LEIBNIZ UNIVERSITY HANNOVER

INSTITUTE OF PHOTOGRAMMETRY AND GEOINFORMATION

MASTER THESIS

Quality Control of Sheet Metal Parts Using Optical Metrology

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STATEMENT OF AUTHORSHIP

Hereby, I declare that this master thesis has been entirely written by me. Any references to previous or external works have been clearly stated and no further sources except those already mentioned were used. I state that this thesis with the same or similar form has not been admitted to any examination board before.

Hannover, Chaman Kirty

ABSTRACT

The present master thesis investigates and proposes a technique to carry out quality control of sheet metal parts using optical metrology. Conventional techniques of quality control in mass production is time taking and reduces the efficiency of the manufacturing. The idea proposed in this thesis provides an alternative to conventional quality testing techniques. Blue light fringe projection is used to 3D scan a sheet metal part, which is compared to reference CAD model using Gaussian curvature values at every vertex. Deformation model is further used for comparison to account for the validation of the method showing differences in the area of mismatch. Descriptive analysis and pixel level color comparison is carried out for quality comparisons.

ACKNOWLEDGEMENTS

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CHAPTER 1

INTRODUCTION

1.1 MOTIVATION

Quality Control and Inspection has been a major factor for industrial production effectiveness and success. Most of the mature organizations nowadays work at a scale of low defects per million parts, as customers expect completely defect free products. Over several decades, different quality and inspection methodologies have been developed like Gauges, Inspection tools etc. During this era of mass production, there is a requirement of fast quality checking. Surfaces are difficult to be quality checked and it is a time taking process using traditional techniques. The motive of my work is to develop a fast quality control methodology using Optical Measurement techniques and CAD model for faster and better quality check compared to traditional measuring techniques. It will help in quantitative as well as qualitative improvement in a manufacturing process.

Sheet metal forming is a widely used and most productive manufacturing technique for mass production used in variety of processes including automotive parts and household articles. Sheet metal forming is done in a press shop where punching operations take place on a flat sheet metal. These are used in variety of product lines like automotive structures, light fixtures, household products like washing Machines, refrigerators etc. The designs are mostly aesthetic and demands precision for better quality. Also the stamping process of sheet metal forming causes defects like dents, pimples, wrinkles as well as geometrical deviations like spring back. Spring back is a geometrical defect which occurs quite often in sheet metal. Sheet metals forming process involves a lot of elastic-plastic bending. As during punching process, sheet metal is shaped by punching. After the removal of the punches and blank-holders, these residual stresses are released causing a spring back and hence causing spring back defect in the sheet metal parts. All these defects must be checked during quality inspection of sheet metal parts. Hence a much precise and quicker technique is required to do quality testing on sheet metal parts, which can detect these defects in a shorter time period with a higher accuracy.

[Jyrkinen et.al, 2003**]** discussed in detail about the origin of production errors in the production flow of constructions based on fabricated sheet metal parts. Using three types of factories in Finland:-

Factory A: manufactures electrochemical locks

Factory B: manufactures sheet metal parts for electronics, telecommunication and Automotive Industry

Factory C: manufactures inner and outer enclosures for telecom applications.

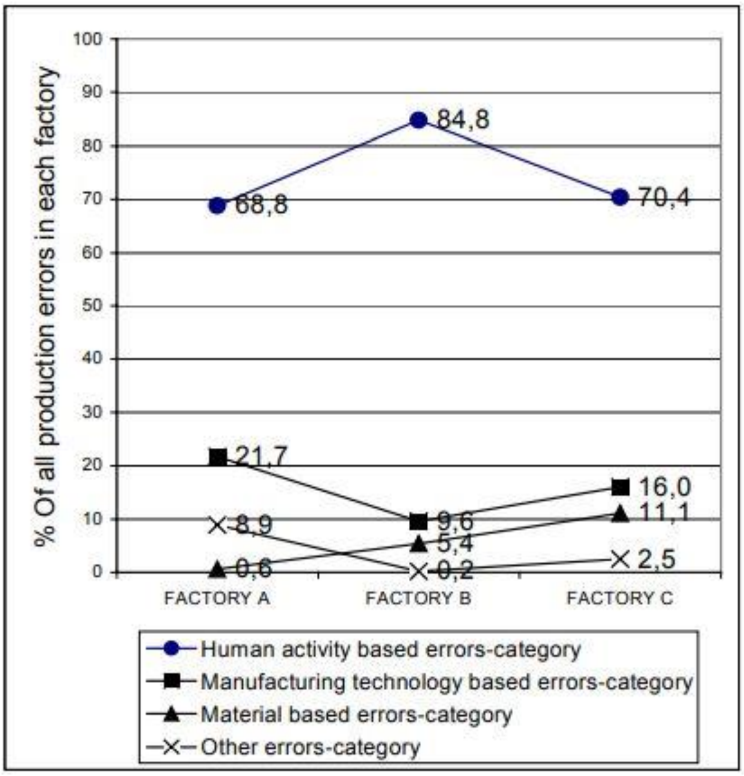


Figure 1-1: Origins of Production errors **[**Jyrkinen et.al, 2003**]**.

Out of 732724 inspected 84011 parts were found defective. The figure1-1 shows the share of the origins of the production errors. It was observed in the experiment that human based errors are comparatively very high. Typically these human based errors are caused by defective process settings and faulty maintenance. In mass production, the production volume is very high and the cycle time is very low.

This advocates the dire need of intermittent line inspection which can be carried out much smoothly and quickly using optical metrology.

Optical Methods for 3D measurement is a very active field of research which is classified as passive and active based on the features they use. Passive method requires features which are present in the object which are getting measured, while active method produces features by projecting a regular pattern of light on the object. Using an active method by projecting fringe patterns on the sheet metal gives sufficient accuracy .Time is a very important factor when it comes to quality checking industrial parts, hence projecting fringe patterns on a surface gives us a very fast method for calculating coordinates of several points at the same time.

Furthermore, 3D measured features of an object (in our case sheet metal part) obtained using optical methods can be compared with the CAD model features of the same object as well as with other defective scanned models. This gives detailed information on the quality of the manufactured object as how good is the surface finish, if there is no surface defects like cracks, proper positioning of holes and other fixture indentation in the parts. The overall process flow is as described in the figure 1-2.

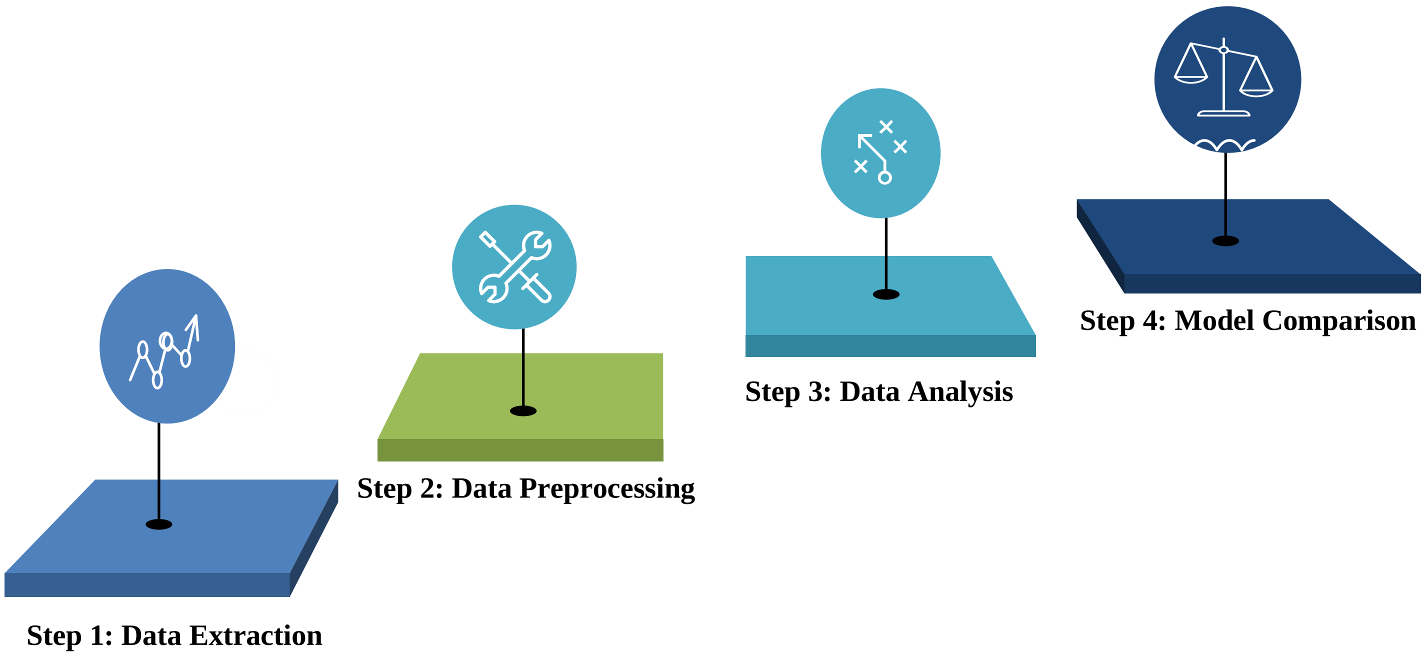


Figure 1-2: 3D Inspection Process

1.2 RESEARCH QUESTIONS AND OBJECTIVES

Given the motivation presented in the previous section, the main research question which arises is '*How well the quality control of sheet metal parts can be done in Industrial condition with precision & shorter time.*' The method adopted is utilising photogrammetric techniques to carry out fringe projective 3D scanning of the sheet metal part and then comparing it to the CAD model. The comparison uses the Gaussian curvature analysis over both scanned model & CAD model and then registering the differences between the values obtained for Gaussian Curvatures. Furthermore, other shape features like holes can be compared to find out the differences and hence controlling the quality.

The main objectives for the work described in the thesis are identified as:

1. To research and identify techniques of comparing different 3D models for quality check.
2. Giving a structural format of doing quality control for industrial purposes. Most of the quality check software provides a method to obtain quality check but it is like a black box.
3. Identifying defects on sheet metals using optical techniques and doing a quantitative analysis for better quality check and shorter checking duration.
4. Finally to investigate the possibility of defining an "Intelligent process model" with general applicability within the sheet metal industries.

CHAPTER-2

FUNDAMENTALS

2.1 GAUSSIAN CURVATURE (k_G)

'Curvature' is one of the concepts that are adapted differently in context of mathematics which causes sometimes a lot of confusion. Intuitively, Curvature measure to what extent an object such as a surface or a solid deviates from being a 'flat' plane. Since most of the discovery in the field of curvature is credited to 'Carl Friedrich Gauss' an excellent mathematician, hence the term is coined as 'Gaussian Curvature'.

As we are dealing with triangulation of meshes over surfaces for measuring the Gaussian curvature, it is important to understand the concept behind it. Hence, according to Euclidean geometry the sum of all the angles inside a triangle sums up to 180 degrees irrespective of the shape but on a plane. We can visualize in the following figure 2-1.

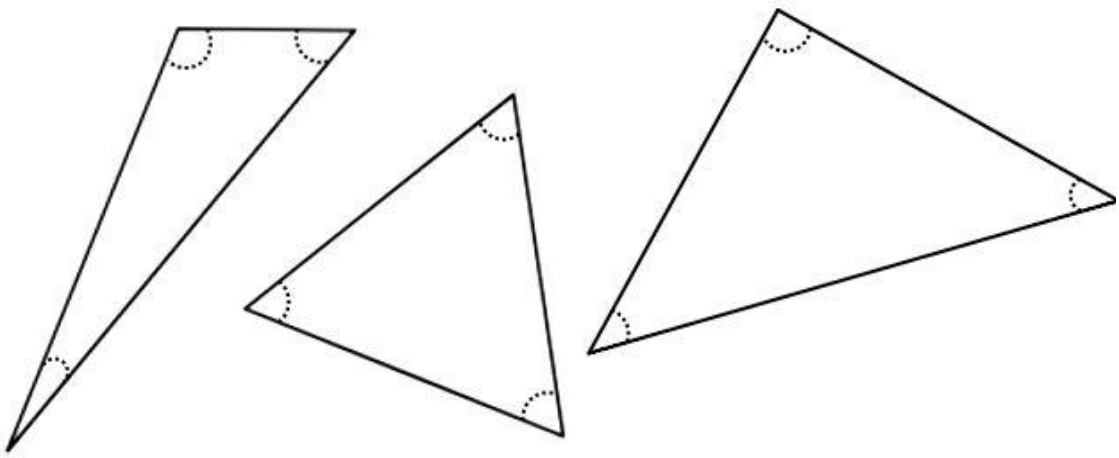


Figure 2-1: Triangles on a plane with different shapes and sizes.

But when we trace a triangle on non planar surface such as sphere, we encounter triangles with different angular sums than 180 degrees. For example in the following figure 2-2, there are three right angles on sphere in one triangle.

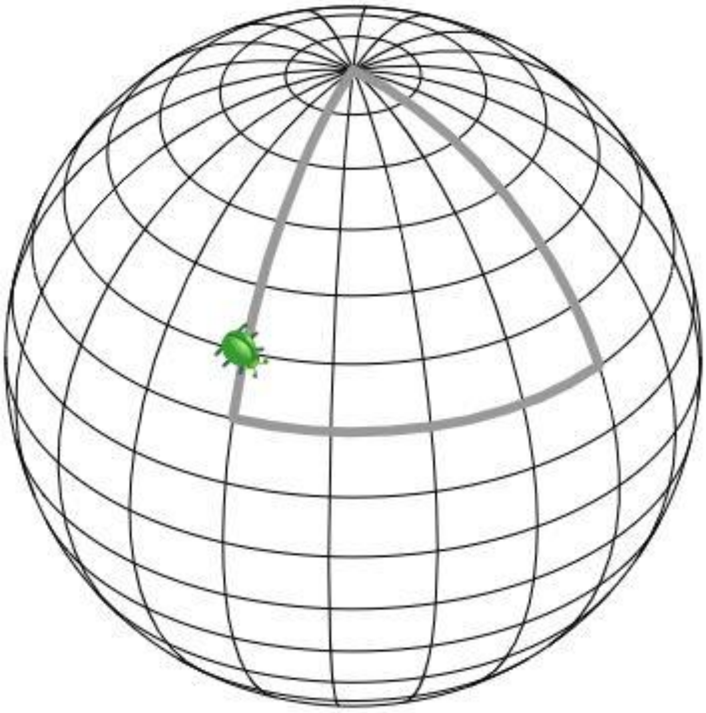


Figure 2-2: 3 right angles in a triangle on a sphere.

Three types of curvatures:

1. *Positive Curvature.*
2. *Negative Curvature.*
3. *Zero Curvature.*

1. *Positive Gaussian Curvature* is the terms used for expressing the curvature which has an angle sum of more than 180 degrees. Intuitively, When $k_G > 0$, it tells how locally spherical or elliptical the surface is.

2. *Negative Gaussian Curvature* is used for expressing an angle sum of less than 180 degrees. When $k_G < 0$, it tells how locally saddle shaped or hyperbolic the surface is.

3. When there is *Zero Gaussian curvature* it means the angle sum is 180 degrees. When $k_G = 0$, it shows how locally cylindrical or parabolic the surface is.

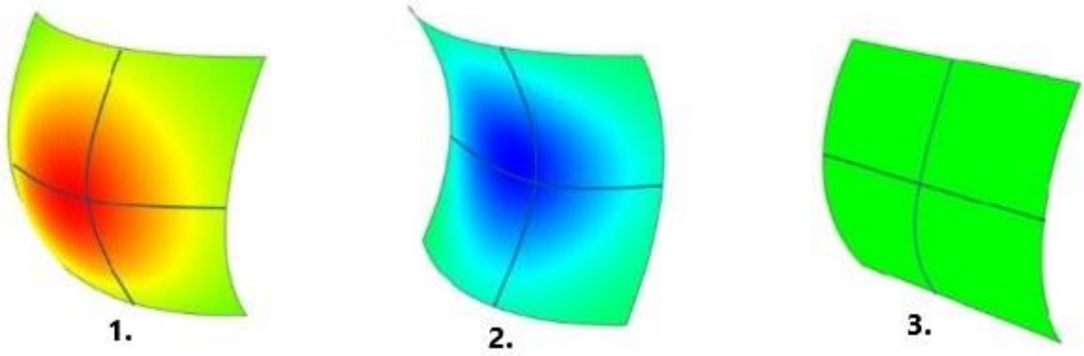


Figure2-3 : Types of Gaussian Curvatures 1.Positive 2.Negative 3.Zero
[Jyrkinen et.al, 2003**]**

Gaussian Curvature (k_G) on a continuous surface is defined as the product of the principal curvatures k_1 & k_2.

$$k_G = k_1 * k_2 \quad Equation(2.1)$$

For any free form surface, its quality depends on Gaussian Curvature. It describes how bent a curve is at a particular point i.e how much the curve deviates from a straight line at a point. This 2D concept can be extended to 3D. A curve can be constructed by mathematically cutting the surface with a plane. Gaussian Curvature can be best described with the intersection of mutually perpendicular planes. As it is an intrinsic measure, it depends on the metric value and not on the orientation of the surface in the 3D space. The most notable challenge in finding the Gaussian curvature is that we need to know the equation of the surface patch locally, so that principal curvatures can be computed.

This challenging problem was solved by finding the 'discrete Gaussian curvature' on a triangle mesh via a vertex's angular deficit [Meyer et.al, 2003]. The triangulated mesh is piecewise linear and at every vertex, the angular deficit is a great tool to inspect the local behaviour.

The Equation is given by:

$$k_G(v_i) = \sum_{j \epsilon N(i)} \theta_{ij} \quad Equation(2.2)$$

Where $N(i)$ are the triangles incident on the vertex *i* and θ_{ij} is the angle at vertex *i* in the triangle *j*.

It is interesting to observe that the value of θ_{ij} is related to the curvature of the vertices in a triangulated mesh [Akelman et.al, 2006]. More Precisely,

- θ_{ij} < 360°, vertex is either on convex or concave surface
- θ_{ij}= 360°, vertex is on planar surface.
- θ_{ij} > 360°, vertex is a saddle point.

The definition of θ_{ij} at a vertex tells how sharp is the convex or concave area and if the vertex is on a planar surface or if it is saddle shaped. It is very important to observe that this definition is different than the one mentioned before for the Gaussian curvature. This concept is used while computing Gaussian curvature using the python library of IGL.

2.2 MESH DATA

As the work is concentrated on Mesh data types, it is important to discuss in depth about the type of data used. CAD model as well as the 3D Scanned model is in STL (Stereolithiography) format. STL data are triangulated meshes which are made by joining point clouds on a surface. Each triangle on a surface is described by an outward normal and the coordinates of three ordered point. Such triangulated meshes stored in STL format data are used for definition of different geometrical properties in several industrial and research applications. In this case, it is used for observing the quality of the surface.

An STL file consists of facet data. Each facet is uniquely identified by a unit normal and by three vertices. Hence in total, 12 numbers are stored for each facet. The two important features of STL data are Facet Orientation and Vertex to Vertex Rule. Facet Orientation is determined by the direction of the unit normal and the order in which the vertices are listed. Vertex to Vertex Rule determines that each triangle must share two vertices with each of its adjacent triangles.

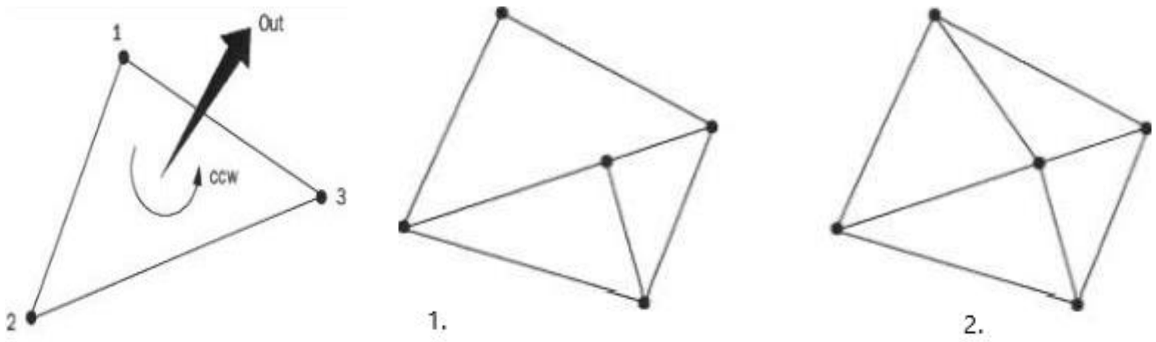


Figure 2-4: Mesh Representation. Vertex to Vertex Rule (Right) and Orientation of the facet (left)

Figure 2-4, shows Vertex to Vertex rule example in which Mark 1 represents the violation of the rule while Mark 2 represents the correct configuration. Orientation of the facet is determined by the direction of the unit normal in the order of which the vertices are listed.

Because STL is a universal format, many different kinds of software can create them. Some of the software may not record all the data properly resulting in errors. Even during the triangulation of scanned point clouds, these data gaps are present.

2.3 POINT CLOUD TO TRIANGULATED DATA SET CONVERSION

The method of 3D reconstruction involves conversion of 3D point clouds to a mesh structure. This is done using Delaunay triangulation algorithm, in which for a given set of discrete points (P) in a plane is a triangulation DT(P) such that no point in P lies inside the circumcircle of any triangle in DT(P). This can be visualized in the Figure 2-5

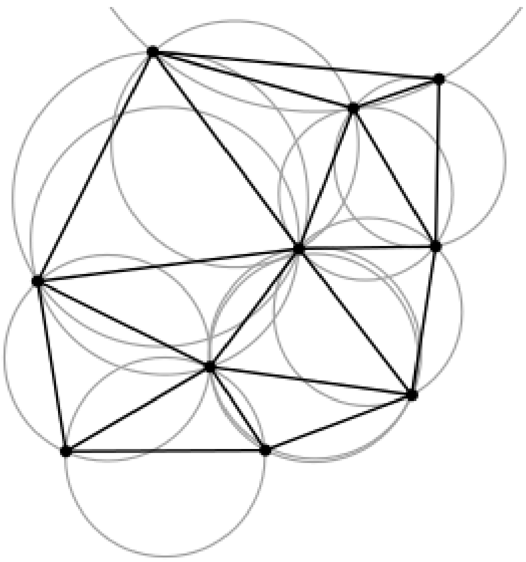


Figure 2-5: Delaunay Triangulation.

For the scattered points, the points are projected to a plane. These points are triangulated using Delaunay algorithm. Then inverse transformation is used to project them for 3D triangulation as depicted in Figure 2-6.

