated producing a cubic Bezier surface within a specific tolerance [4].
• Mengoni et. al. (2006) depicted the fundamental outcomes related to the meaning of a shape-based convention for the analysis of the aesthetic information that is based on the application of principles used by the designer during the creative process and on techniques for the representation of creative ideas [5].
• Yoo (2011) introduced an effective strategy for the 3D Bio-CAD model remaking of human bone from a scanned point cloud data or a sequence of CT image data was presented based on a B-spline interjection scheme. After generating the base implicit surface from points cloud, different
sorts of CAD models, for example, surface and solid were constructed by utilizing the base implicit surface [6].

- Srdjan et.al. (2018) presented an algorithm for describing the segmentation and constrained fitting. By implemented reverse engineering on a sample (a heavy-duty rotating turbine blade) to get the drawing geometry. The algorithm performs segmentation separately for the pressure side and independently for the suction side [1].

- Wang et.al. (2019) proposed a technique for building a mesh surface from a point cloud by following three steps. First, preprocessing to improve the quality of point cloud dissemination and upgrade sharp features. Second, dividing the point cloud into segments. Finally, build a curve skeleton for each part and guide the surface reconstruction with insignificant user interaction. The method approved its efficiency in producing state-of-art results in terms of preserving sharp features and handling missing data [7].

Most of the previous researches did not deal with NUBS surface in reconstruction the part surface although its merits in the possibility of controlling and editing the model by managing the control point's weight.

This research aims to reconstruct part surface utilizing the points of cloud digitized from the scanning device. To achieve this aim, a methodology has been proposed for preprocessing points cloud data and interactively the object surface segmentation and reconstruction using NURB surface. A mathematical model and PC program using MATLAB will be introduced to execute the methodology.

2. Point cloud data preprocessing

The precept of processing the data is to reduce massive data and smooth it in the premise of not downing the precision of the generated surface. Figure 1 shows the regular-used pre-processing procedure.

The commonly used pre-processing procedure passes through the following major steps but using different approaches.

- Delete noise data.
- Data smoothing.
- Data reduction.

![Figure 1. Procedure for common used pre-process procedure [3]](image)

The characteristics of data are determining the detailed and sequence of the processes. Favorable pre-processing will secure the required accuracy in data for the following stages; not just uptrend the accuracy of the following stages but also eliminate the complexity of the following stages [3].

3. Surface segmentation

Segmentation aimed to logically divide the point cloud into subsets, a set for each natural surface so that each subset including just those points group from a specific surface [8]. However, subdividing objects in 3D point clouds is an essential task. The sampling density of points is ordinarily unequal due to the divergent in scanners specifications. Likewise, the surface shape can be subjective with
sharp features and the absence of a statistical distribution model for the data. These issues represent a challenge in developing a segmentation rule.

There are many methodologies that have been suggested for the segmentation of 3D point clouds. Generally, these methods can be categorized into five groups; as shown in figure 2 [9].

![Figure 2. Categories of 3D point cloud segmentation methods [9]](image)

3.1. **Edge Based Method (EBM)**

The EBM principle is attempting to find borders in the point data representing ledges between surfaces. If sharp edges are being seen, places where surface normal estimated from the point data change direction suddenly must be found. While if smooth (tangent continuous) edges are also possible, it needs to look for places where surface curvatures or other higher derivatives have a discontinuity. In this approach, several, user-specified ‘seed loops’ are appeared to obtain edge-loops of faces [8].

3.1.1. **Region-Based Methods (RBM)**

The RBMs use neighbourhood information to join the close points that have identical properties to acquire detached regions and consequently discover the difference between the distinctive regions. These methods are more accurate to noise than edge-based methods. But they have a problem with over or under segmentation and deciding region borders precisely. These methods can be divided into two categories: seeded-region (or bottom-up) methods and non-seeded region (or top-down) methods [9].

3.2. **Model-Based Methods (MBM)**

MBMs utilize geometric primitive shapes (for example, sphere, cone, plane, and cylinder) for grouping points. The points which have a unique mathematical representation are grouped as one segment [10].

3.3. **Attributes Based Methods (ABM)**

ABMs are robust approaches dependent on bunching characteristics of point cloud data. These methods incorporate two separate steps. The first step is attribute computation, in the second step; point clouds will be clustered based on the computed attributes [9].

