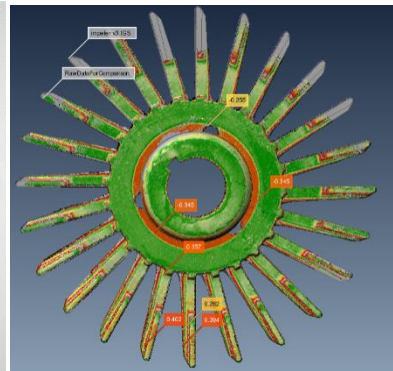
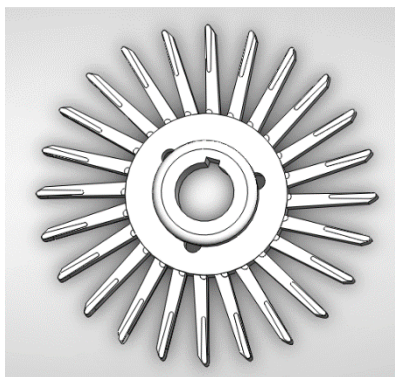


Dissertation:

Reverse Engineering of an Impeller by using Laser Scanning Technology.

Evaluation of the Technology's Accuracy by measurements with Tactile Measuring Systems



Athanasios Giannelis
Mechanical Engineer HND

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ABSTRACT

The dissertation applies to demonstrate the Reverse Engineering of mechanical parts with freeform surfaces.

Reverse engineering of mechanical parts is used to design spare parts for the following reasons:

- When the spare part is not anymore available in the market
- To reduce the cost of an original part by manufacturing it in house
- to redesign and improve the function of the spare part

For this research an impeller is chosen as object in order to generate a 3D cad model by using reverse engineering processes.

The impeller is handled as the most representative part of mechanical spare parts with the following details:

- freeform surfaces
- operation in assembly
- high technical requirements for functionality

An impeller is used in many mechanical applications like turbines & pumps. The impellers are operating under difficult circumstances with high temperatures and with high speed.

The replacement of the impeller is very often required after specific operation hours or after material failure. Since it is an expensive spare part the reverse engineering of it could be offer many benefits such as the redesign and improvement of the operation.

For the reverse engineering of the impeller a Laser Scanner – Non Contact Measurement is used.

The final outcome of the technology will be evaluated regarding to their accuracy and the difficulty of applying. For the evaluation a Coordinate Measuring Machine (CMM) with touch trigger probe – Tactile Measurement with a high accuracy will be used. With the CMM the part will be re-measured and the measured data is compared to the created 3D CAD model with a specialized measuring software.

Acknowledgements

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1. Introduction

1.1. General Review

The growing needs of industry to cheaper and improved parts and the long lifetime of the machinery lead to make it more and more necessary to accurately reverse engineer mechanical parts.

The process of duplicating an existing part, subassembly, or product without the aid of drawings, documentation, or a computer model is known as reverse engineering. Reverse engineering is also defined as the process of obtaining a geometric CAD model from 3D points acquired by scanning/ digitizing the existing products.

Reverse engineering plays an important role in the field of mechanical design. This technology plays an important role in the product design cycle. In the computerized manufacturing environment, the operation order usually starts from the product design and ends with machine operation manufacture the product. It is often necessary to recreate a CAD model from existing part using several digitization technologies.

If original drawings are not available for analysis and modifications are required in order to construct an improved product. In reverse engineering approaches the important steps are characterizations of geometric models and related surface representations, segmentation and surface fitting of simple and free-form shapes, and creating accurate CAD models (Kumar a., Jain, P. K. & Pathak, P. M. 2013)

1.2. Purpose – Objectives

The aim of this paper is to review the reverse engineering process of mechanical parts that can be used by designers who use or want to use reverse engineering techniques. After a brief introduction, the various stages involved in reverse engineering have been discussed extensive.