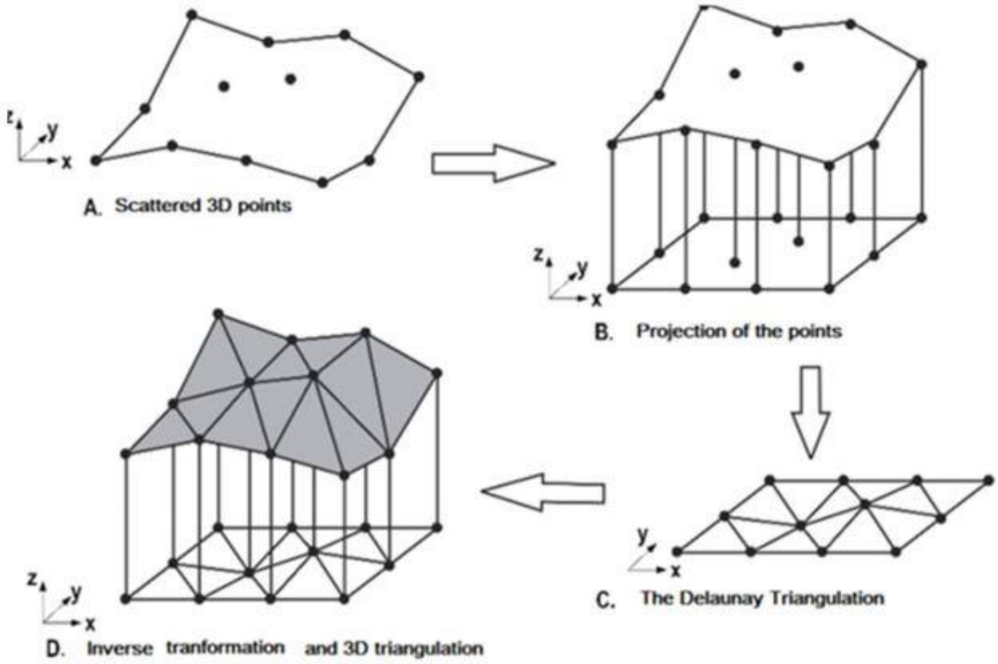


Figure 2-6 : Process of 3D reconstruction [Ioannides et.al,2013]

Typical errors which are accounted:

Self Intersection: When triangles contain mismatched coordinates and do not line up as expected. This creates an error because the surface can be in two places at once or create areas with zero thickness.

Open Faces: Missing data results in holes or open faces. This happens very often during the scanning process.

Inverted Normals: This occurs when the coordinates of the triangle are stored in an incorrect order, resulting in the 'inside' face being inconsistent with the surrounding triangles.

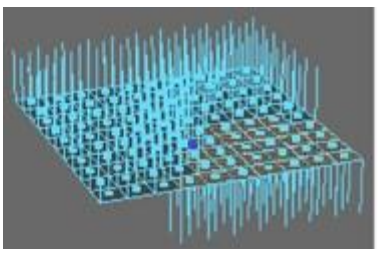


Figure2-7:Inverted Normal

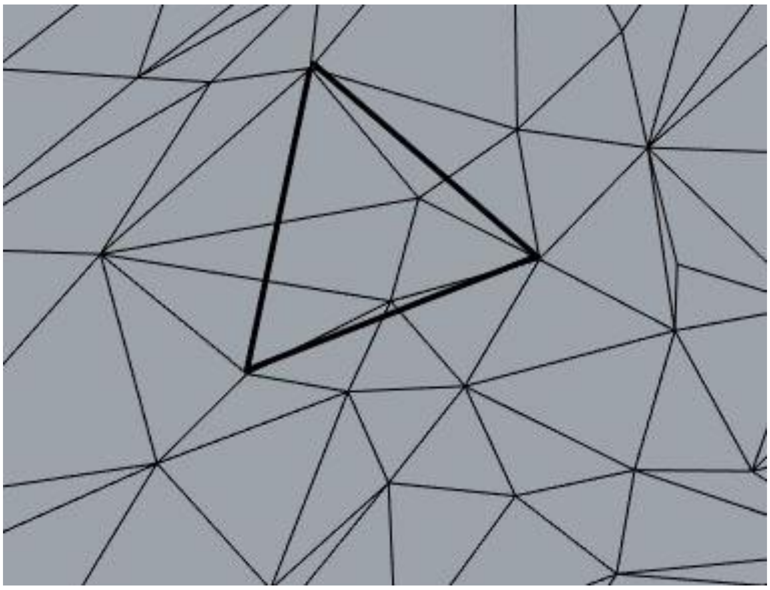


Figure 2-8 : Self Intersection

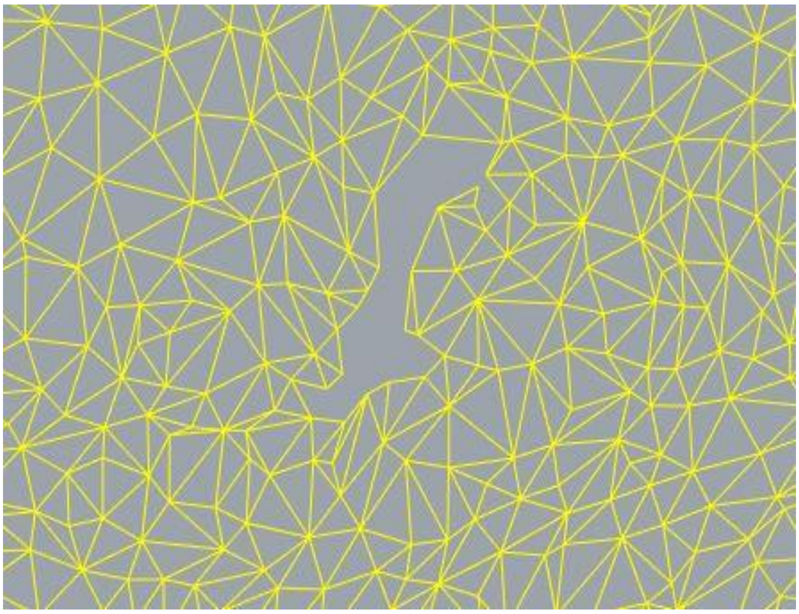


Figure 2-9: Open Faces

These errors are important to be dealt with before further computation in pre-processing, so that the data can be processed for Gaussian Curvature comparison. Hence it is a very critical part to know Mesh errors as it tell us the quality of our test. These errors are the main reason for the pre-processing of the CAD data before analysis.

2.4 OPTICAL SCANNING TECHNOLOGY

Reverse Engineering is a process of obtaining an identical CAD model from an existing physical object. It is beneficial in the field of quality control. Optical scanning technologies are potential tools for faster reverse engineering to find surface finish, default lines and bottlenecks in design & productivity.

Optical scanning is a method for capturing surface contours of an object. Optical scanning using Blue Light Technology is used in the thesis work because it provides a shorter wavelength, filtering out the ambient light making it suitable for reflective surfaces. Its homogeneous frequency range makes it more precise than white light.

Blue Light Technology recognizes contour by triangulating the line of sight of a photographic lens and the line of sight of a light source that projects a "fringe" pattern on the surface being measured. Then the software is used which in the background does the resection in space to determine the exterior orientation of the cameras and furthermore forward resection to determine the 3D object coordinates.

2.5 OPTICAL TARGETS

There are different kinds of targets which can be used for 3D scanning of the model, depending upon the surface and the requirements. DOT and CODE targets are the most common types of targets used. These targets are applied on the object or on the surfaces around the object for referencing. They each have a unique shape and ID and therefore can be detected and distinguished from each other in every image. These targets provide a base for a coordinate system for the 3D scanned model as the markers were placed on a round turning table. As the whole model is scanned multiple times to register all the points on the surface, targets also provide a merging strategy for converting all the individual scans to a complete scan. In this master thesis, DOT target of 5mm diameter is used.

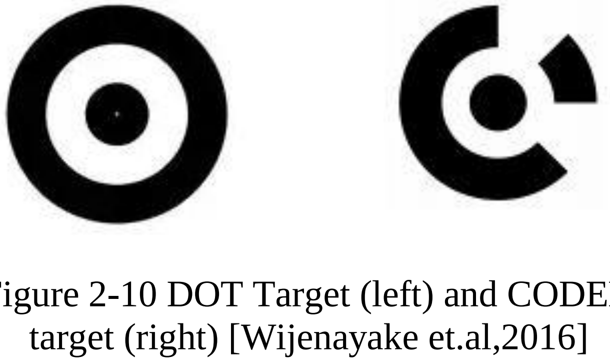


Figure 2-10 DOT Target (left) and CODED target (right) [Wijenayake et.al,2016]

2.6 SURFACE DEFECTS

In Automobile sector, Class A surfaces (a freeform surface) are used intensively to provide an aesthetic appearance to the body. The freeform surfaces have curvatures. These surfaces are formed by dies and punches which involves the process of applying pressure. Also the whole manufacturing process involves assembly and other processes. It causes defects like dents and pimples. Hence in this master thesis, Dents and Pimples are analysed using Gaussian curvature. These defects were made on the surface by a hammer and also by using Meshmixer for deforming the surfaces. It can be seen in the Figure 2-10 and 2-11

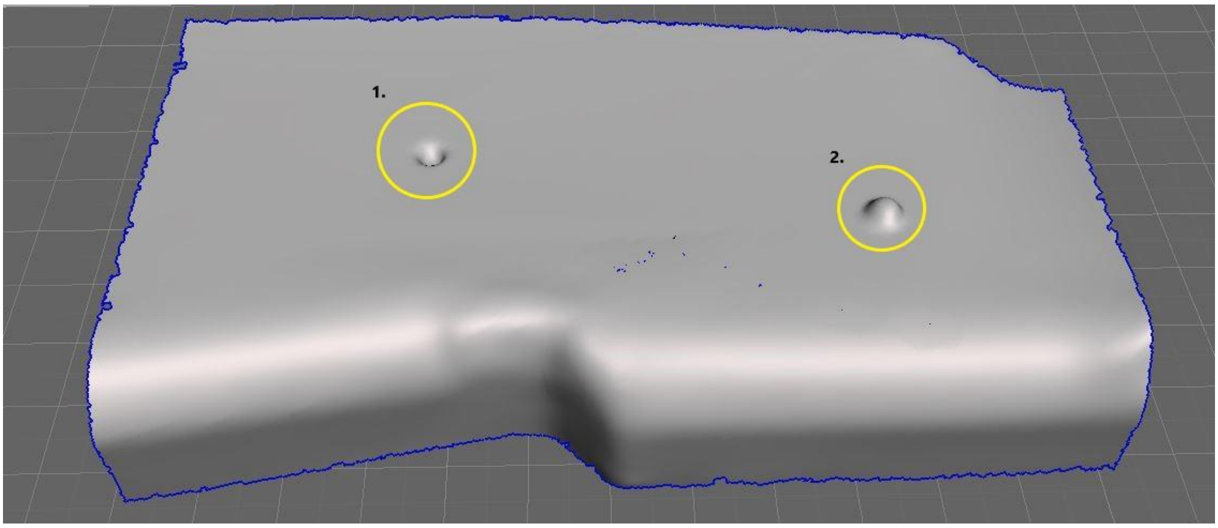


Figure 2-11: Surface Defects 1.Dent 2.Pimple made using Meshmixer.

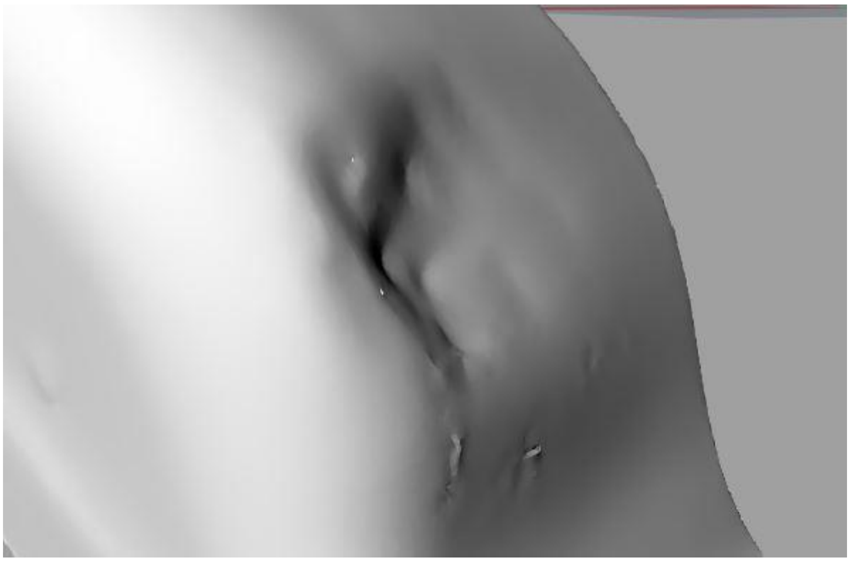
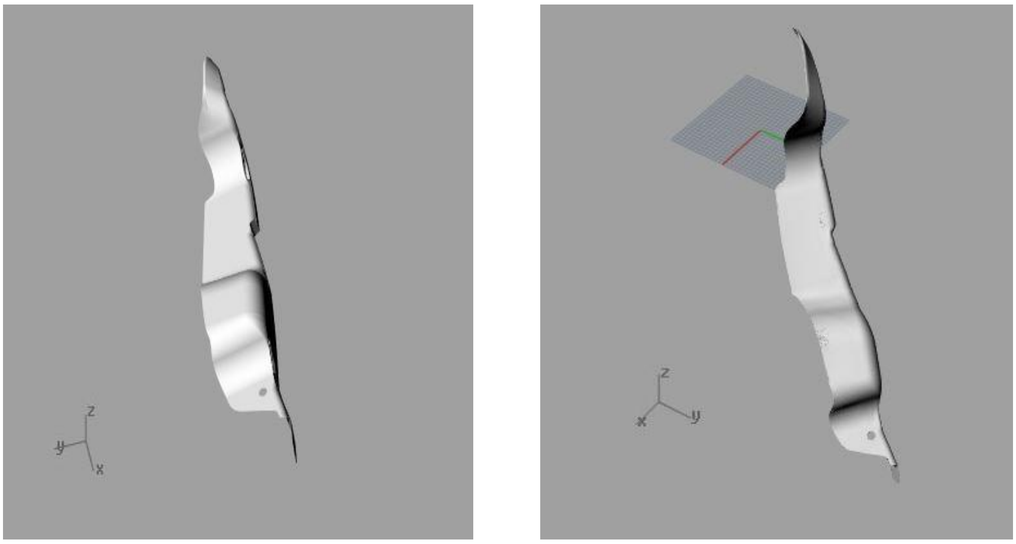


Figure 2-12: Dent made using a Hammer on the Manufactured Model

2.7 COORDINATE SYSTEMS

The most common way of comparing two 3D models is by transforming them to the same reference system. Generally, 3D models obtained from different acquisition methods have different local coordinate system. As in the case of the master thesis, CAD model has different coordinate system as compared to the scanned model depicted in Figure 2-12.



CAD Model   Scanned Model

Figure 2-13: Coordinate Systems

For finding the similarity, Iterative Closest Point algorithm is often used, by which the transformation parameters of two point sets are calculated through the correspondence of matching points on the 3D surfaces. However, the major challenge is that initial values are required for the iteration and finding correspondences.

To avoid this conventional way of surface comparison, Gaussian curvature computation as a scalar value at every vertex is used. Irrespective of the coordinate systems, the comparison between different models can be done to observe the defects and deformations.

CHAPTER-3

METHODOLOGY

3.1 SCANNING SYSTEM

In the process of obtaining surface quality, 3D scanning is done using GOM ATOS core 500. It is a 3D coordinate measuring system with narrow band Blue Light Technology and Split design stereo camera system which provides high resolution data and rapid measurement. It handles complex metrology applications and generates high resolution meshes. GOM ATOS professional software is integrated with the scanner to provide .stl data for further processing.

Figure 3-1: GOM ATOS Core 500.

Technical Data	ATOS Core 500
Measuring Area	500x300 mm
Working Distance	400mm
Point Spacing	0.19mm
Sensor Dimension	361x205x64 mm
Weight	2.9 kg
Power Supply	90-230 V AC
Operating Temperature	+5°C to +40°C, non-condensing

Table 3.1: Technical Specification of GOM ATOS Core 500. [GOM, 2020]

Table 3.1 provides an overview of the technical specification of the scanner. It is evident from the table above that it is good for small and medium size measuring surfaces with the point spacing accuracy of 0.19mm. Also the sensors provide 2 Million points per scan which helps in a faster scanning of the whole part. All the details are obtained from the Technical Specification Guide of GOM ATOS series [GOM, 2020].

The fringe projection sensor ATOS is based on Triangulation. Different fringe patterns are projected on the object and observed with two cameras. With its highly efficient calibration method, the cameras can be calibrated in 10 minutes. For the complete measurement of the 3D object, multiple views have to be integrated in one set of data. To allow automated transformation of the digitized data, reference markers are placed either on the object or on the turn table. It is very important to have at least 3 markers in every consecutive scanning, so that the integration can be done. In case of less than 3 markers, the ATOS software gives an error message of having insufficient referencing for integration.

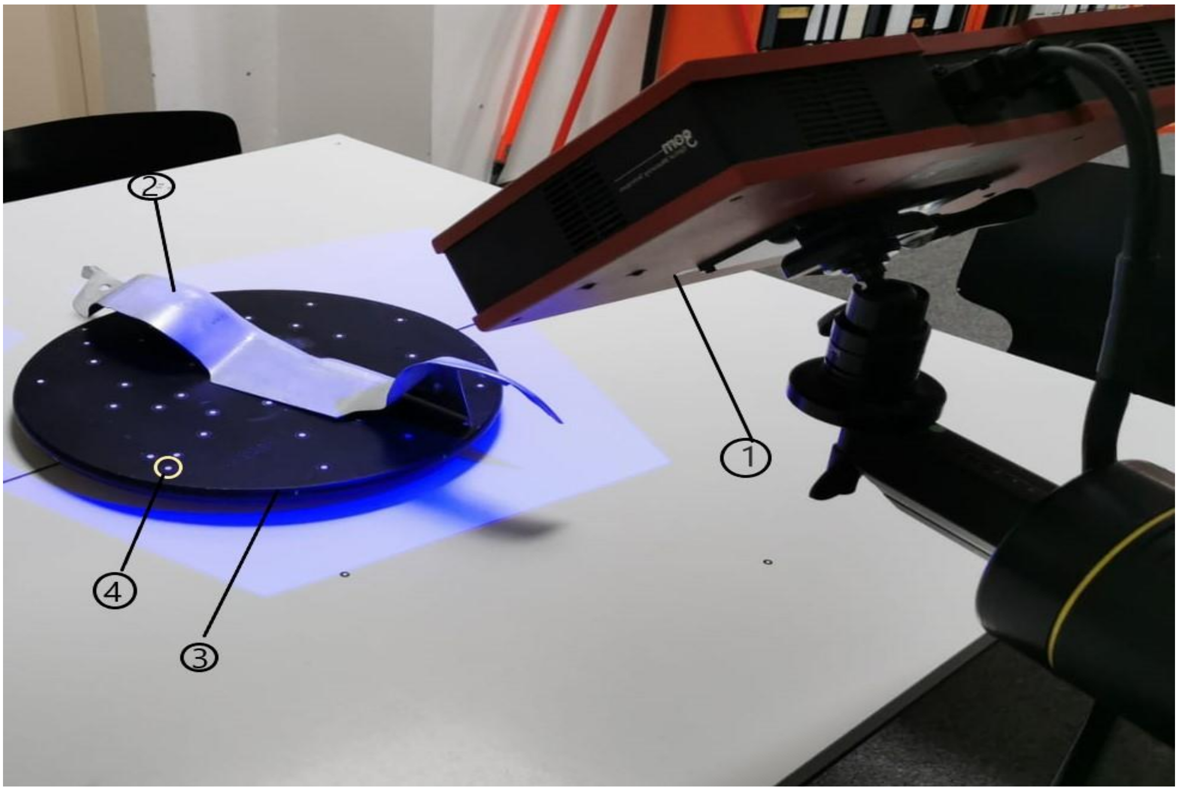


Figure 3-2: Set up for 3D Scanning of the part

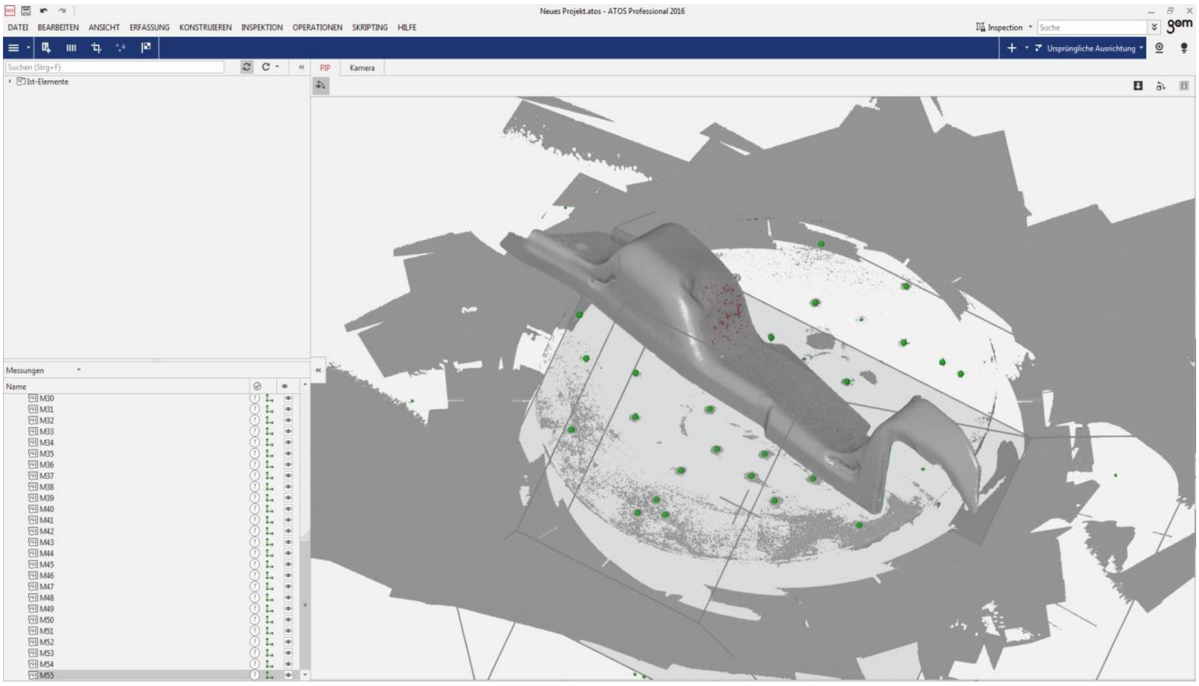


Figure 3-3: ATOS Professional Software linked to Scanner

In Figure3-2, Mark 1 is the ATOS Core 500 scanner which is projecting blue light fringes on Mark 2 which is the measuring sheet metal Industrial part. It is mounted on a rotating round table Mark 3 which can be rotated manually to scan the object from all the sides. The round table has several markers Mark 4 which are the DOT targets of 5mm size.