4. **Surface Reconstruction**

In general, the problem of segmentation can be solved by constructing the following steps:

- Logically divide the point set into subsets, one for each establishing surface, with the goal that every subset contains only those points sampled from a specific surface.
- Decide to what type of surface each subset of points belongs (e.g. planar, cylindrical, rotational, free-form).
- For the points in the given subset, find the surface type with the best fitting to those points. It ought to be clearly noted that in practice these tasks cannot be completed sequentially, since deciding whether certain points belong to a particular subset requires some measure of better matching for the underlying surface the points may represent [11].

There are two essential methods for surface reconstruction: curved surface reconstruction and mesh reconstruction.
4.1. Curved surface reconstruction
The theory is based on constructing the matrix-distributed data into smooth continuum curves, curved surface model by using the algorithm of curved surface reconstruction. In the CAD/CAM system considering Bezier, B-Spline, and NURBS (Non-Uniform Rational B-Spline Curve as the most commonly used free curves and free curved surfaces. They are utilized to reconstruct the curved surface and smooth it. And most of them have good partial control ability, so convenience for model edition is provided [3].

4.2. Mesh reconstruction
Creating a triangle mesh that interpolates all or most of the points is denoted as mesh or triangle reconstruction. It is widely used recently due to its rapid model reconstruction of mass point clouds data and its accordance with industry and computer display [12].

5. The proposed methodology
In this research, a simple user interactive Reverse Engineering process has been adopted to rebuilt readable CAD model for a physical part by applying the following steps:

- Data Acquisition (Part Scanning)
- Pre-Processing the Points Cloud.
- Part Segmentation and Surface Reconstruction.

These steps are shown in figure 3:

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure3.png}
\caption{The proposed methodology}
\end{figure}

5.1 Data acquisition (Part Scanning)
There are different techniques have been used for gaining geometric data. In this research, a three dimensions laser scanning device that has the accuracy of +/-0.1 mm has been utilized for data acquisition. After disassembling, the parts the resulted points cloud are (2102492) points, these results can be demonstrated in figure 4.
Figure 4. The 3D point cloud for the part before deleting noise

5.2 The scanned point cloud Pre processing

3d laser scanning process resulted in numerous undesirable points. These points often resulted from light reflected from the bright part surface. Another reason for noise points is the complex and compound features the part containing. Those undesired points have been abridgment to keep up the nature of surface reconstruction. In practice, pre-processing and surface reconstruction is not necessary to be successful, thus, in some cases, it is necessary to iterate or backtracking between these steps. The resulted points cloud after noise deletion decreased to (1707965) points with a reduction of 18.7%; the consequence geometry can be seen in figure 5.

Figure 5. The 3D point cloud for the part after deleting noise

5.3 Segmentation and Surface Reconstruction

After points cloud noise deletion the part surface must be reconstructed. For the proposed work, the reconstruction process has been divided into three steps will be explained as follows:

- Segmentation of Point Clouds.
- Curve Reconstruction.
- Surface Reconstruction.

Because of the complexity of the part and the multiplicity of features and free form surfaces, interactive assistance has been used for high-quality results.

5.3.1 Segmentation of point clouds.

The adopted part has many simple and compound features making it difficult to reconstruct one surface representing the whole part. For this reason, the part should be segmented into separated subsets and each set is used to construct a complete feature belong to the original part. That means the points cloud are breaking into subgroups, and each group containing the whole points belonging to the intended feature. In the same manner, the points cloud for the specific feature should be subdivided into sets representing the surfaces that building that feature. For the proposed case study, the feature...
inside the rectangle in figure 6 will be taken as an example and will be stated as (segment (1)). Segment (1) consists of three basic surfaces, the outer, the inner and plan surface.

Figure 6. Demonstration of segment (1)

5.3.2 Curve Reconstruction
Because of the characteristic of the scanning device, the obtained date needs to be reorganized in order to be useable for reconstructing the intended surface. A total of 90 points had been chosen (30 for each surface). These points are still huge and need to be summarized. For this reason, data smoothing (mean method) and data reduction (Chordal method) techniques have been used. A flow chart and computer program using MATLAB has been built to implement mean and Chordal methodologies by specifying the Chordal height of (0.5mm). The output points after pre-processing are (30) points (10 points for each surface), as shown in figure 7. These points represent the control points that construct the contour of the reconstructing curve. Figure 8 demonstrates a flow chart for the program that built for data smooth methodology using the mean method and data reduction using the Chordal method.