Figure3-3 shows the ATOS professional software on which the scanned .stl file is generated after scanning the whole part in several scanning steps. It provides an easier way of observing all the scanning measurement and then redoing it by just deleting that scanning step and scanning again. Depending on the requirement, different markers can be used like DOT or Coded Magnetic Markers. Furthermore, triangulation of all scanned points is done in the software to get a scanned 3D CAD model. ATOS Professional also provides the analysis tool to know about the quality but it is not used, because the sole purpose of this thesis is to design a quality control technique and not to use software which is more like a black box.

3.2 ANALYSIS SYSTEM

3.2.1 CAD VISUALIZATION

After obtaining the scanned data of the sheet metal part, the whole process of analysing starts. Firstly, CAD model (obtained from Volkswagen AG Hannover) is inspected in PTC Creo 3.0 Academic Edition. This is done to check the CAD model representation in .stl format and remove some pre-existing extra assembly part. CAD model serve as a reference model which is the benchmark for the quality.

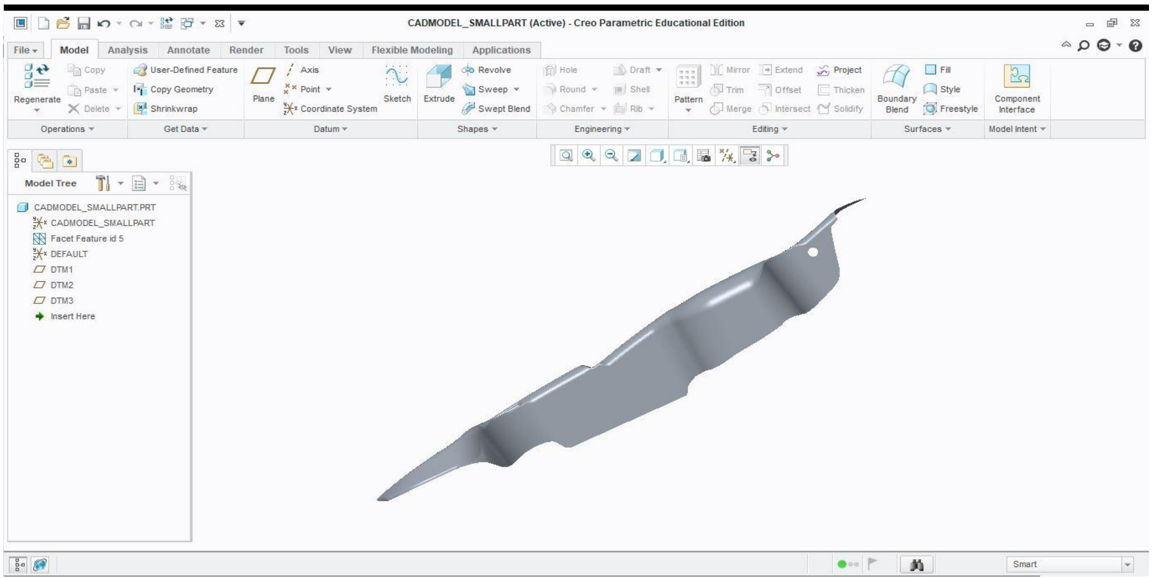


Figure 3-4 : CAD Model inspection [Creo,2020]

3.2.2 PRE-PROCESSING

Pre-Processing is one of the most critical step before performing any analysis. It is very important to obtain 3D models with comparable features. So as to say in a broader way, 3D model in .stl format should have equal number of triangulated meshes or in classical computer vision terminology as equal number of segmentation. In descriptive analysis, it will help to compare plots to deduce some result about the method. Also during the scanning process, sometimes there are mesh defects like holes, self-intersecting meshes and inverted normals. They need to be rectified so that the comparison can be done for quality.

To summarize, the pre-processing includes the following rectifications:

1. Mesh Defects like holes, self-intersection and inverted normals.
2. Mesh Reduction i.e to reduce the number of vertices and faces.

The above mentioned process is done using Rhinoceros 5.0 Evaluation version. The mesh reduction techniques primarily reduce mesh size by iteratively merging/collapsing edges into vertices with the goal of geometrical and topological preservation [Savio et.al, 2013]. The mesh decimation step uses a cost function to minimize error. These metrics of error minimization uses geometric measure of distance and curvature. It also decreases the computational time of the whole method.

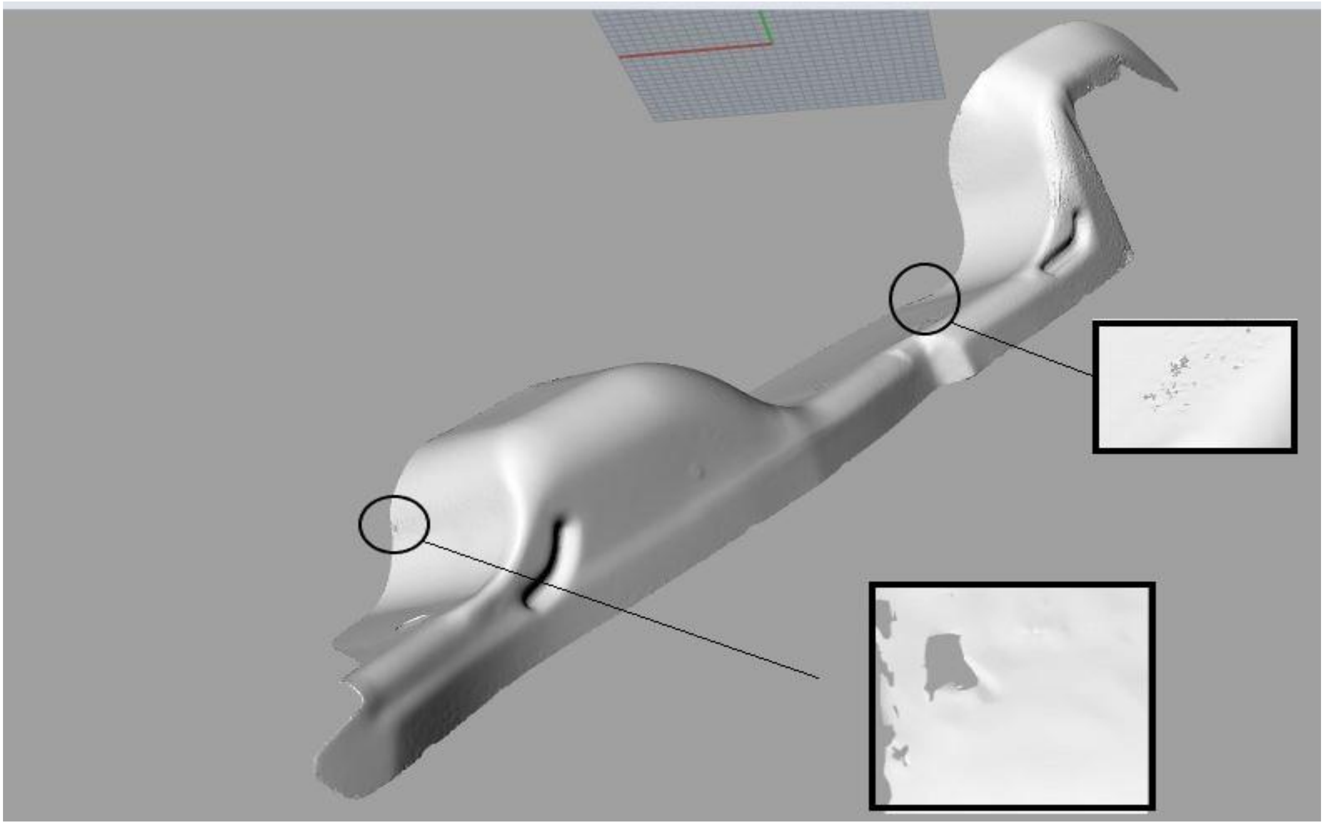


Figure 3-5: Defects in Scanned Model [Rhinoceros 5.0,2020]

Figure 3-5 depicts the scanned model which was obtained using GOM ATOS Core 2 stereo camera system using Rhinoceros 5.0 evaluation software. It can be observed that it has some small gaps and holes during the scanning process. These data gaps required to be filled for attaining a better surface quality which can be used further for data set comparisons.

After complete integration of data by scanning the model with multiple views and fixing the mesh defects, it can still be observed that the mesh is noisy in figure 3-6. This is a very common phenomenon in 3D scanning, because the camera sensor calculate 3D coordinates several times in multiple views causing noisy data set .[Magid et.al,2018]. Hence the process of Mesh Reduction is a crucial pre-processing step for quality comparison between different models.

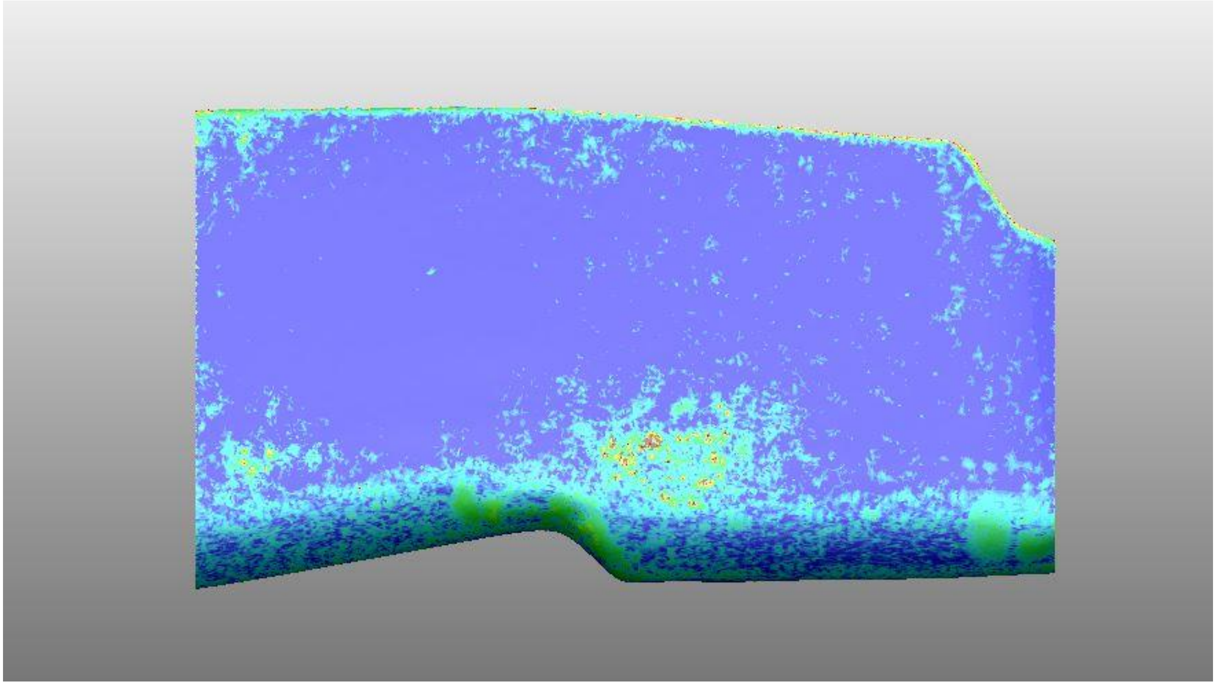


Figure 3-6: Noisy Scanned Model before data reduction.

3.2.3 PYTHON BASED ANALYSIS

The STL file data sets are further analysed in Python using igl library [Libigl, 2020]. Libigl is a simple C++ based geometry processing library which provides the broad range of functionality from sparse discrete differential geometry operators to finite element analysis on geometry. It has a python based binding which is used in the master thesis.

It is forged in python by using:

```
conda install -c conda-forge igl
```

It has few dependencies which includes numpy, scipy and meshplot. Also for doing statistical analysis & plotting, matplotlib and seaborn is used.

Igl library from python is used to read all the .stl files which are obtained after scanning and also the reference CAD files. It gives us the vertices and faces values in a numpy data frame. These values of vertices and faces are used to obtain Gaussian Curvature at every vertex. Furthermore, statistical analysis could be done using Gaussian Curvature for validity and quality control.

```
import os
os.system('cls' if os.name == 'nt' else 'clear')

#Importing all necessary libraries for the computation
import igl
import scipy as sp
import numpy as np

from meshplot import plot, subplot, interact

## Load a mesh in stl format
v, f = igl.read_triangle_mesh("CADmodel_referencepart.stl")

## Print the vertices and faces matrices
print("Vertices: ", len(v))
print("Faces: ", len(f))

plot( v,f, c=v[:, 0])
```

```
Vertices:  255072
Faces:  85024
```

Figure 3-7 : Python Code for CAD Model data extraction

```
## Load a mesh in stl format
v1, f1 = igl.read_triangle_mesh("remeshed_surface_small_part.stl")
## Print the vertices and faces matrices
print("Vertices: ", len(v1))
print("Faces: ", len(f1))

plot( v1,f1, c=v1[:, 0])
```

```
Vertices:  255072
Faces:  85024
```

Figure 3-8 : Python Code for Scanned Model data extraction.

Figure 3-7 and 3-8 depict the python script for reading the .stl files for CAD and Scanned Model. It can be observed that vertices and faces obtained are equal in both cases. This is done in pre-processing and hence reducing the errors involved in the analysis.

3.2.4 DESCRIPTIVE ANALYSIS

There are different types of distributions. We can use probability, frequency or cumulative distributions to analyse a data set. In overall, we can distinguish distribution being discrete and continuous. Discrete distribution is often represented by histograms while continuous distributions are numerous, because they correspond to mathematical models. Gaussian or Normal distributions are few examples for continuous distributions. In computational methods, most of the value sets are discrete. So to generalize for continuous spaces, it is necessary to approximate a discrete distribution with a continuous model. Hence when discrete Gaussian Curvature is computed using angular deficit, it is more suitable to compute a histogram with kernel type estimation. Gaussian kernel is chosen because digitized meshes with only one feature often gives Gaussian type curvature distribution [Gauthier et.al, 2017]. This continuous estimation makes histograms less sensible to noise and bin numbers.

Furthermore, statistical analysis is done using matplot and seaborn library in python. It is used for plotting the values of Gaussian curvature values which are in numpy matrix data structure. It is incorporated in the python script using the below mentioned command line:

```
import matplotlib.pyplot as plt

import seaborn as sns
```

The kernel density estimation is done in seaborn using

```
sns.distplot()

sns.distplot(k,fit=None,fit_kws={'color':'black'},kde=Tr
ue,kde_kws={'bw':0.03},hist
=False,color="black",label="CAD Model_area_1)
```

The bandwidth for kernel smoothening is chosen to be 0.03 as it represents the data without over smoothening the curvature values.

3.2.5 VISUALIZATION TECHNIQUE FOR SURFACE ANALYSIS

Colour coded mapping is a widely used technique for visualizing functions over a surface. A colour map associates a specific colour to a scalar function. Colours are principally used to visualize either continuously or discontinuously any scalar function over a surface. Colour provides a fourth dimension and shows the user immediately and quantitatively how the function varies over the surface [Hahmann, 1999].

The Gaussian Curvature map shows the information about the local surface shape. It conveys unwanted local behaviours, as well as surface irregularities as Gaussian Curvature values are very sensitive to small changes if the colour is well encoded.

There are different colour mapping schemes which are used namely RGB, HSV and there are other available different self-customised techniques.

Here in the thesis, primarily linear RGB colour mapping scheme is used to analyse the values for further comparison.

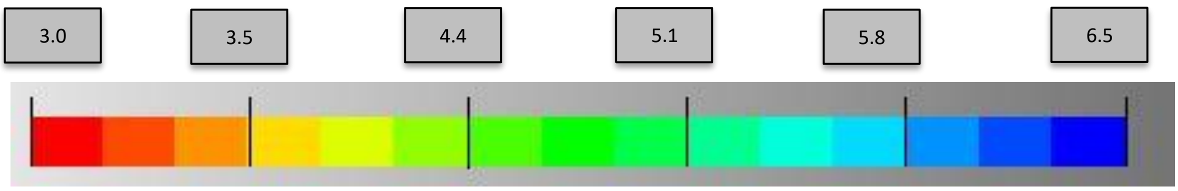


Figure 3-9 : Linear Colour Space Mapping

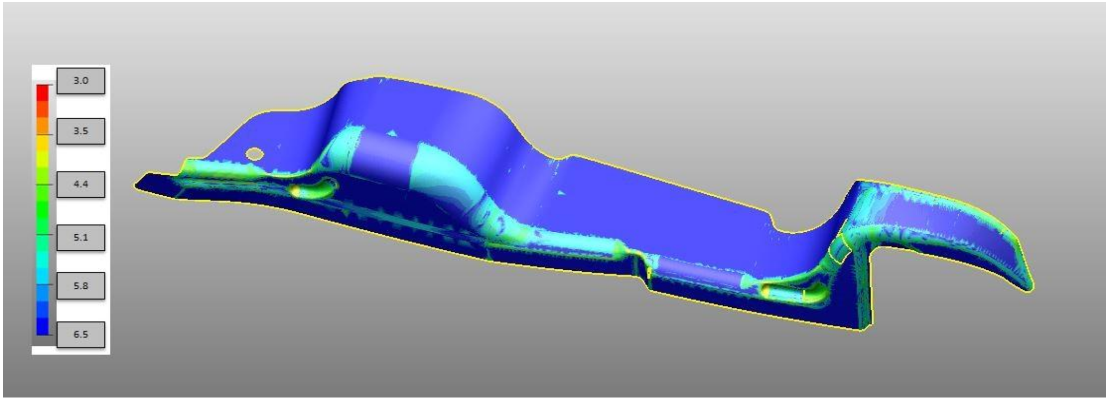


Figure 3-10: Colour Code Mapping of CAD Model.

3.3 METHODOLOGY OVERVIEW

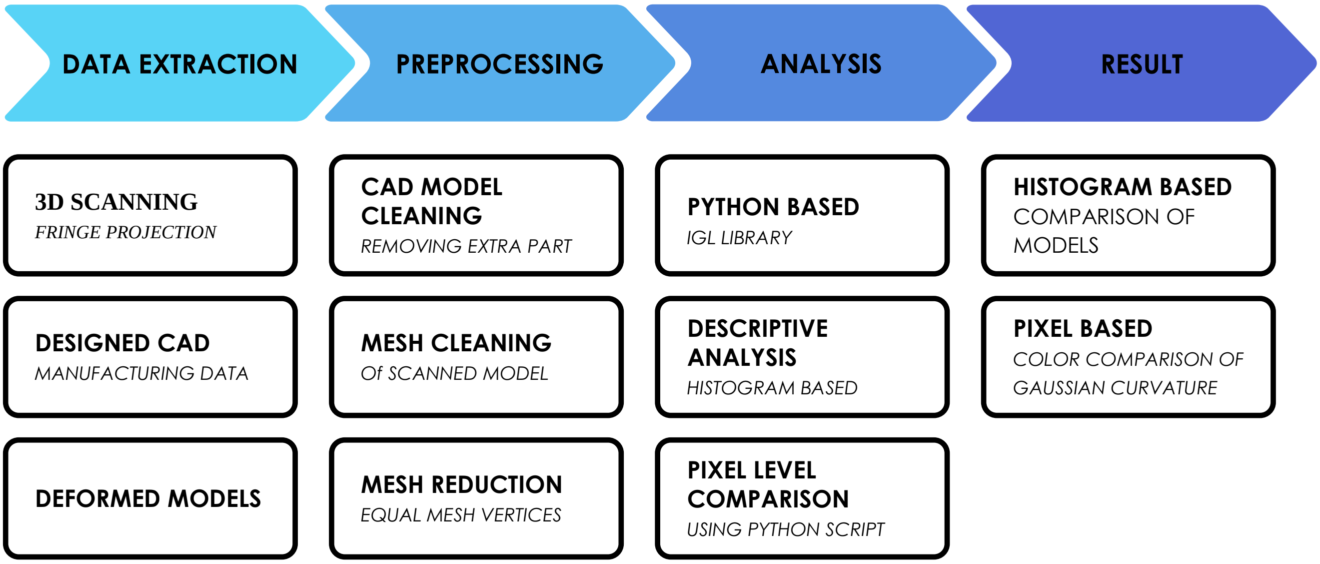


Figure 3-11: Flow chart for the whole process

Figure 3-11 summarizes the overall methodology from the scanning process till the result extraction for the comparison of models. It has 4 divisions, namely Data Extraction, Pre-Processing, Analysis and Result. Every division has its own further processes inside it depicted below the division. It gives a brief idea about the processes adopted during finding the solution to the problem statement.

CHAPTER-4

ANALYSIS

Analysis of the whole research is based on three main models which are used to do a quality check.

4.1 CAD MODEL
4.2 SCANNED MODEL
4.3 DEFORMED MODELS

4.1 CAD MODEL

In the entire thesis work, CAD Model is referred to the designed model of the industrial part, which was used as a reference model. The designed model was obtained from Volkswagen AG Hannover, which is a sheet metal part used in Volkswagen Van outer body.

It was observed that while getting CAD model, it was having a pre-existing assembly which was cleaned using PTC Creo 3.0 Student version. It is important to remove these parts for analysis, as these artefacts can affect the results adversely.

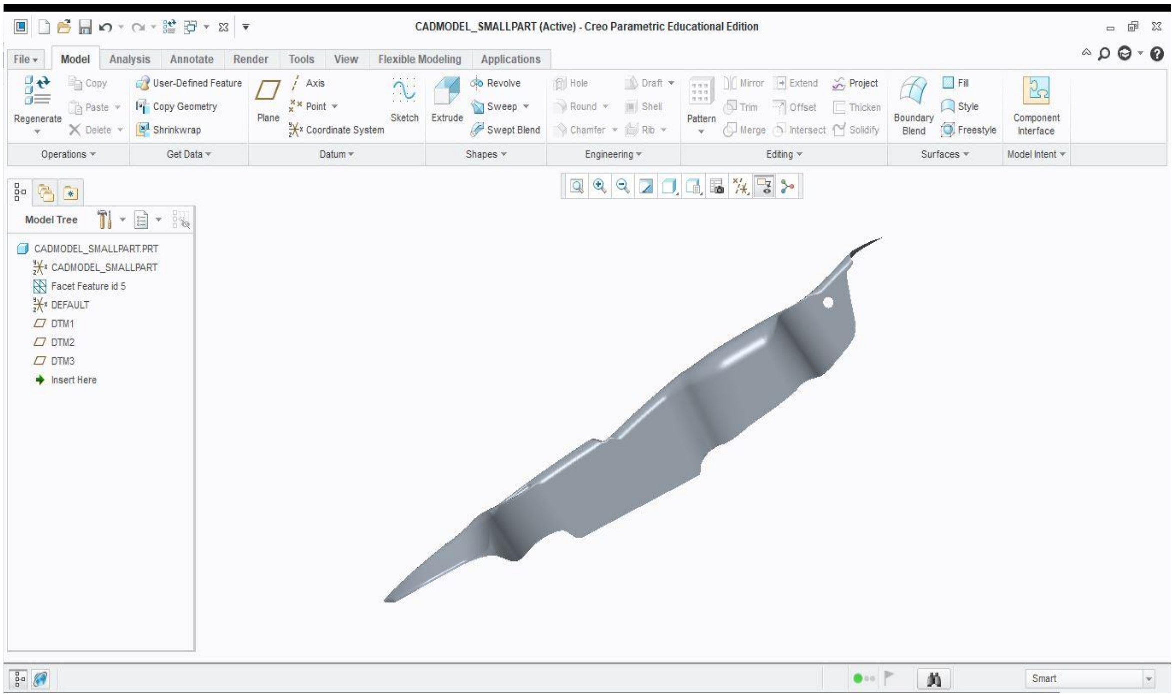


Figure 4-1: CAD Model after removing the extra assembly part.[Creo,2020]

The CAD model shown above in the Figure 4-1 is in stereolithiography format (.stl) which has triangulated meshes. It also shows there are no holes or gaps in the model, so further pre-processing is not required.

The CAD model is further divided into three areas, namely Area 1, Area 2 and Area 3 as shown in figure 4-2.This is done for faster computation of the Gaussian curvature, as well as finding differences and similarities between different areas, and drawing a better conclusion over the involved method. This is done similarly for Scanned and Deformed models.

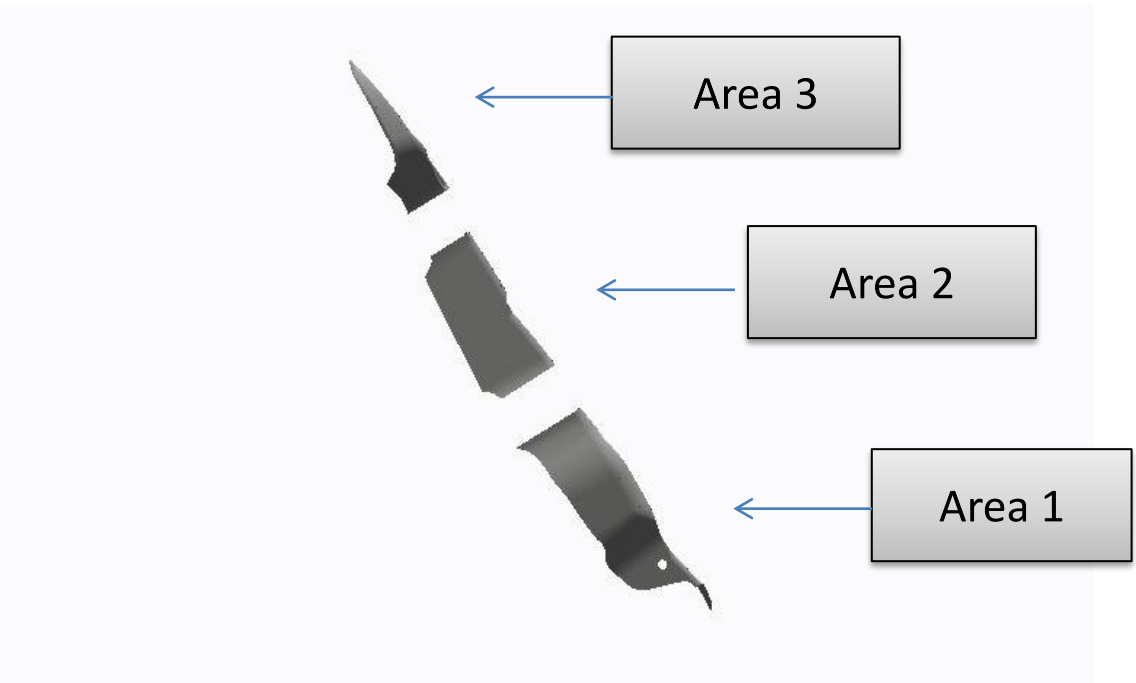


Figure 4-2: Division of the Model in three parts

Analysis will be done separately on different areas to better understand the behaviour of Gaussian Curvature numerically as well as visually.

Now Python script is used to do numerical analysis of the CAD model using IGL Library. The CAD model areas are read using IGL library in python.

```
v, f = igl.read_triangle_mesh("CADmodel.stl")
```

v, f are vertices and faces respectively. Both are numpy arrays.

CAD Model	Area1	Area2	Area3
Number of vertices	107589	30816	118914
Number of faces	35863	10272	39683

Table 4.1 : Vertices and Faces in CAD Model

Gaussian Curvature via angular deficit is done in python using igl library by:

```
K = igl.gaussian_curvature(v,f)
```

Where K is the Gaussian Curvature Values, v and f are vertices and faces respectively.

After obtaining the Gaussian curvature values, descriptive analysis is done on the data set to know the behaviour. Histogram provides local feature information at every vertices which characterizes that surface. But as Curvature values are real, it is more suitable to compute histogram with continuous estimation. Hence, Histogram with Gaussian kernel type estimation is used.

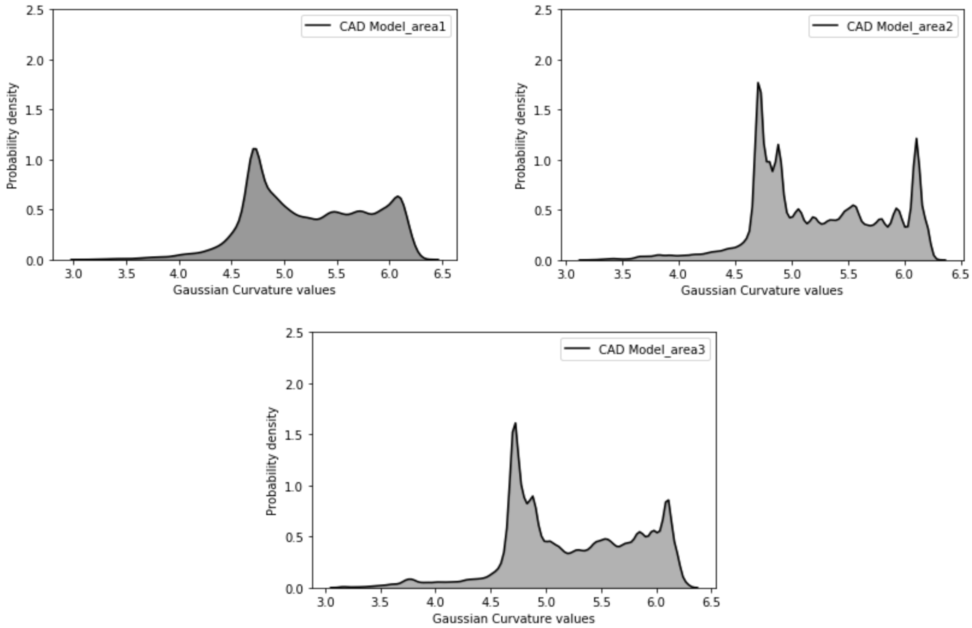
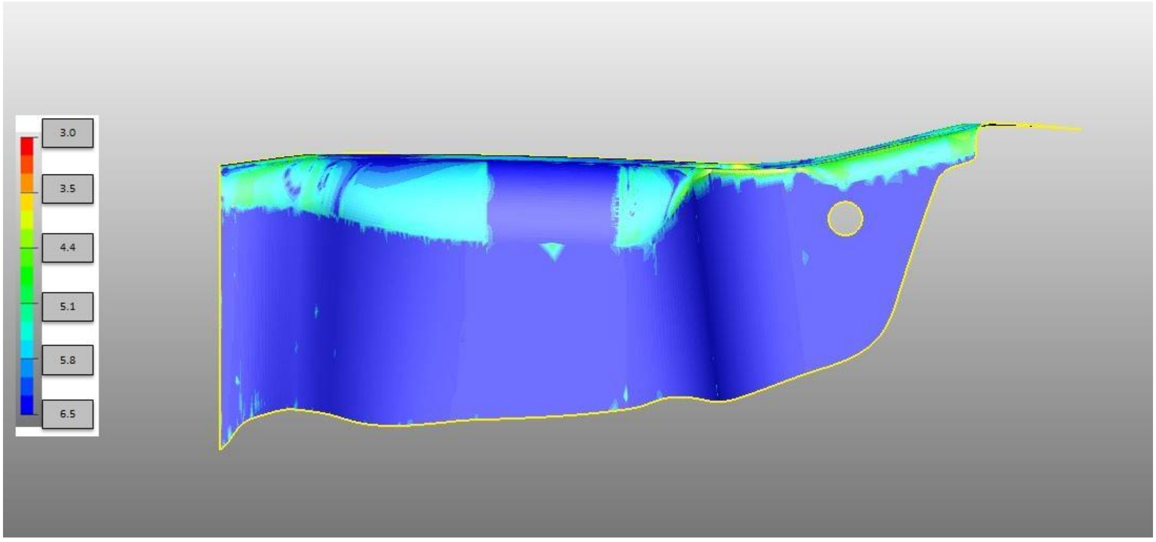


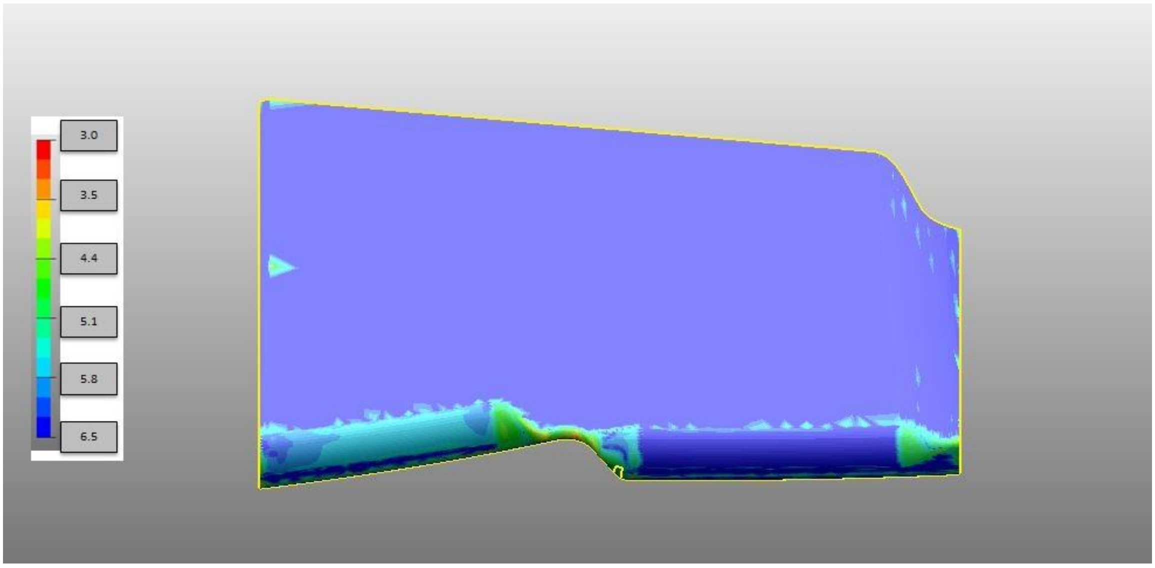
Figure 4-3 : Histogram Plotting of GCV Values on different areas of CAD Model

For doing visual analysis on the 3D surface, the values of Gaussian Curvature are mapped as a scalar value at every vertex. This is done by using rhinoceros

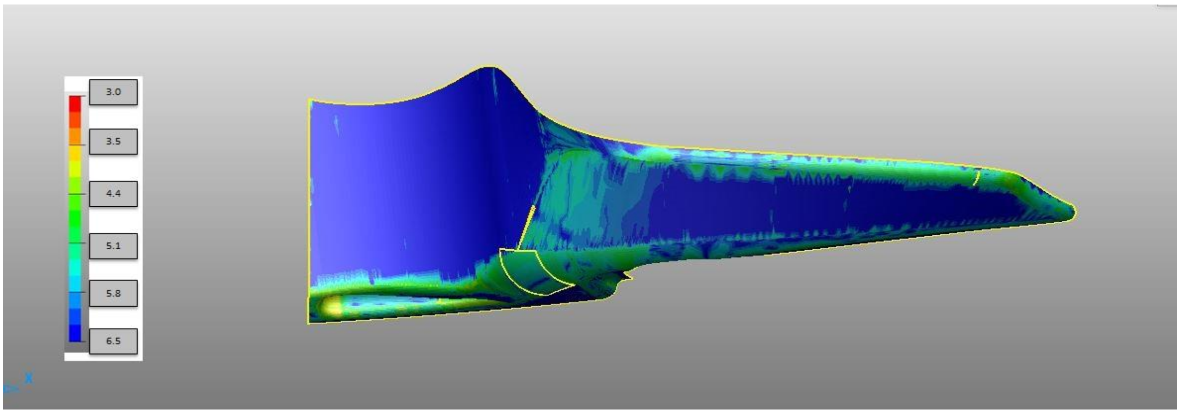
5.0 AdvMesh plugin[Savio et.al, 2013] and Polyscope library in Python. The color mapping is done linearly with RGB color space. As it is evident from the descriptive analysis, the values of Gaussian Curvature vary from 3.0 to 6.5 range. Hence, color space is also divided in the same range. The obtained visual plotting is shown for the areas in Figure 4-4 along with the colour mapping.



CAD Model Area 1



CAD Model Area 2



CAD Model Area 3

Figure 4-4 : Linear Colour Mapping of Gaussian Curvature values (CAD Model)

4.2 SCANNED MODEL

Scanned Model is referred to the 3D scanned model using GOM ATOS Core 500. It is done by Blue light fringe projection system with fast scanning and hence the measurements were taken in mere 10 minutes. After obtaining the scanned model, ATOS professional software is used to visualize it.

It was observed that the scanned model has data gaps (holes), self- intersecting meshes and inverted normals. These defects require to be corrected, as it will give rise to incorrect computation of Gaussian Curvatures on vertices,hence wrong comparison of our sheet metal part. Also for doing the comparison with the CAD model, the mesh reduction is carried out to reduce the number of vertices and faces, because mesh is noisy in the case of scanned models.

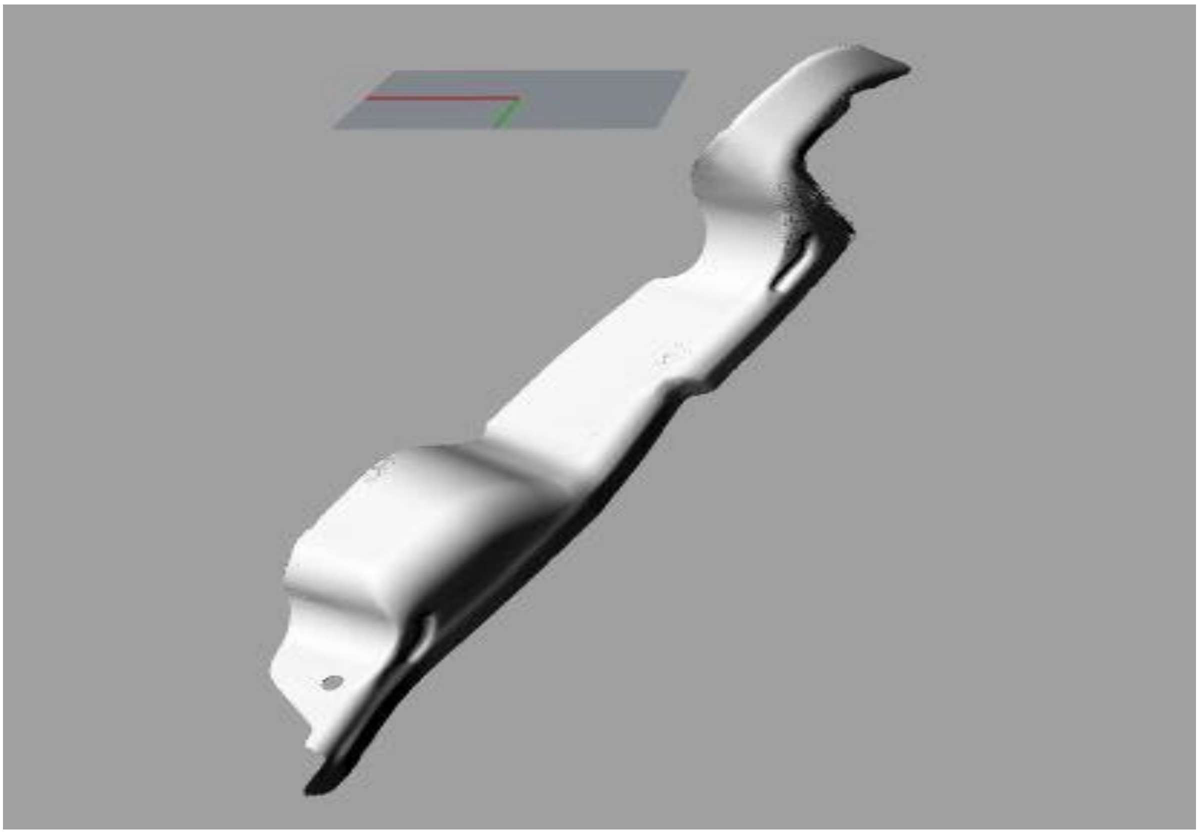


Figure 4-5 : The scanned model visualized in Rhinoceros 5.0

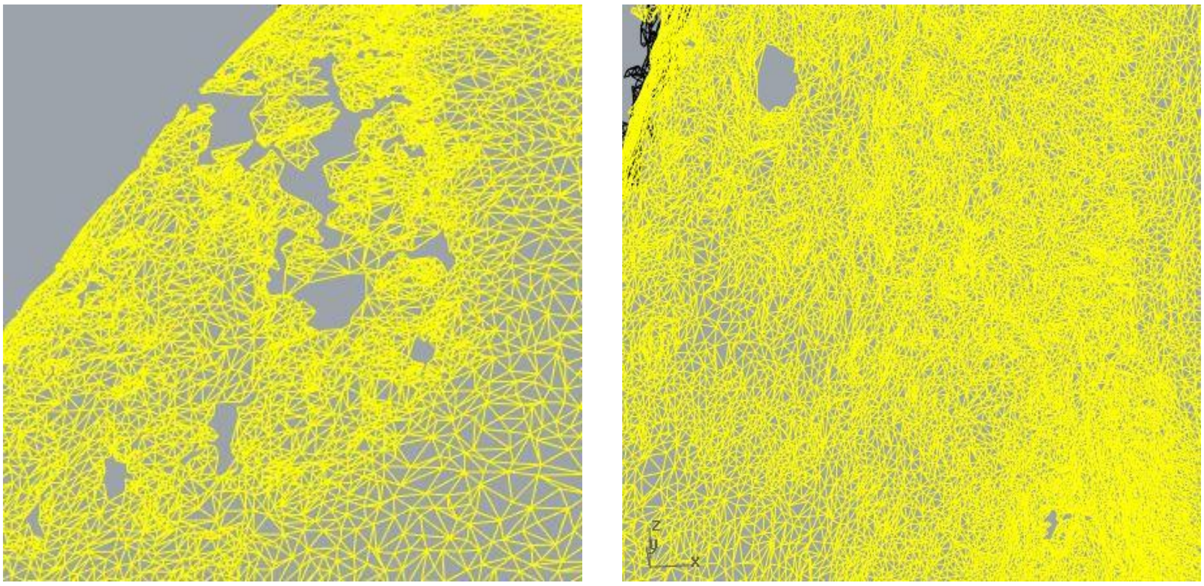


Figure 4-6 : Data Gaps in the scanned model [Rhinoceros 5.0,2020]

Figure 4-6 depicts the data gaps in the triangulated mesh data. These defects are fixed using rhinoceros 5.0 mesh repair tools.