Figure 7. Point cloud after pre-processing
Figure 8. A flow chart for the program that built for Data Smooth methodology using mean method and Data Reduction using Chordal method.

The curved surface reconstruction method has been adopted in this research to reconstruct this surface. The contour of the proposed surface has been represented using a NURB curve using the following formula:

\[
C(u) = \sum_{i=0}^{n} N_{i,k}(u) * W_i * P_i
\]

A NURB curve equation for (ten) control points and k=3 have been derived resulting in eight segments that have the following equations:
\[ p_0 w_0^* (u^2 \ u \ 1) * \begin{pmatrix} 1 \\ 1 \end{pmatrix} + p_1 w_1^* (u^2 \ u \ 1) * \begin{pmatrix} -1.5 \\ 2 \end{pmatrix} + p_2 w_2^* (u^2 \ u \ 1) * \begin{pmatrix} 0.5 \\ 0 \end{pmatrix} \]

\[ C_1(u) = \begin{pmatrix} \begin{pmatrix} u^2 & u & 1 \end{pmatrix} * \begin{pmatrix} 1 \\ -1.5 \\ 0.5 \end{pmatrix} \\ \begin{pmatrix} -2 & 0 & 0 \end{pmatrix} * \begin{pmatrix} w_0 \\ w_1 \\ w_2 \end{pmatrix} \end{pmatrix} \]

\[ p_1 w_1^* (u^2 \ u \ 1) * \begin{pmatrix} 0.5 \\ 2 \end{pmatrix} + p_2 w_2^* (u^2 \ u \ 1) * \begin{pmatrix} -1 \\ 3 \end{pmatrix} + p_3 w_3^* (u^2 \ u \ 1) * \begin{pmatrix} 0.5 \\ -1 \end{pmatrix} \]

\[ C_2(u) = \begin{pmatrix} \begin{pmatrix} u^2 & u & 1 \end{pmatrix} * \begin{pmatrix} 0.5 & -1 & 0.5 \end{pmatrix} \\ \begin{pmatrix} -2 & 3 & -1 \end{pmatrix} * \begin{pmatrix} w_1 \\ w_2 \\ w_3 \end{pmatrix} \end{pmatrix} \]

\[ p_2 w_2^* (u^2 \ u \ 1) * \begin{pmatrix} 0.5 \\ 4.5 \end{pmatrix} + p_3 w_3^* (u^2 \ u \ 1) * \begin{pmatrix} -3 \\ -5.5 \end{pmatrix} + p_4 w_4^* (u^2 \ u \ 1) * \begin{pmatrix} 0.5 \\ -1 \end{pmatrix} \]

\[ C_3(u) = \begin{pmatrix} \begin{pmatrix} u^2 & u & 1 \end{pmatrix} * \begin{pmatrix} 0.5 & -1 & 0.5 \end{pmatrix} \\ \begin{pmatrix} -4 & 7 & -3 \end{pmatrix} * \begin{pmatrix} w_2 \\ w_3 \\ w_4 \end{pmatrix} \end{pmatrix} \]

\[ p_3 w_3^* (u^2 \ u \ 1) * \begin{pmatrix} 0.5 \\ 8 \end{pmatrix} + p_4 w_4^* (u^2 \ u \ 1) * \begin{pmatrix} -1 \\ -11.5 \end{pmatrix} + p_5 w_5^* (u^2 \ u \ 1) * \begin{pmatrix} 0.5 \\ 4.5 \end{pmatrix} \]

\[ C_4(u) = \begin{pmatrix} \begin{pmatrix} u^2 & u & 1 \end{pmatrix} * \begin{pmatrix} 0.5 & -1 & 0.5 \end{pmatrix} \\ \begin{pmatrix} -5 & 9 & -3 \end{pmatrix} * \begin{pmatrix} w_3 \\ w_4 \\ w_5 \end{pmatrix} \end{pmatrix} \]

\[ p_4 w_4^* (u^2 \ u \ 1) * \begin{pmatrix} 0.5 \\ 12.5 \end{pmatrix} + p_5 w_5^* (u^2 \ u \ 1) * \begin{pmatrix} -1 \\ -19.5 \end{pmatrix} + p_6 w_6^* (u^2 \ u \ 1) * \begin{pmatrix} 0.5 \\ 8 \end{pmatrix} \]