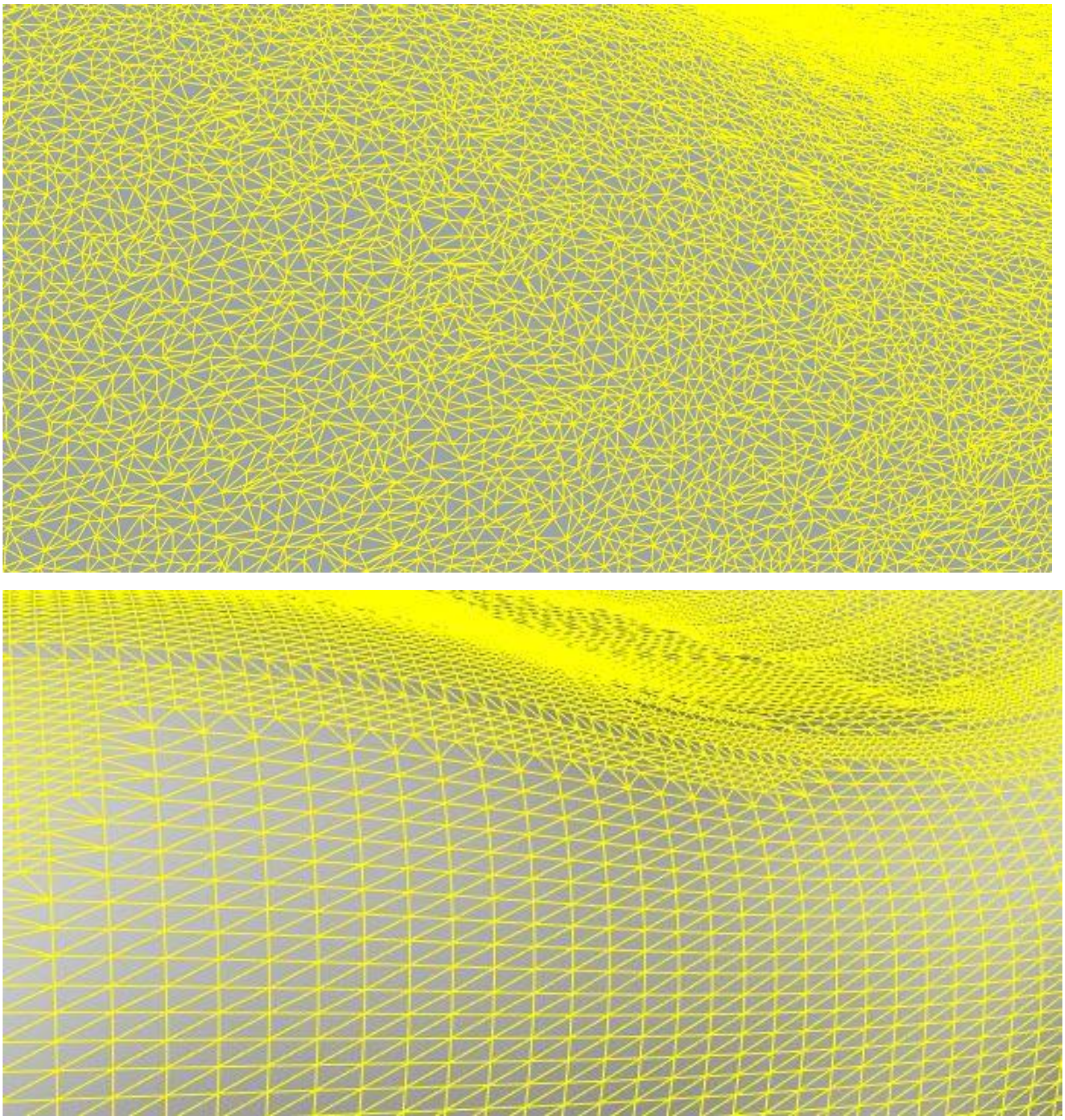


Figure 4-7 : Actual triangulated Mesh (Above) & Reduced triangulated Mesh (Below)

Figure 4-7 shows the triangulated mesh before and after reduction. As in scanning process so many points are scanned in different iterations, there is a lot of noise on the surface. For the sake of comparing the mesh values with CAD model, mesh reduction is done to the number of vertices and faces in CAD model using mesh reduction tool in Rhinoceros 5.0 which smoothen the mesh reducing the noise from the surface. The mesh reduction reduces the number of polygons and re-triangulation is done by calculating geodesic distances between the remaining vertices, hence preserving the shape of the object.

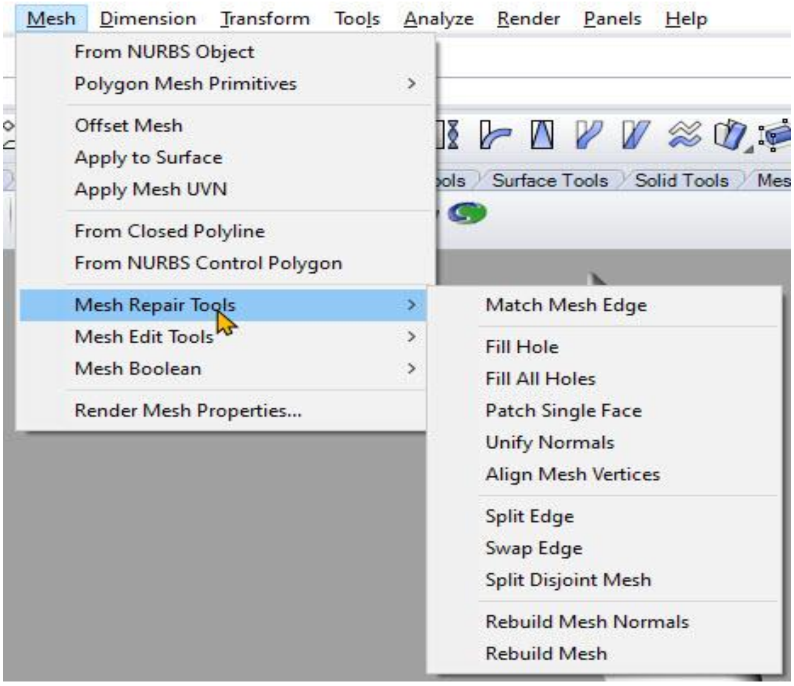


Figure 4-8: Mesh Repair tool.

Similar to the CAD model, scanned model is also divided into three areas and the polygonal data is read in python using igl library

```
v1,f1=igl.read_triangle_mesh("remeshed_surface_small_part.stl")
```

v1, f1 are vertices and faces respectively. Both are numpy arrays.

Scanned Model	Area1	Area2	Area3
Number of vertices	213429	60771	158262
Number of faces	71143	20257	52754

Table 4.2 : Vertices and Faces in Scanned Model

Scanned model	Area1	Area2	Area3
Number of vertices	107589	30816	118914
Number of faces	35863	10272	39683

Table 4.3 : Vertices and Faces in Scanned Model after mesh reduction

Table 4.2 and 4.3 represents the vertices and faces value before and after mesh processing. It is observed that now the mesh value of Table 4.3 is similar to that of the Table 4.1 of CAD model.

Gaussian Curvature is now computed for the pre-processed mesh of scanned model.

```
k1 = igl.gaussian_curvature(v1, f1)
```

Descriptive analysis for the scanned model is done similarly as in the case of CAD model by kernel estimated histogram plotting in figure 4-9

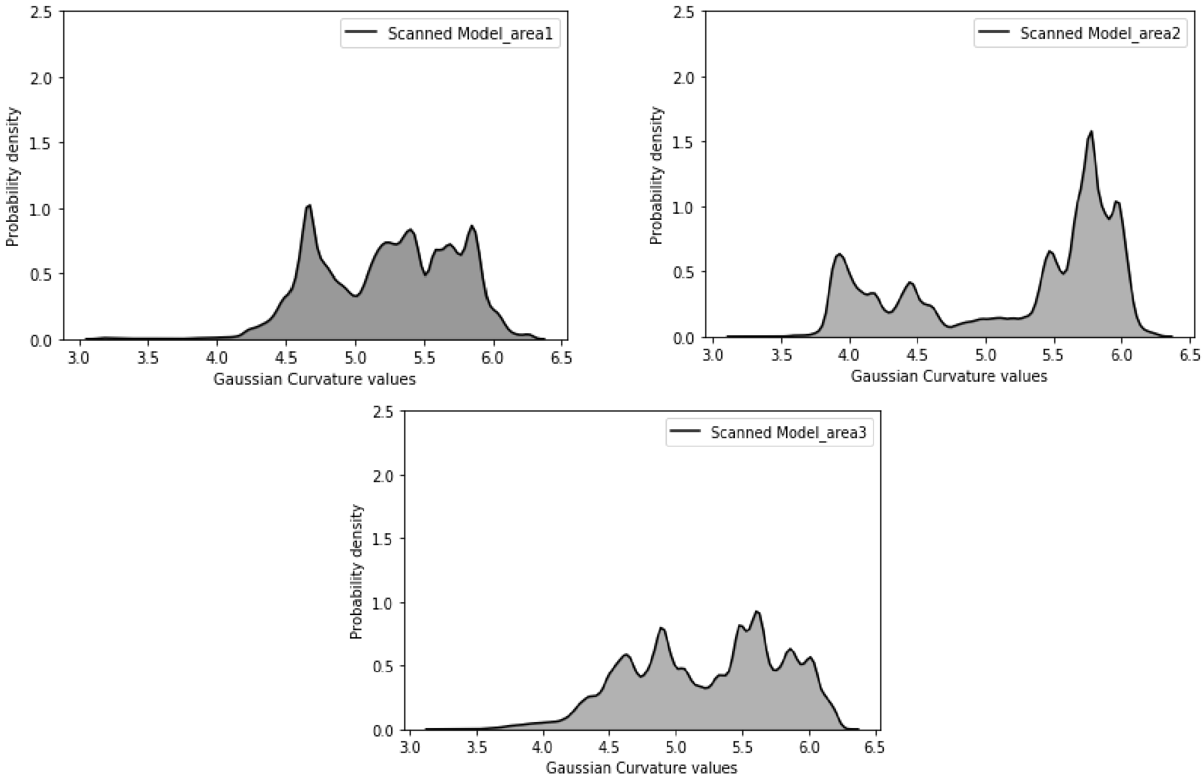


Figure 4-9 : Histogram Plotting of GCV Values on different areas of Scanned Model

The range of the colour mapping is between 3.0 to 6.5, similar to CAD model. Gaussian Curvature is visualized both with and without mesh reduction to observe the noisy areas in Figure 4-10.

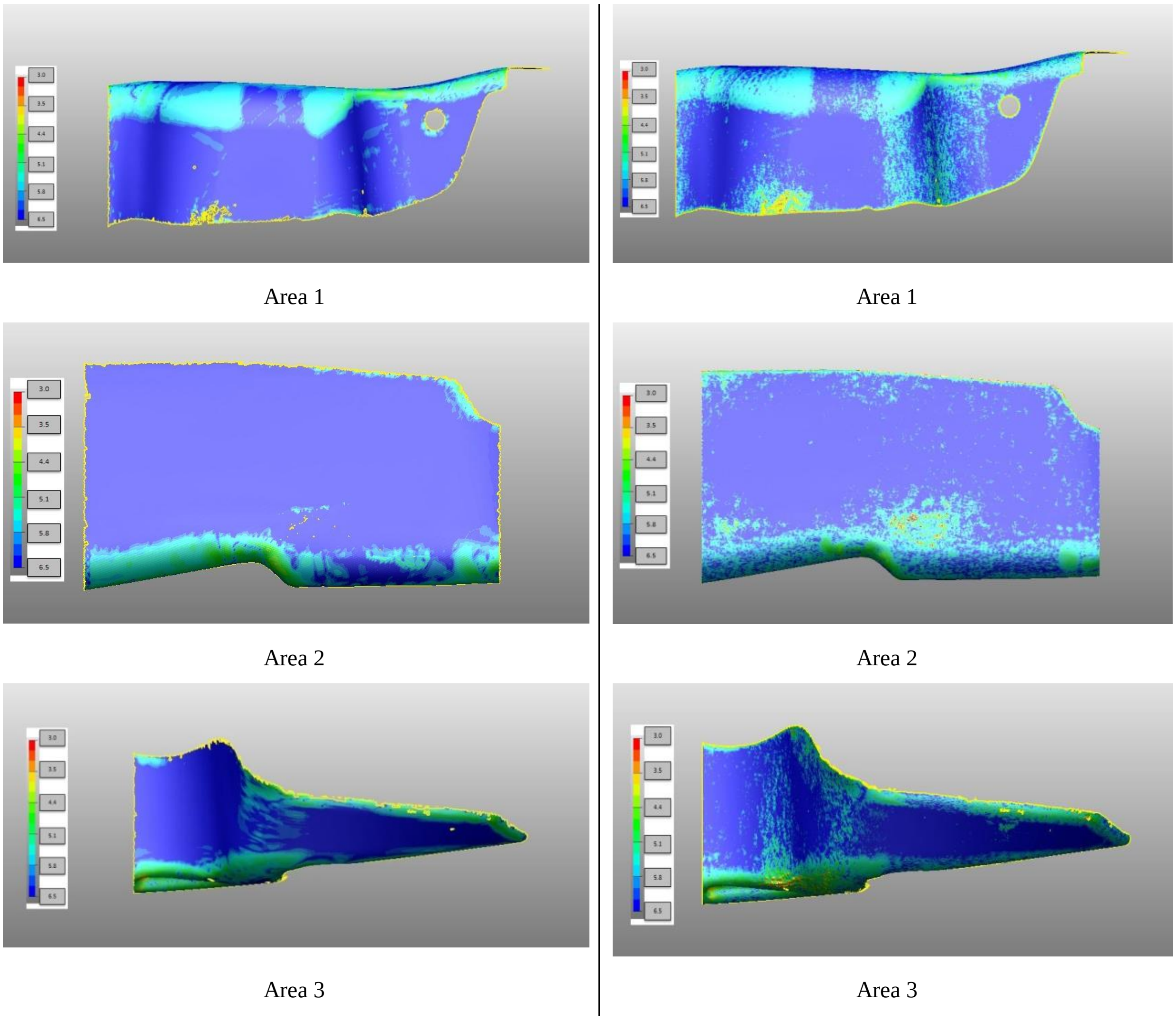


Figure 4-10: Colour Mapping of GCV on Scanned model with(left) and without(right) Mesh Reduction

From Figure 4-10, it is quite evident that scanned data sets have a lot of noise and these noise needs to be smoothened, so that comparison with other models can be done. All the areas had noise, which were smoothened using rhinoceros 5.0 mesh reduction tool.

4.3 DEFORMED MODELS

4.3.1 Deformed Model I

Deformed Model I refers to the scanned model, which was created as a test model, by making a dent using a hammer in the sheet metal part. Similar to the Scanned Model, Deformed Model is also obtained using GOM ATOS Core 500. It also takes same time of mere 10 minutes for scanning.

The .stl data file is visualized in Rhinoceros 5.0. It can be seen that there is a dent in the scanned triangulated mesh. This is done to observe, if the method developed will observe the change of the shape around the deformed part as Gaussian values are changing around that part.

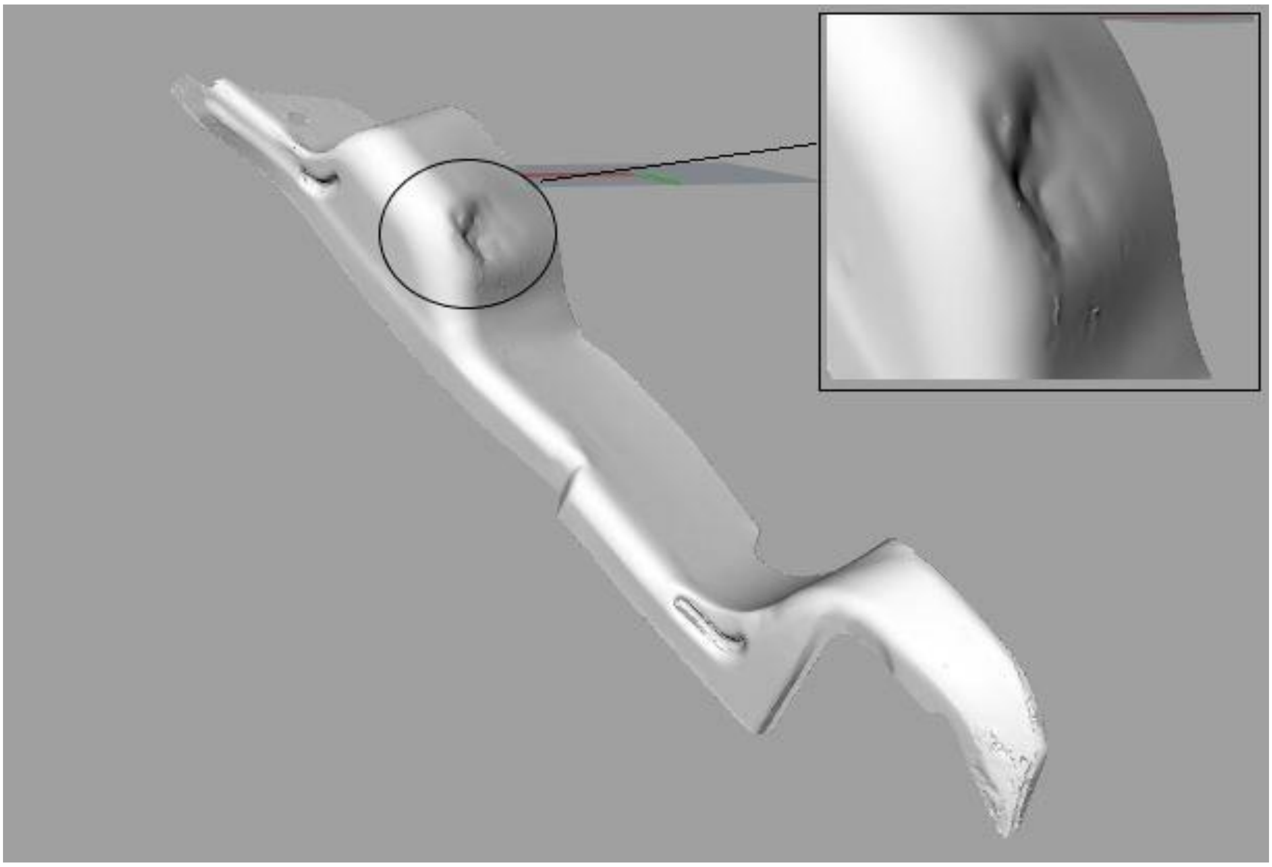


Figure 4-11 : Deformed Model visualized in Rhinoceros 5.0

Similar to the scanned model, the deformed model also had small holes, self-intersecting vertices and inverted normals, which were corrected in the same manner as of the scanned model using rhinoceros 5.0 mesh edit tools. Also the mesh reduction is done for comparable data sets.

The deformed model is read in python using igl library as:

```
V2,f2=igl.read_triangle_mesh("experiment3_deformed_meshed.
stl")
```

V2 and f2 are vertices and faces respectively of deformed model data sets in numpy frame.

Deformed Model I	Area1	Area2	Area3
Number of vertices	144534	59679	131685
Number of faces	48178	19893	43895

Table 4.4 : Vertices and Faces in Deformed Model

Deformed model I	Area1	Area2	Area3
Number of vertices	107589	30816	118914
Number of faces	35863	10272	39683

Table 4.5 : Vertices and Faces in Deformed Model after mesh reduction

Gaussian Curvature is found out by:

```
K2 = igl.gaussian_curvature(v2, f2)
```

Where k2 is a numpy array of Gaussian Curvature values at every vertex.

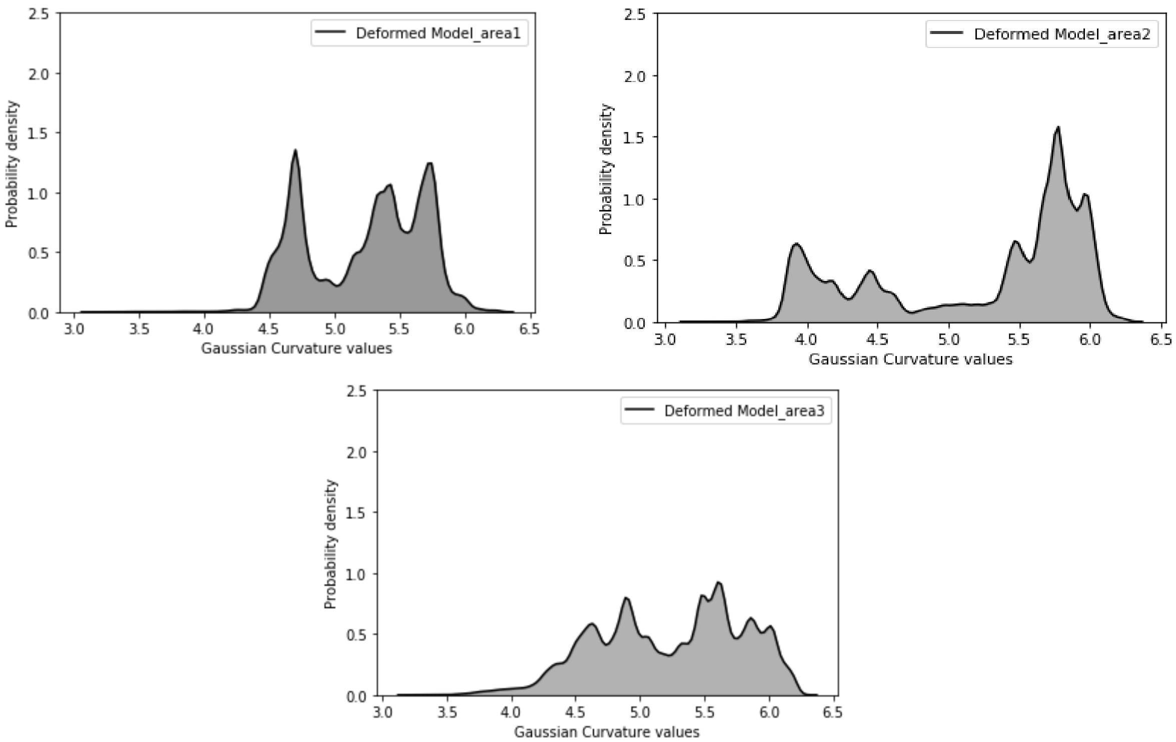
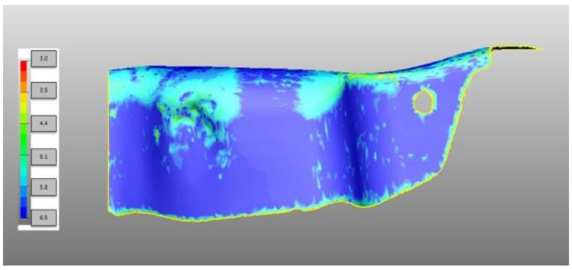
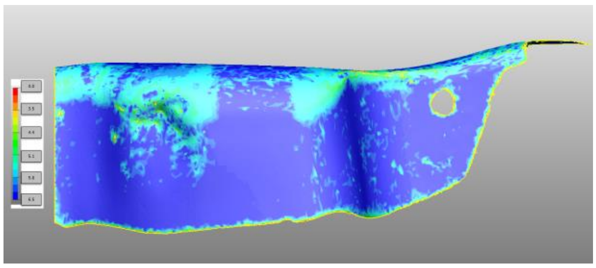


Figure 4-12 : Histogram Plotting of GCV Values on different areas of Deformed Model

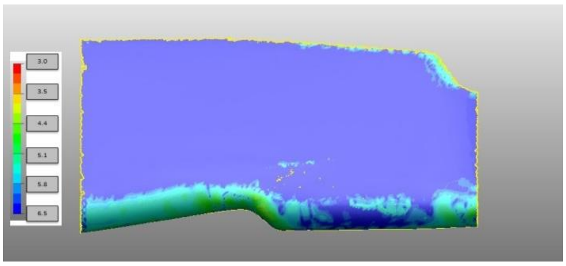
The plot in Figure 4-12 depicts the descriptive statistical analysis with the help of kernel density estimation Histogram plot. Colour based mapping is done similarly to the CAD and scanned model in rhinoceros 5.0 ADVMesh plug in tool and polymesh in python. The colour bar is kept the same as in CAD and scanned model.



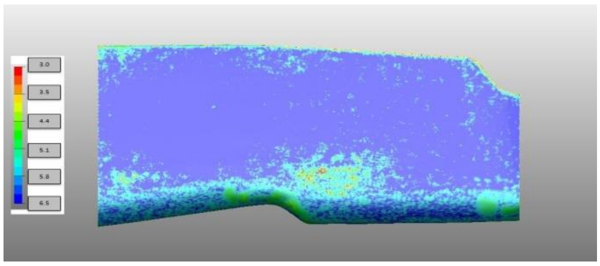
Area 1



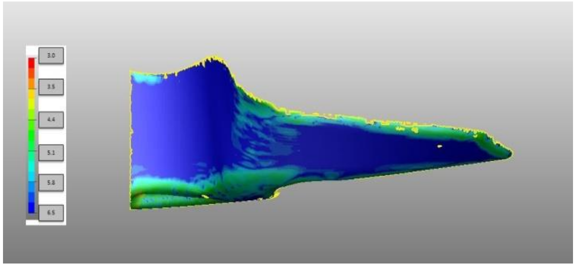
Area 1

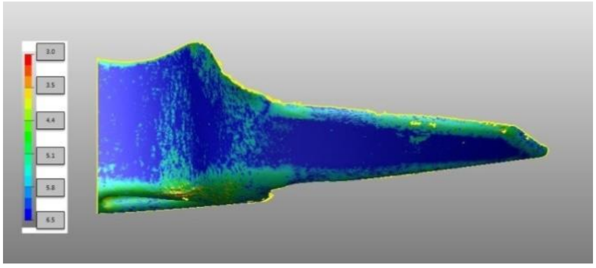


Area 2



Area 2



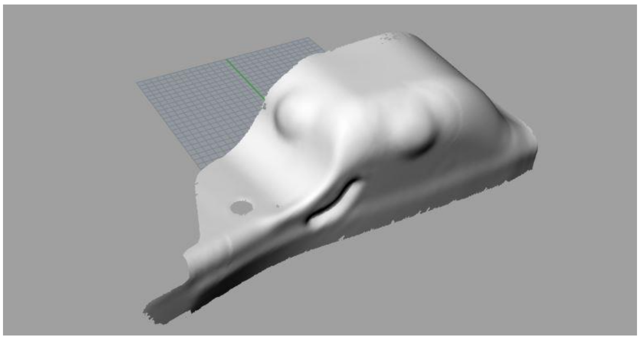


Area 3 Area 3

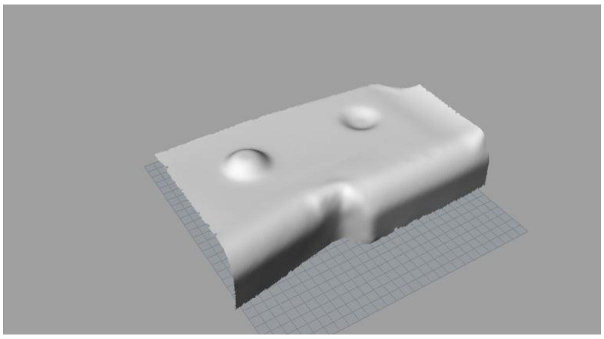
Figure 4-13:Colour Mapping of GCV on Deformed model with(left) and without(right) Mesh Reduction.

4.3.2 Deformed Model II

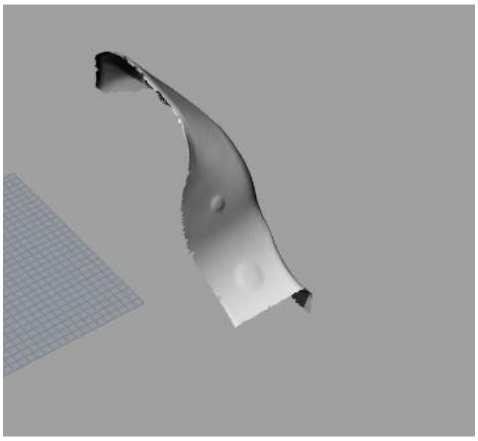
Deformed Model II refers to the scanned model in which dents were made using design software Meshmixer, so that different defects like dents and pimples can be analysed over the surfaces. Dents and pimples were made in all the three areas of the scanned model. The rendered stl file is visualized in rhinoceros 5.0



Area 1



Area 2



Area 3

Figure 4-14 : Deformed Model II with different defects visualized in Rhinoceros 5.0

Similarly to all other models, Descriptive and Visual Analysis are done on the deformed model II, so that changes in the Gaussian Curvature can be further observed in different cases and at different locations over the 3D surfaces, using igl library in python and rhinoceros tools for visual inspection. It should be noted that the mesh reduction is not required on this model, as the scanned model for which the mesh reduction has already been done, is used for making dents and pimples.

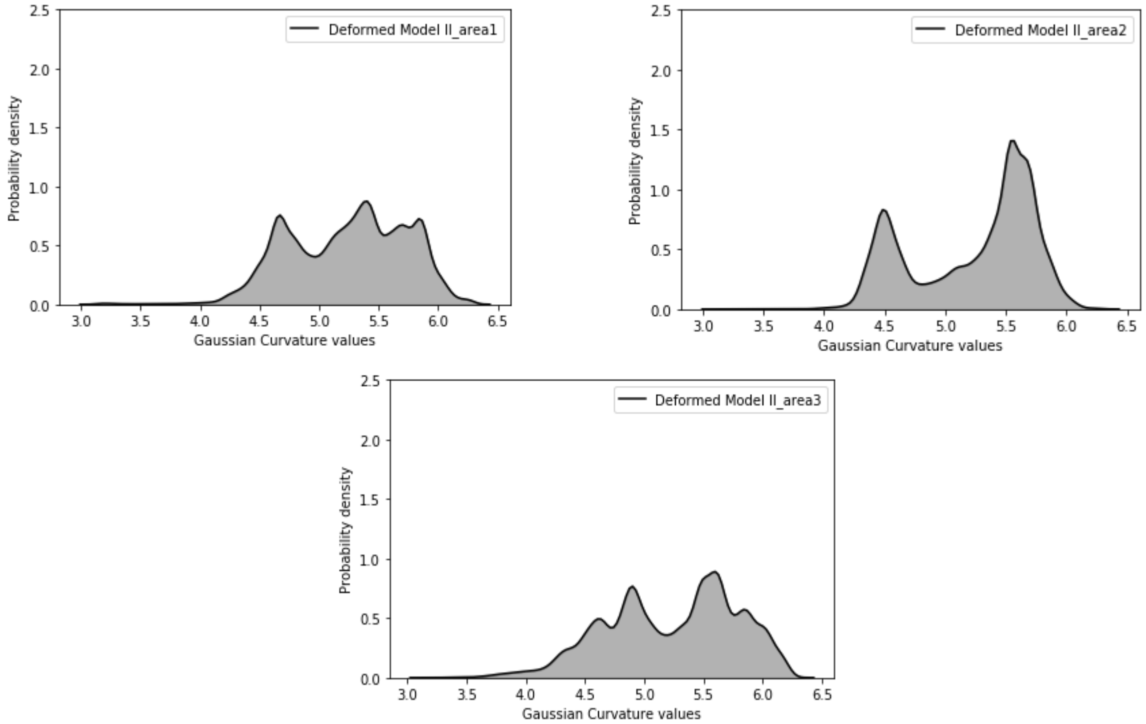
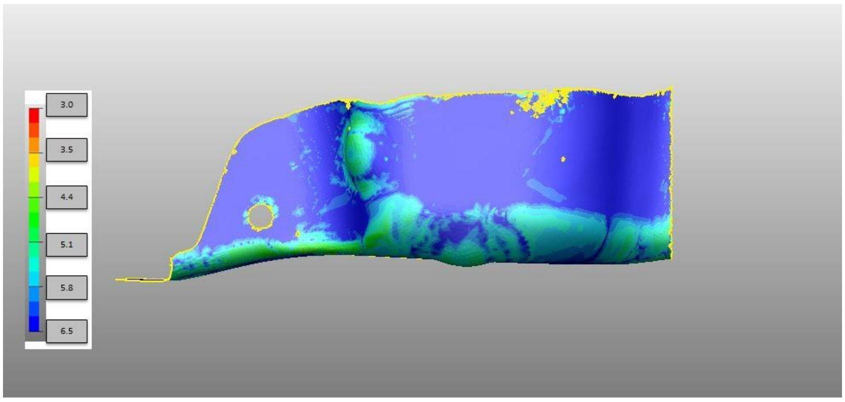
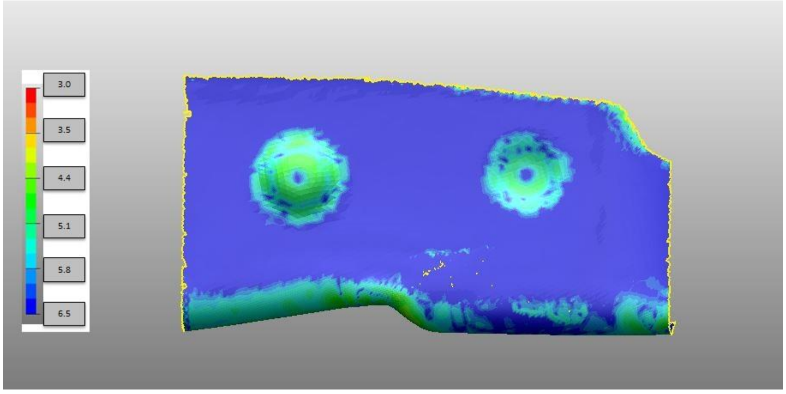


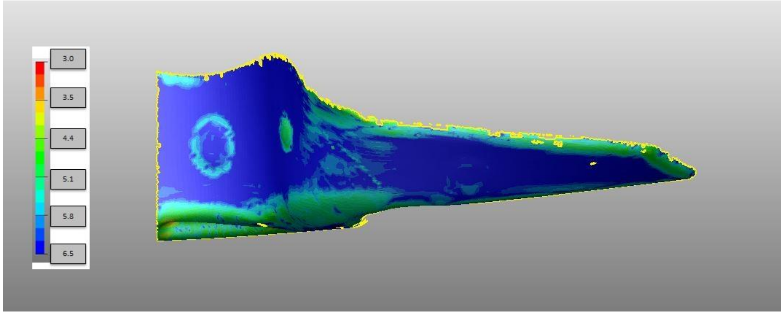
Figure 4-15 : Histogram Plotting of GCV Values on different areas of Deformed Model II



Area 1



Area 2



Area 3

Figure 4-16 : Linear Colour Mapping of Gaussian Curvature values (Deformed Model II)

4.4 TEST SCENARIOS

Test Scenario 1: Area 1 of CAD, Scanned and Deformed Model I is compared
Test Scenario 2: Area 2 of CAD, Scanned and Deformed Model I is compared
Test Scenario 3: Area 3 of CAD, Scanned and Deformed Model I is compared
Test Scenario 4: Area 1, 2 and 3 of Deformed Model II compared with Scanned Model.

All these tests scenarios are used to validate that the computation of Gaussian Curvature values can be used for the detection of defects on the 3D surface and can be further used for fast quality check of sheet metal parts in industrial setup.

CHAPTER-5

RESULTS

5.1 GAUSSIAN CURVATURE CALCULATION

In this master thesis, Gauss Bonnet scheme discussed in [Meyer et.al, 2003] is used for the computation of Gaussian Curvature. The local integral of angle is computed around every vertex. This gives a deficit of angle, as in Euclidean space the sum of angles around a vertex sums up to 360°. Calculation of angular deficit is shown by picking up a vertex on the surface and calculating angles around it in a 3D space.

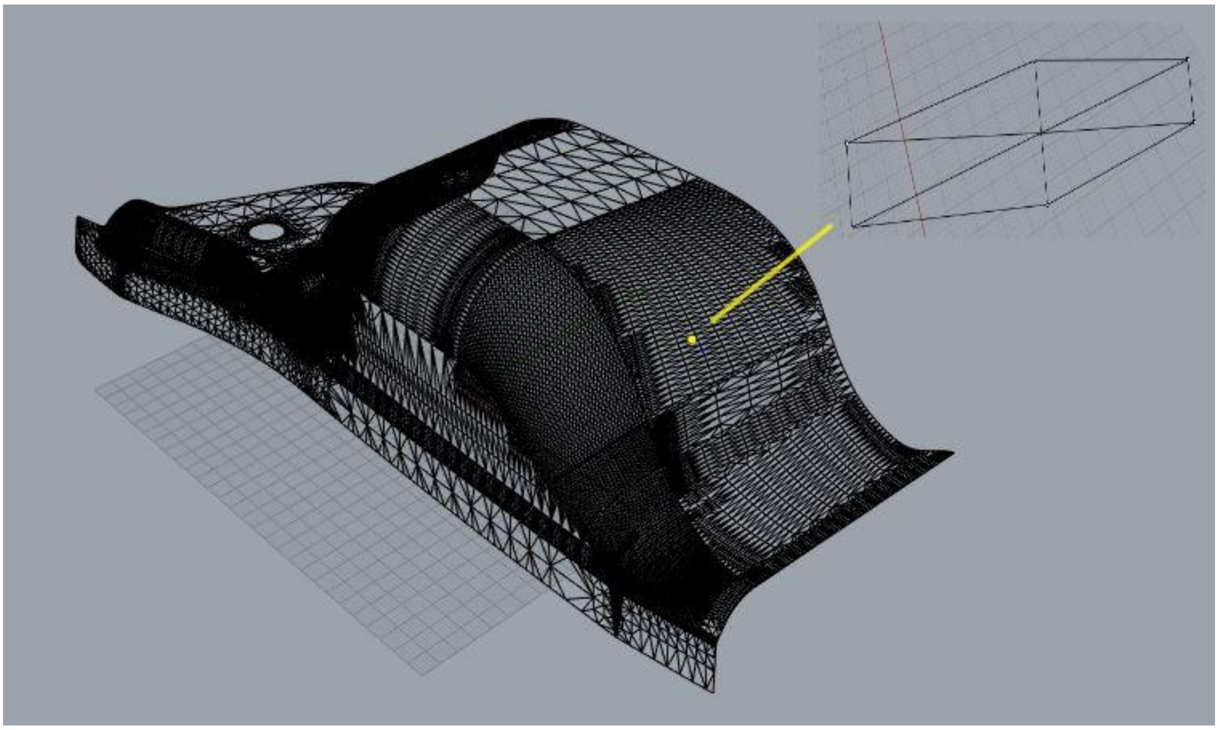


Figure 5-1: Location of the vertex on the CAD model.

Figure 5-1 depicts the location of the vertex on the CAD model which is used as an example to show how the Gaussian curvature is computed. The vertex shares 6 Edges with the intermediate neighbouring vertices, hence so called Valence of the vertex is 6.

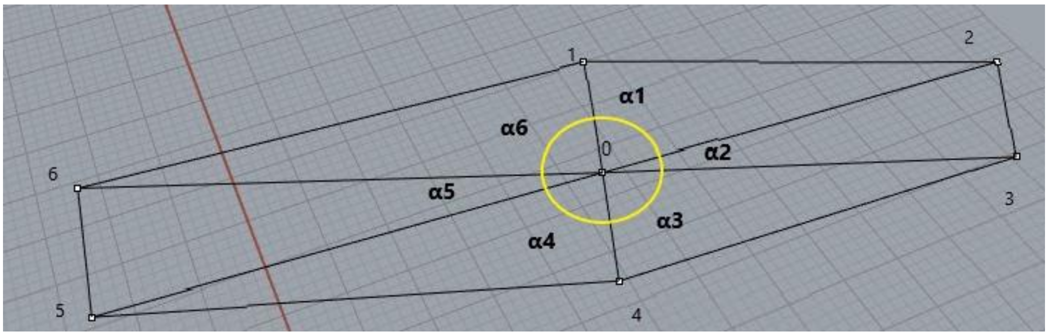


Figure 5-2: Vertex for Gaussian Curvature computation.

The vertex representation is shown by vertex id number as represented in Figure 5-2

The coordinate value in local coordinate system is depicted in Table 5-1.

Vertex ID Nr.	Coordinate values in mm		
	x	Y	z
0	80.976	2.235	60.686
1	80.060	2.430	61.466
2	81.183	7.527	60.393
3	82.088	7.424	59.590
4	81.876	2.040	59.885
5	80.773	-3.053	60.986
6	79.864	-2.765	61.765

Table 5-1: Coordinate values at each vertex

The edge length is computed between all the vertex combinations by:

$$l_{1-2} = \sqrt{(x1 - x2)^2 + (y1 - y2)^2 + (z1 - z2)^2} \quad \ldots \text{ Equation (5-1)}$$

Where l_{1-2} Edge Length between vertex id 1-2

$(x1, y1, z1)$ Coordinates at vertex ID 1 &

$(x2, y2, z2)$ Coordinates at vertex ID 2

All the computed edge lengths are shown in Table (5-2)

Edge length with vertex ID	Edge Length (mm)
l_{0-1}	1.2819
l_{0-2}	5.3041
l_{0-3}	5.4188
l_{0-4}	1.2207
l_{0-5}	5.2997
l_{0-6}	5.2337
l_{1-2}	5.3281
l_{2-3}	1.2144
l_{3-4}	5.3955
l_{4-5}	5.3261
l_{5-6}	1.2314
l_{1-6}	5.2068

Table 5-2: Edge Length Computation

The angle computation is done using Law of Cosines, three sides length of a triangle is given by:

$$cos\ \alpha = \frac{a^2+b^2-c^2}{2ab} \quad \ldots \text{ Equation (5-2)}$$

Where a, b and c are side lengths of a triangle and α is the angle

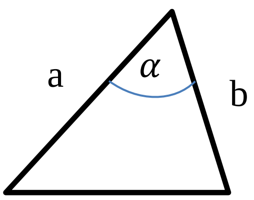


Figure5-3: Law of Cosine

The angles computed are tabulated below:

Angles around Vertex ID 0	In Degrees
α1	80.98
α2	12.95
α3	82.43
α4	84.63
α5	13.41
α6	82.04

Table 5-3: Angle Computation around vertex

Sum of all angles around vertex ID 0 = $\alpha 1 + \alpha 2 + \alpha 3 + \alpha 4 + \alpha 5 + \alpha 6 = 356.44° = 6.22$ Radians

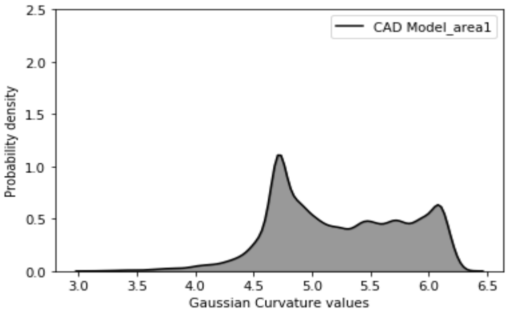
Kg = 6.22 Radians.

This shows there is an angular deficit around the vertex, as it is not equal to 360°.

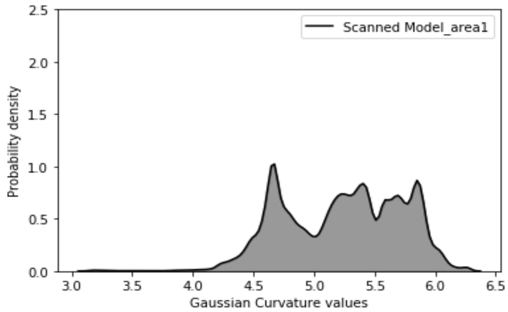
Similarly to the above mentioned procedure, angular deficits are computed at every vertices of the triangulated mesh, which gives an estimate of the discrete Gaussian Curvature locally. This method is used in the master thesis for the quality control of the sheet metal parts.

5.2 TEST SCENARIO 1

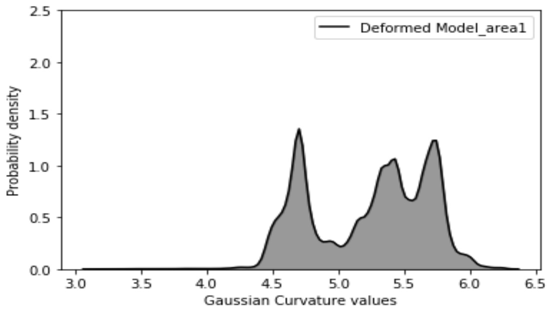
In the Test Scenario 1, the area 1 of CAD, Scanned and Deformed Model I is compared.