\[ C_5(u) = \begin{pmatrix} \begin{pmatrix} u^2 & u & 1 \end{pmatrix} * \begin{pmatrix} 0.5 & -1 & 0.5 \end{pmatrix} \\ \begin{pmatrix} -5 & 9 & -4 \end{pmatrix} * \begin{pmatrix} w_4 \\ w_5 \\ w_6 \end{pmatrix} \end{pmatrix} \]

\[ p_5 w_5^* (u^2 \ u \ 1) * \begin{pmatrix} 0.5 \\ 18 \end{pmatrix} + p_6 w_6^* (u^2 \ u \ 1) * \begin{pmatrix} -1 \\ -29.5 \end{pmatrix} + p_7 w_7^* (u^2 \ u \ 1) * \begin{pmatrix} 0.5 \\ 12.5 \end{pmatrix} \]

\[ C_6(u) = \begin{pmatrix} \begin{pmatrix} u^2 & u & 1 \end{pmatrix} * \begin{pmatrix} 0.5 & -1 & 0.5 \end{pmatrix} \\ \begin{pmatrix} -6 & 11 & -5 \end{pmatrix} * \begin{pmatrix} w_5 \\ w_6 \\ w_7 \end{pmatrix} \end{pmatrix} \]

\[ p_6 w_6^* (u^2 \ u \ 1) * \begin{pmatrix} 0.5 \\ 24.5 \end{pmatrix} + p_7 w_7^* (u^2 \ u \ 1) * \begin{pmatrix} -1 \\ -41.5 \end{pmatrix} + p_8 w_8^* (u^2 \ u \ 1) * \begin{pmatrix} 0.5 \\ 18 \end{pmatrix} \]

\[ C_7(u) = \begin{pmatrix} \begin{pmatrix} u^2 & u & 1 \end{pmatrix} * \begin{pmatrix} 0.5 & -1 & 0.5 \end{pmatrix} \\ \begin{pmatrix} -7 & 13 & -6 \end{pmatrix} * \begin{pmatrix} w_6 \\ w_7 \\ w_8 \end{pmatrix} \end{pmatrix} \]
A flow chart, as well as a computer program using MATLAB, has been built to generate the NURB curve for the contour of the selected surface, as shown in figure 9.

**Figure 9.** A flow chart for NURB curve reconstruction for the contour of the selected surface and the resulted curves

### 5.3.3 Surface reconstruction

The surface reconstruction goal is to produce a higher-level representation of the shape of the proposed object in the form of a set of surfaces. Considering the free-form surface elements, it is worth considering the tabulated surface (sweep) surface. The surface will be generated making use of translation sweep transformation (moving a line, curve, segment of the curve, or polygon along a defined distance using the following formula:

\[
G(u, v) = F(u) \times T(v)
\]

Where:

\[
T(v) = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
v^x & v^y & v^z & 1
\end{bmatrix}
\]

F(u) is the parametric equation of the line, curve or segment of the curve, T(v) is the transformation matrix and v_x, v_y, & v_z is the translation distance along x, y & z-axis respectively. A flow chart and computer program has been build using MATLAB program (as shown in figure (10) to generate the tabulated surface from the NURB curve along the x-axis for a distance of (15) mm. Figure 11 demonstrates the reconstructed surfaces for segment (1) using the proposed approach.
Figure 10. The flow chart for the tabulated surface for the NURB curve

In the same manner, other segments can be transformed into surfaces and all patches of the surfaces are connected. The generated surface then will be transformed into solid to be easy use by CAD/CAM programs.

6. Conclusions:
A user interactive Reverse Engineering methodology has been exhibited to reconstruct part shape. The proposed approach comprised many steps starting from data acquisition using the laser scanning
device. Then, the acquired data (points cloud) had been manipulated and decreased up to 66.6%. After that, and because of the part complexity, the surface had been segmented into subsets; each segment was treated separately. A mathematical derivation for the NURB curve with No. of control points of 10 and \( k=3 \) had been constructed. Using the NURBS curve permit control and model edition by managing the control point's weight. Algorithms and computer programs using MATLAB software had been generated to reconstruct tabulated and plan surfaces. Finally, the part geometry had been mathematically described. This description was more organized and useable by divers CAD systems than points cloud.

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