Area 1 CAD Model



Area 1 Scanned Model

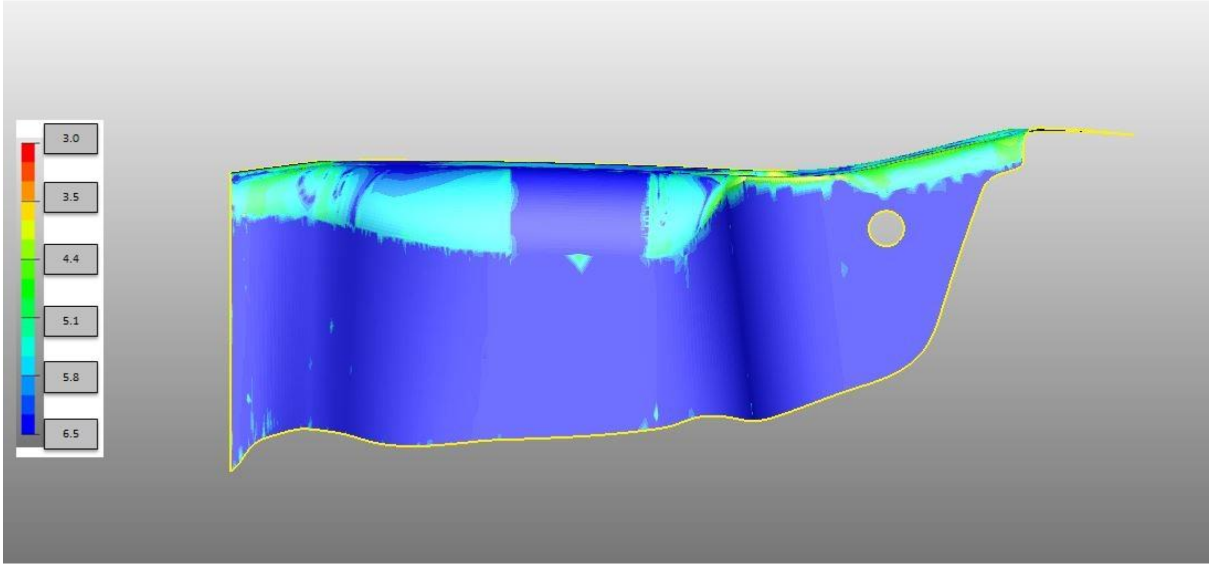


Area 1 Deformed Model I

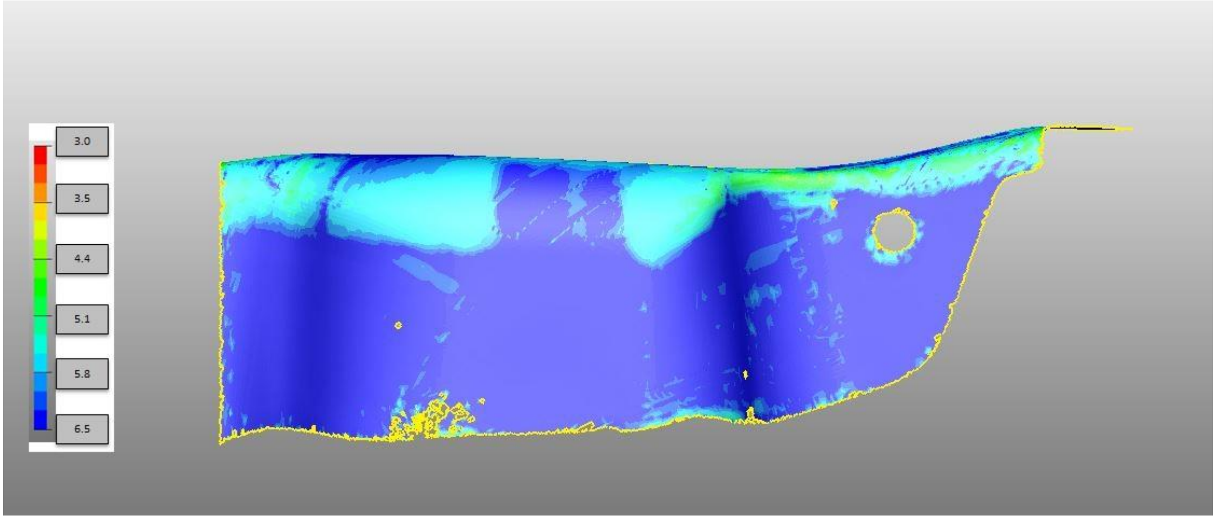
Figure 5-4: Descriptive Analysis of Test Scenario 1

Descriptive analysis comparison is done to check the behaviour of Gaussian Curvature numerically. For descriptive analysis, kernel density estimation of histogram plot is used. Area 1 of CAD Model has two peaks which are dominant and other peaks are quite small. In Scanned Model, Area 1 has more pre-dominant peaks and valleys which indicates that there is a difference in the Gaussian Curvature values between these models, mostly because of noise which are quite dominant considering these are measured values in scanned models using an optical measuring instrument. Also the computation on the edges of the scanned model for Gaussian Curvature is not precise, because of the irregular scanning around the edges thus causing less information for the angular deficit.

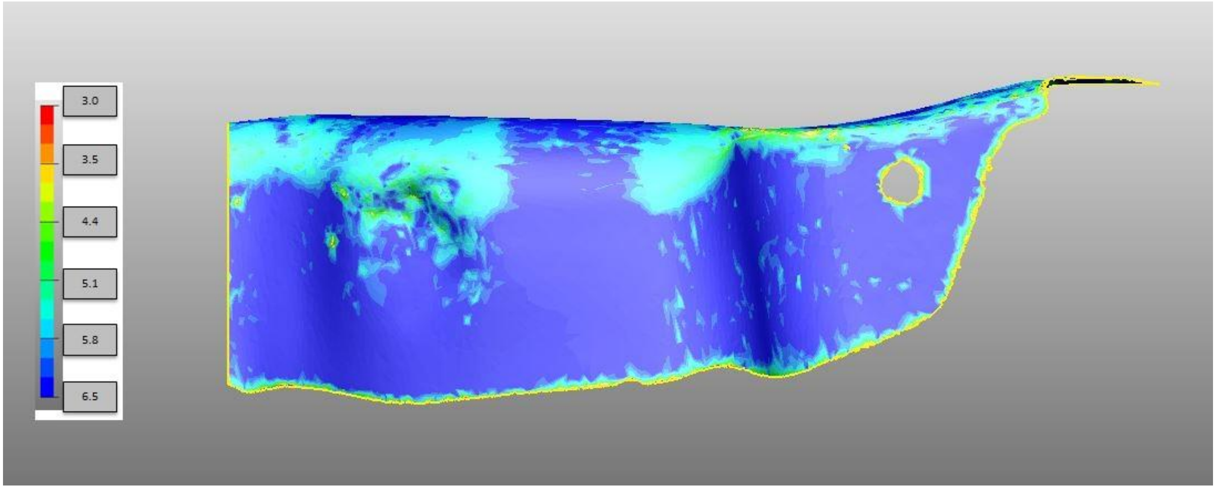
Area 1 of Deformed Model I shows further steeper valleys and higher peaks, primarily due to the deformed area present in the model. Hammering causes a slight change of the shape around the dent, which can cause change in angular deficit in nearby areas also.



CAD Model



Scanned Model

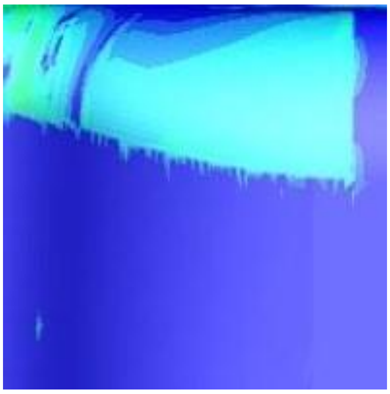


Deformed Model I

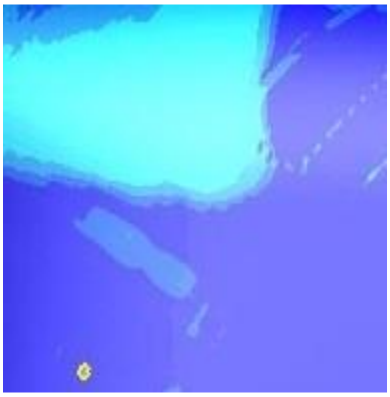
Figure 5-5 Visualization of Gaussian Curvature Values on Area 1

In the visualization, it is clear that Area 1 of CAD Model have really smooth edges, while there is disturbance on the edges of Scanned and Deformed Model

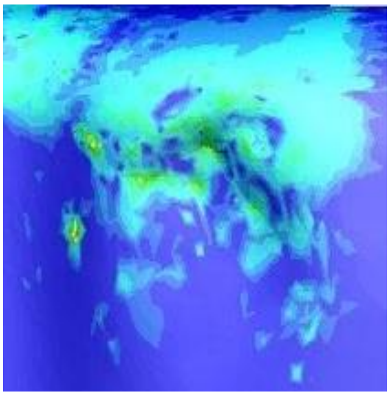
I. Also there is evident noise present on the Scanned Model and Deformed Model. Area of deformation is evident from the figure 5-5 in Deformed Model I, where the values changed from the range of 5.8-6.5 to 5.1-5.8. The zoomed area around deformation makes it more clear in Figure 5-6.



CAD Model



Scanned Model

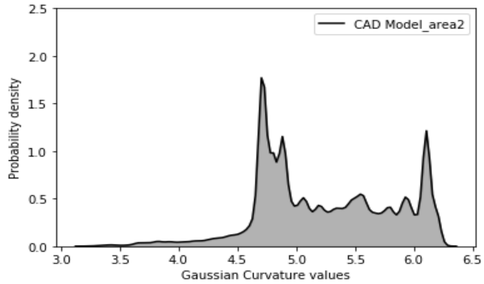


Deformed Model I

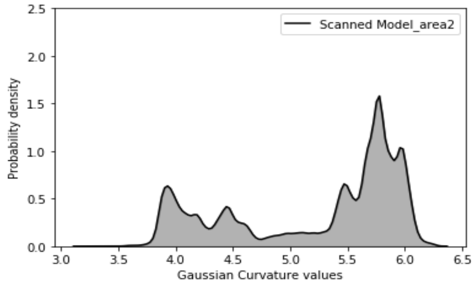
Figure 5-6: Close up View around areas of Deformation.

5.2 TEST SCENARIO 2

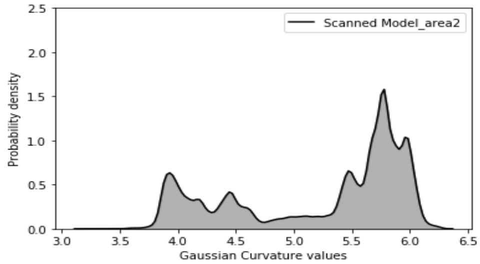
In Test Scenario 2, Area 2 of CAD, Scanned and Deformed Model I is compared both descriptively as well as visually.



CAD Model



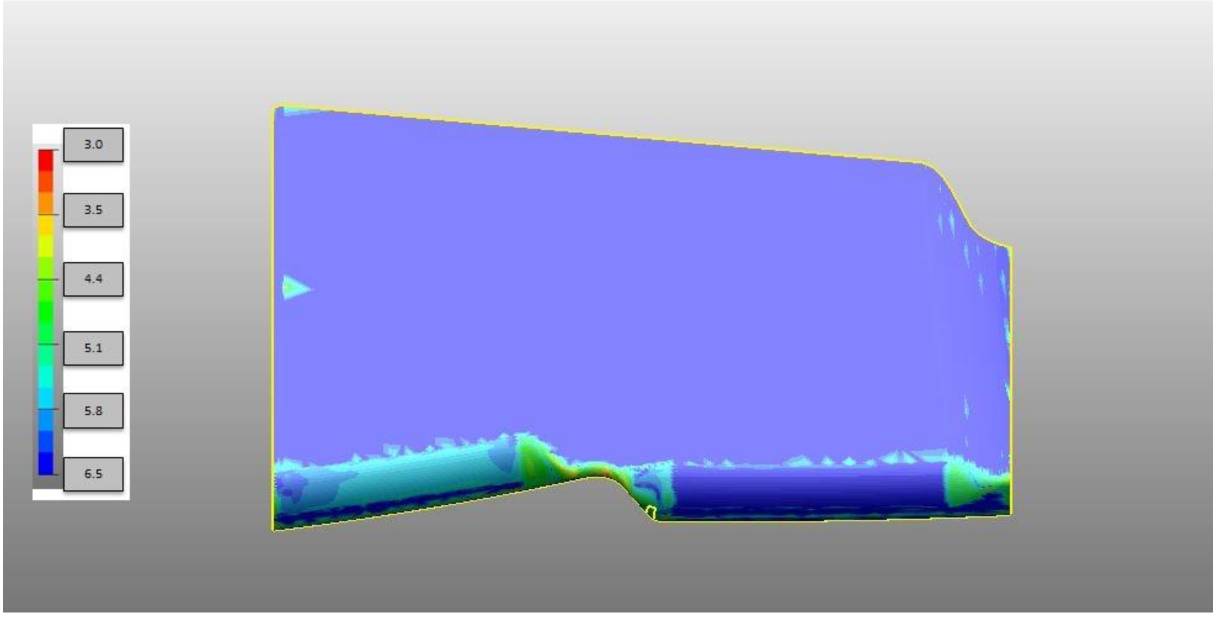
Scanned Model



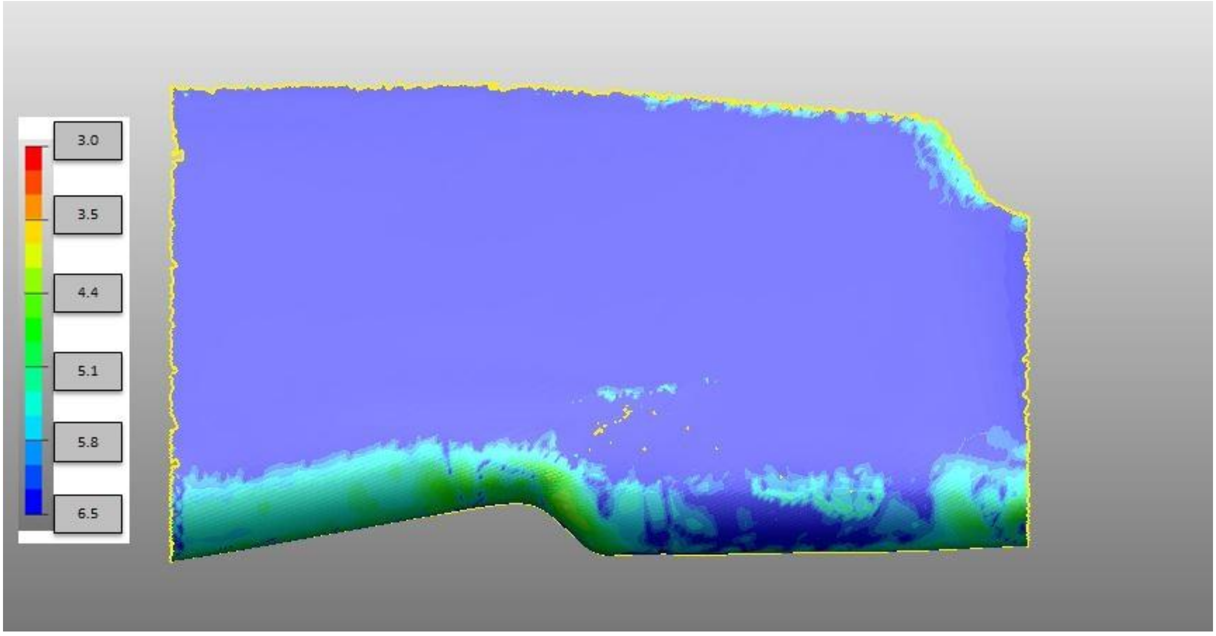
Deformed Model I

Figure 5-7: Descriptive Analysis of Test Scenario 2

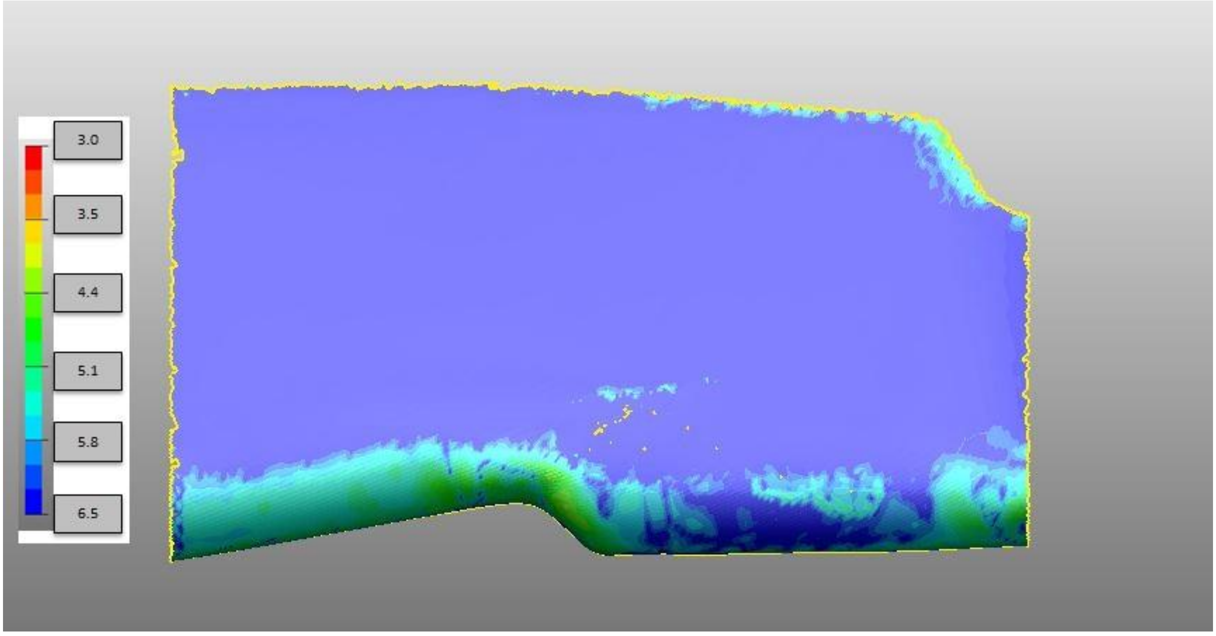
The kernel density estimation plot makes it evident that there is a difference in CAD and scanned model due to noise as well as edge mesh angular deficit calculation. But it is evident from the plots of Scanned and Deformed Model I area 2 that when there is no deformation in the area, it is giving same kernel distribution of histogram of Gaussian Curvature values. So it is gives an idea that if the scanning of the model is done with accuracy, it can be considered as a reference model for doing quality comparison with other scanned models like here with the Deformed model I.



CAD Model



Scanned Model



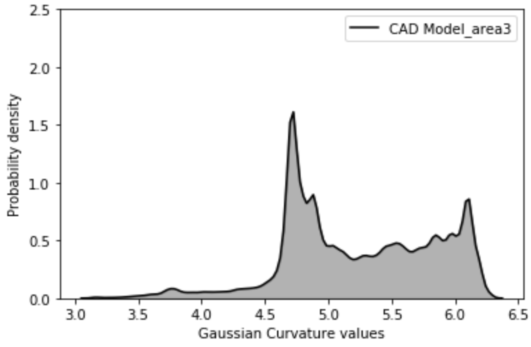
Deformed Model I

Figure 5-8 Visualization of Gaussian Curvature Values on Area 2

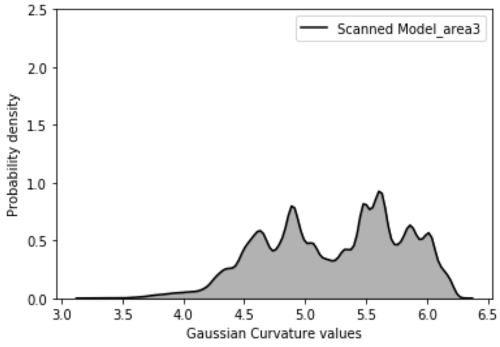
Visualization of the area 2 shows that there is evident difference between the CAD and Scanned Model Gaussian Curvature values. But the Scanned Model has the same plot as compared to Deformed Model I as seen in the descriptive analysis too. Values are mostly in the range of 5.8-6.5 as it is almost flat structure where the angular summation should be close to 360° (6.28319 radian). In descriptive analysis the values around 6.28319 radian is having less density, because meshing on the flat parts is coarse while on the areas where there is a curvature, there should be finer meshing so that any small change of deformation can be taken into account. It is very important to realise that the 3D scanning of both Scanned Model and Deformed Model I is done in the same setup. If the setup is disturbed, it will cause differences in Gaussian curvatures values over the surface and also the noise values can differ.

5.3 TEST SCENARIO 3

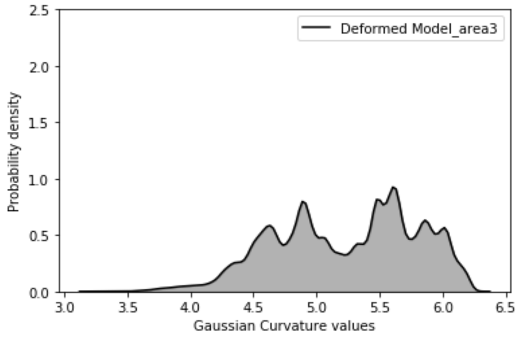
In Test Scenario 3, Area 3 of CAD, Scanned and Deformed Model I is compared similarly to validate the methodology of quality check by descriptive as well as visual methods.



CAD Model



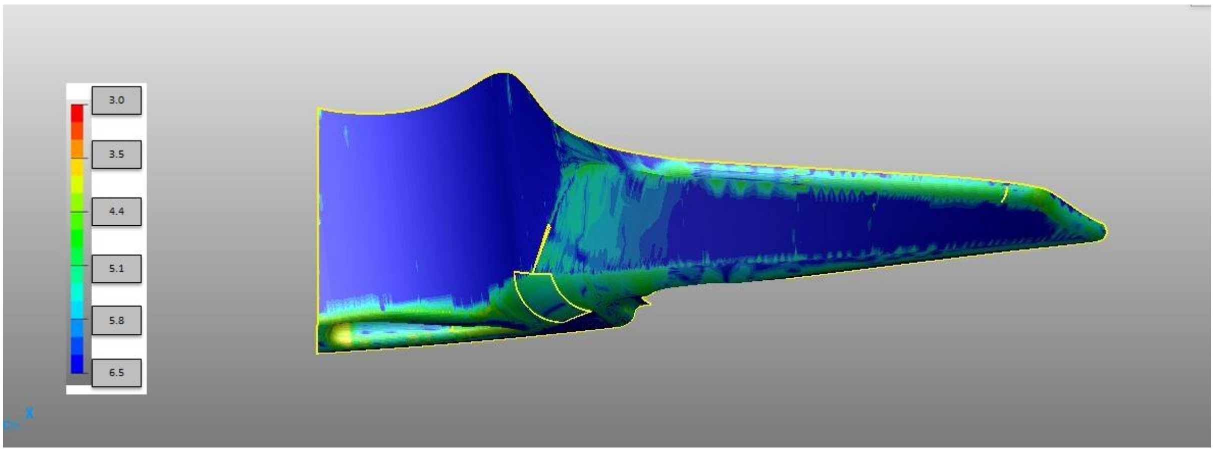
Scanned Model



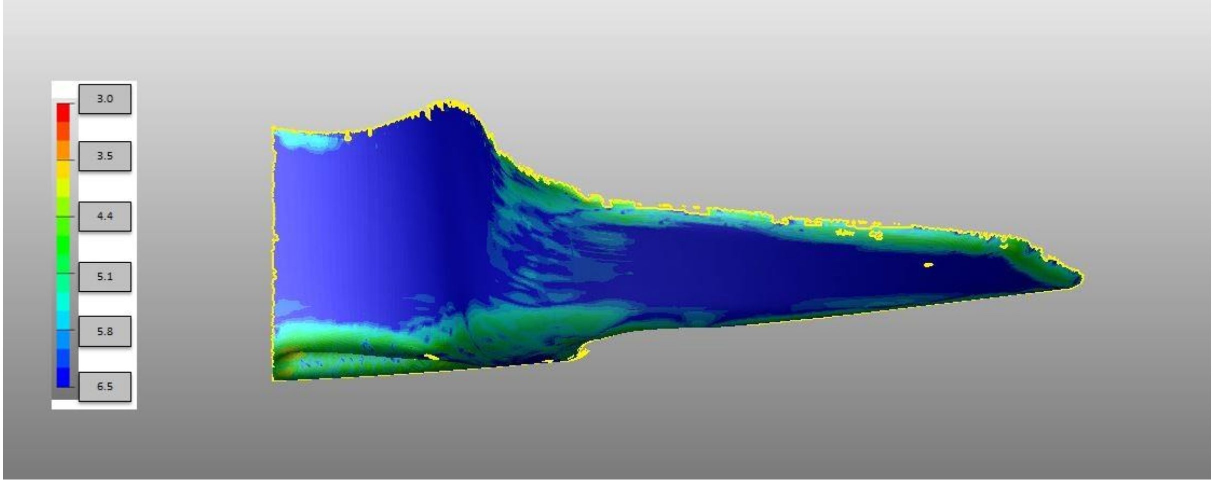
Deformed Model I

Figure 5-9 Descriptive Analysis of Test Scenario 3

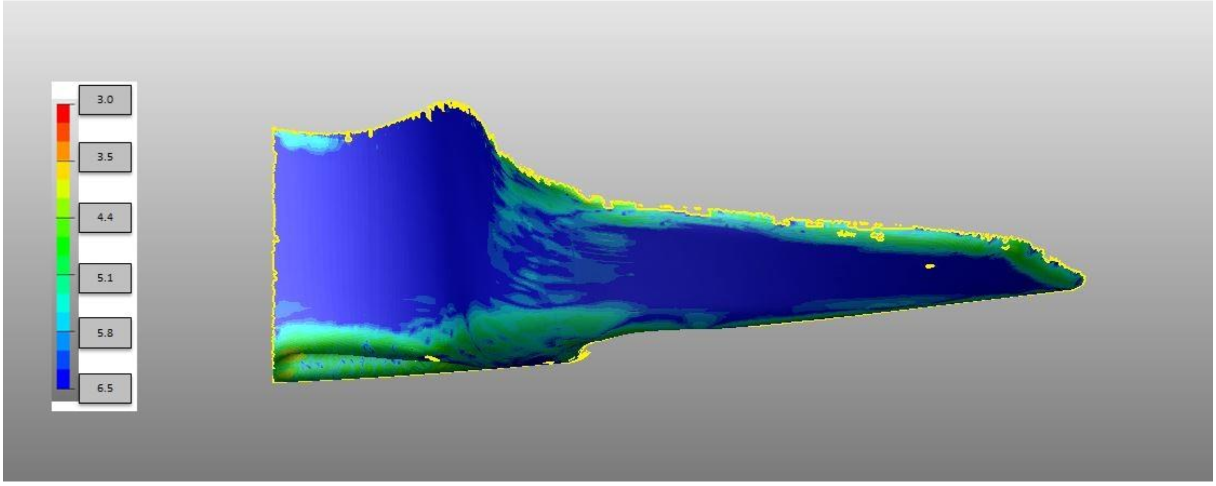
The kernel density estimation of histogram in the test scenario 3 also reveals that CAD and Scanned Model have different distribution but the Scanned Model and the Deformed Model have the same distribution evident to the fact that there is no deformation caused in the area 3 of the Deformed Model.



CAD Model



Scanned Model



Deformed Model I

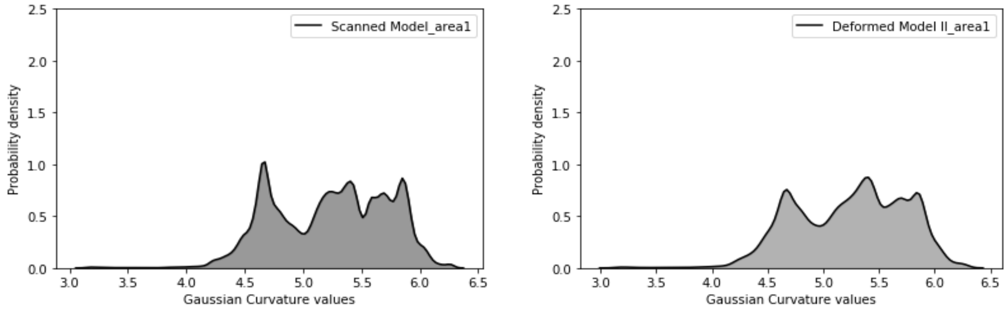
Figure 5-10 Visualization of Gaussian Curvature Values on Area 3

Visualization of the models in the test Scenario 3 also shows evident similarity between the Scanned and Deformed Model I considering there is no deformation. It gives a base for considering the Scanned model as the reference model for doing comparison with other deformed models to find surface defects or surface deformations. Both descriptive as well as Visual analysis of the Gaussian Curvature values reveal that the values obtained are similar. Again it is very important to consider that the scanning setup should stay the same.

5.4 TEST SCENARIO 4

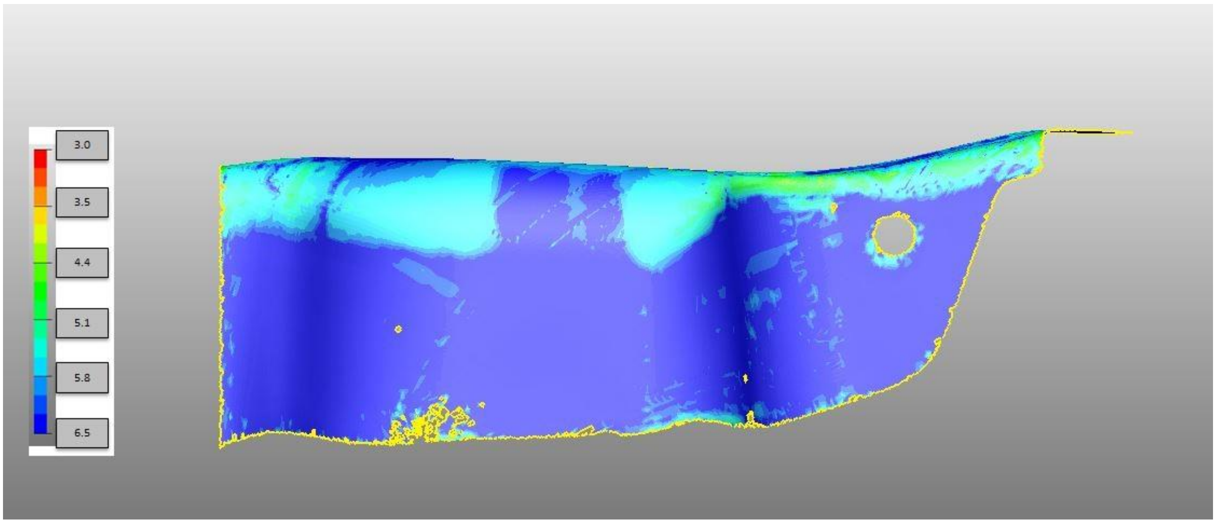
In Test Scenario 4, Scanned Model is taken as a reference model considering all the above scenarios where Scanned Model gave similar results if there is no deformation in the deformed model. Also in this test scenario, two types of Class A surface defects are made on the surfaces of Area 1, 2 and 3 of the Scanned Model namely Dents and Pimples, to find if the proposed technique is finding out the defects on the surface in Deformed Model II.

5.4.1 Area 1 Analysis

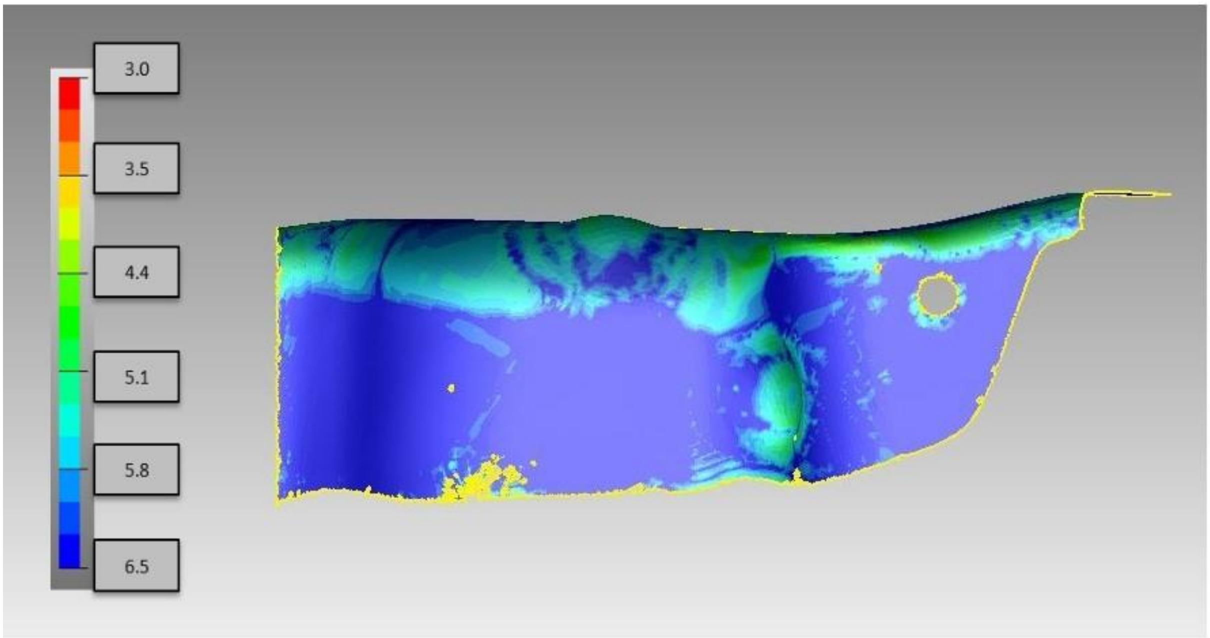


Scanned Model Deformed Model II

Figure 5-11: Descriptive Analysis of Test Scenario 4 Area 1



Scanned Model

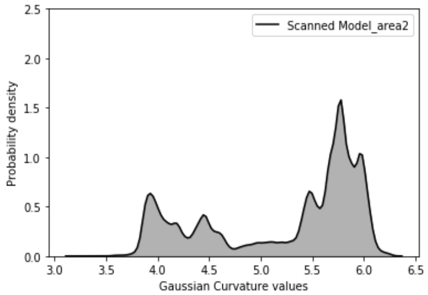


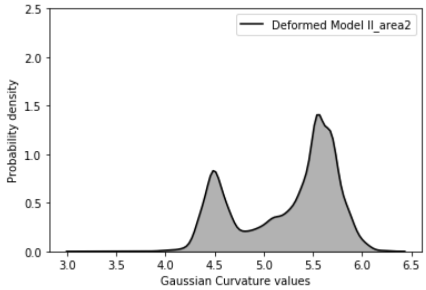
Deformed Model II

Figure 5-12: Visualization of Test Scenario 4 Area 1

In Descriptive as well as Visual Analysis it is evident that the Gaussian Curvature values have changed due to the two pimples which were the defects in the Deformed Model II. As Scanned Model is taken as a reference for comparison, the change in the values on the plot and visualization is solely due to the deformation. The peak in the range of 5.5-6.0 reduced and in the range of 5.0-5.5 increased in the Deformed Model II as compared to the Scanned Model. This is verified both in descriptive as well as visual analysis.

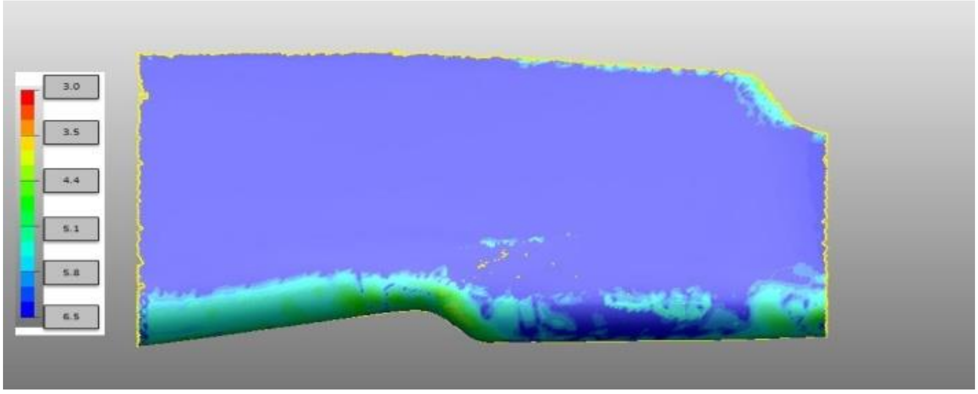
5.4.2 Area 2 Analysis



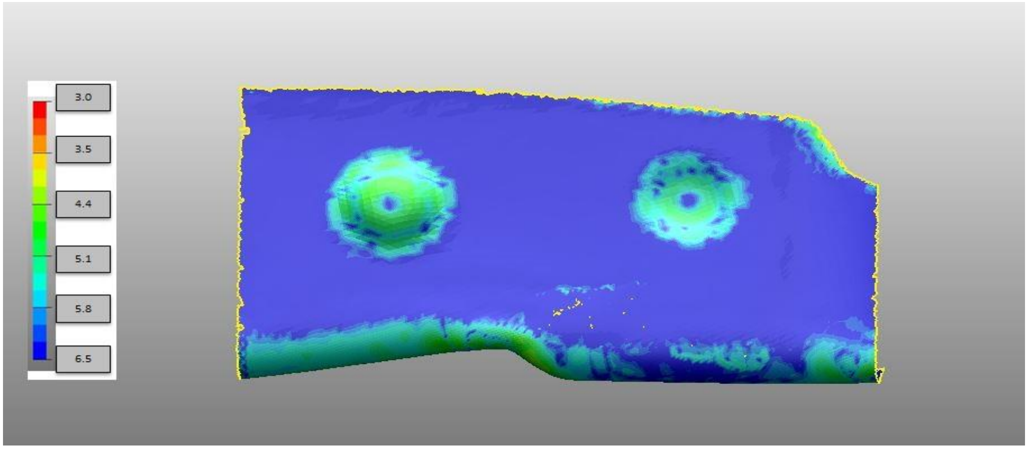


Scanned Model Deformed Model II

Figure 5-13: Descriptive Analysis of Test Scenario 4 Area 2



Scanned Model

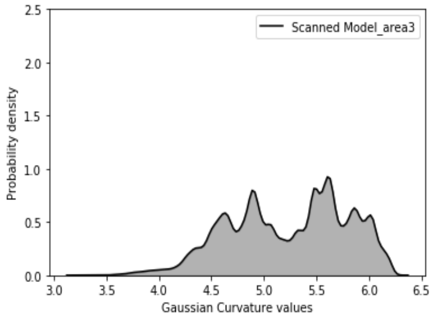


Deformed Model II

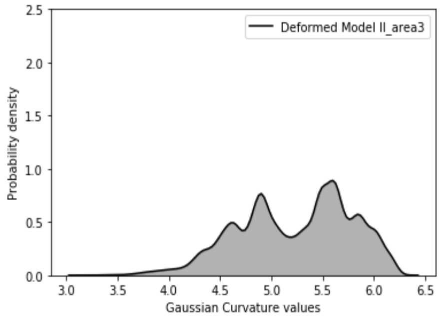
Figure 5-14: Visualization of Test Scenario 4 Area 2

From both models, it can be seen that the deformation type of dent as well as the pimple are getting detected quite well. From visualization as well as descriptive plots, it can be seen that the region where the Gaussian Curvature values are close to 6.28319 radian have shifted in the plot of Deformed Model II and the peak near 4-5 range values has increased as the shapes of pimple and dent are causing that increase.

5.4.3 Area 3 Analysis

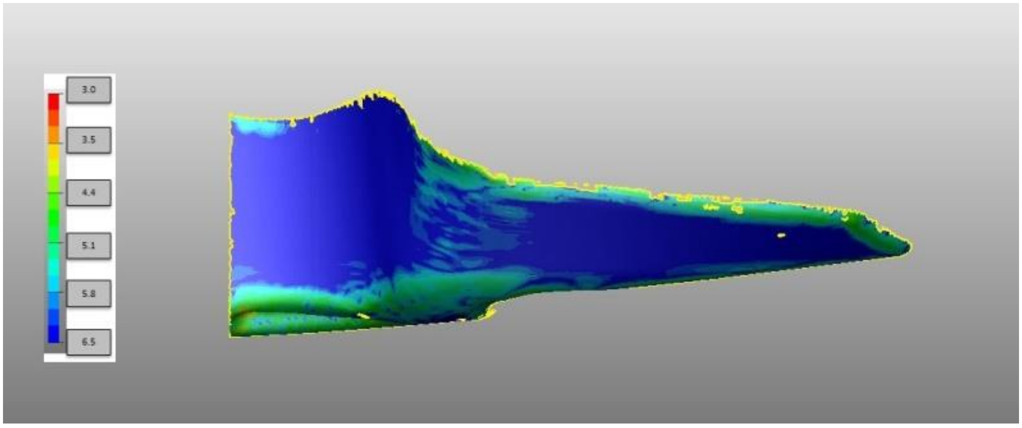


Scanned Model

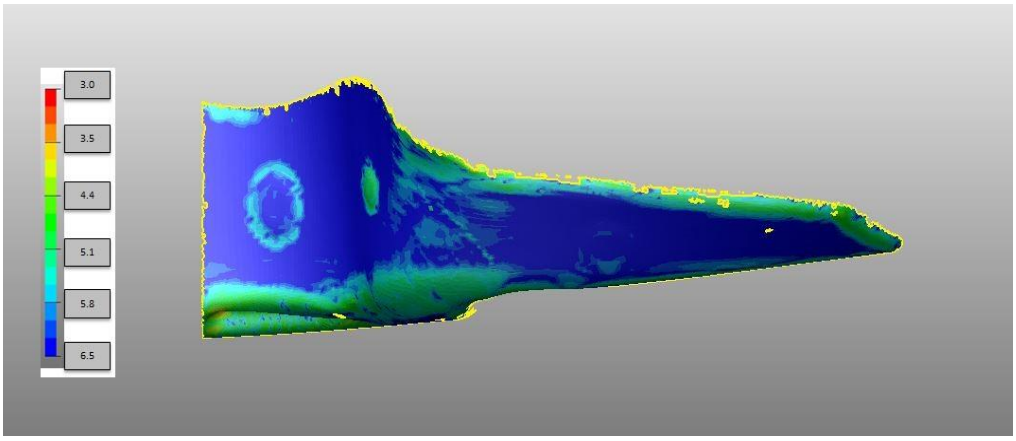


Deformed Model II

Figure 5-15: Descriptive Analysis of Test Scenario 4 Area 3



Scanned Model



Deformed Model II

Figure 5-16: Visualization of Test Scenario 4 Area 3

In area 3 similar to the other two cases of Test Scenario 4, it is observed that the distribution plot as well as visual analysis are encountering the formation of pimple defects on the surface. The values in the range of 5.8-6.5 shifted more towards 5.1 because of deformation on the surface.

Considering all test scenarios, it is quite clear that the methodology adopted in the thesis is able to detect different kinds of surface defects including dents and pimples of varying sizes. By colour mapping the values on the surface, it is possible to find location of the deformations. Test Scenarios 1, 2 and 3 made it evident that noise affects the result and pre-processing of the data is very important for quality check. Also CAD model should not be considered as a reference model because it is parametric modelling with precise triangulation on the surface. Scanned models are measured surfaces and considering them as reference model needs experience, because high quality scanning of the sheet metal surface with less noise is very important. It should also be considered that the 3D scanning of the surfaces should not be done in high number of iterations as it showed increase in noise. Mesh Reduction is also a critical step in the whole analysis as it does the smoothening over the surface for getting comparable data.

CHAPTER-6

CONCLUSION & OUTLOOK

6.1 CONCLUSION

Quality control of sheet metal parts using fringe projection technique is an active field of research. In this master thesis, a method to do a fast quality control over the sheet metal part is proposed and surface parameter of Gaussian Curvature is used to do the comparison. It is worth noticing that there are other surface quality control techniques like Geodesic Line comparison and Mean Curvature calculation, which can be utilized further for the comparison. In this master thesis, the shape of the surfaces were compared for quality.When there is a dent or pimple on the surface or manufacturing defect in production, it can detect the mismatch between the reference and scanned models. It can provide a simple and faster technique for quality check of surfaces for industrial parts which are manufactured for mass production. Comparison of the scanned model using fringe projection with the reference CAD model involves pre-processing and data reduction (mesh reduction). After obtaining the scanned model, it was observed that it had some defects like small gaps, self-intersecting meshes and inverted normals. These defects need to be rectified before comparing with the CAD model. Also mesh reduction of the scanned model is a very critical step. Comparable data sets are important for comparing Gaussian Curvature values. Pre-processing and mesh reduction were done using rhinoceros 5.0 software which is a mesh processing and CAD modelling software. It provides Gaussian Curvature preservation for triangulated faces.

All the 3D models were divided in Area 1, 2 and 3 to observe differences and similarity for the quality control. Based on the different areas, it was concluded that noise and Gaussian Curvature values on the edges play a vital role while comparison. Considering CAD model as a reference model is not recommended, because it is a parametrically perfect triangulated mesh, which is quite tough to observe in scanned models, due to the presence of disturbances. The comparison of different areas also showed a possible way of considering the best scanned model as the reference model and comparing all other 3D scanned models with it for deformations and defects. The Scanned Model and Deformed Model I comparison showed the areas having no deformations giving statistically as well as visually similar results while the deformation areas were detected clearly. Deformed Model II comparison with Scanned Model showed that different kinds of surface defects including dents and pimples can be investigated. Several surface defects were made on the Scanned Model and then compared with the reference Scanned Model. It showed that statistical and visual analysis depicted clearly the deformities on the surfaces.

Future research perspective can be to model the error for all the steps in the methodology in depth. Pre-processing steps involve mesh refinement and correction for which error modelling can be done more in depth. Also for making the whole process more robust, lexicographical sorting of the vertices and faces can be done so that the exact vertices number can be found out where the deformational changes occurred. It will help in knowing the exact areas of defect.

6.2 OUTLOOK

The main objective of this master thesis was to develop a fast and smart technique for determining the quality control of sheet metal parts in industrial setup. It showed promising results which can be used for finding shape defects. But there are few research topics which can be further examined and the whole method can be further improved. 3D scanning can be done using a robotic arm carrying the projector, which can reduce the time consumption of scanning, as well as it can provide a precise measurement reducing the human error involved during the process.. The mesh refinement process can be further investigated to find out techniques to minimize errors. Modelling error for the whole technique is also one of the most interesting and challenging fields of research. Furthermore, Gaussian Curvature was computed using angular deficit technique. There are other techniques like Paraboloid fitting, Taubin and Watanabe Approaches to find Gaussian Curvatures which can be further examined to see the behaviour of the values on the surfaces. In particular, computation of the values on the edges of scanned models gave poor results, because of the less number of vertices to calculate angular deficit precisely. More techniques should be investigated to model the Gaussian curvature values on the edges of scanned models. Other defects like stress analysis under load and spring back analysis can also be investigated for using this technique for other quality measures in the future.

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