Scope is to analyze the advantages and the disadvantages of the procedures applied creating the 3D model. For this purpose the errors created during the process in the different stages will be measured and evaluated.

Objectives of this work are to study the accuracy of the reverse engineering procedures, to detect weaknesses of them and to propose improvements for implementation.

2. Literature Review

2.1. Preliminary Review

3-D modeling owns a significant part of the market in our days as an important tool in the field of quality control, research and production. As a matter of fact 3-D digitization devices are even more affordable than earlier years so it made it easy for more businesses to use.

The products from a 3-D scanning device are very precise and give the opportunity to examine an object in lower scale than the original. In addition it is easy to physically store or display an object, even more to keep certain data of interest.

Beside the research and duplication purposes, 3-D information of objects are used for virtual reality projects more and more. Virtual reality products are no more than 3-D data from material world displayed on high end devices.

In order to scan an object and achieve a high quality of the outcome, some parameters must be taken under consideration. Light, surface, scanner capability, colors and object texture are some factors that affect the printing result. In case of 3-D laser devices the surrounding light consists of a major factor for the outcome. For those reasons certain actions must take place in order to adjust the settings of the scanning device. Like in the field of photography, in order to scan any object, must regulate the scanner sensor as different object have different attributes. (Lemeš, 2009).

The easiest and quicker way to create an object is to use laser scanners as they offer quick results without the need of any mold.

2.2. Reverse Engineering

2.2.1. Introduction: Reverse Engineering RE and Computer – Aided Reverse Engineering CARE.

Raja (2010, pp.2) introduces engineering as the ‘process of designing, manufacturing, assembling, and maintaining products and systems’. He classifies the engineering in two fields, the forward engineering and reverse engineering.

The forward engineering is the classic way to produce an object. Initially, the engineer makes schematics of an object and study all mechanical principles in order to understand if the production of such object is achievable. In order to do that, the engineer uses CAD designs and measuring tools. When everything are combined together, the next stage is the production of the object using appropriate materials.

The reverse engineering introduced in the market as a tool to duplicate an existing object even to make in more efficient. Reverse engineering started as a tool for someone that wishes to produce an already existing object that a certain factory produces. Even if it started that way, the market accepted this idea in order to make existing objects even better.

Reverse engineering uses 3-D data of an existing product in order to create a CAD design and create an improved product. In plain words, reverse engineering takes any system and disassembles it in order to understand its design and functionality and comprehend the basic principles of its operation.

Abella et al. (1994) introduces a new terminology for reverse engineering. It can be used in order to create an entity without the use of an engineering schematic. In addition Yau et al. (1993) proposes that reverse engineering is the “process of retrieving new geometry from a manufactured part by digitizing and modifying an existing CAD model.”

The most common reasons to use reverse engineering is the following:

- 1) Some parts are no longer being produced because the manufacturer produces new ones or the manufacturer is no longer exist.
- 2) The market needs excessive number of parts and the manufacturer can nor satisfy the need.
- 3) Reverse engineering is used in the field of quality control. Engineers can observe the operation of a part and compare it with the designs in order to see if its purpose is as should be.
- 4) It can be used as a data base of blueprints and save in servers for future works.
- 5) It is used to compare similar products developed by different manufacturers.
- 6) It is used by the movie industry to lower the scale of objects and film them with less cost.
- 7) Reproduction and display of ancient works
- 8) It reduces the technological risk because one can create something from a system that is already proved that is operational.
- 9) It aids market that need to fill a huge technological gap compared to others
- 10) In now days reverse engineering entered the area of medicine. Specifically, it is used for dental prosthetics and, even if it is in early stage, in recreation of body parts. (Bilalis,2013 & Raja, 2010).

There are several prototyping tools available in order to create a 3-D model of a project. The significant part of such tools is to experience virtually any object designed before production. In Computer Aided Engineering (CAE), designer use the standard method in order to produce anything. From design with the aid of computers to production also with the aid of computers. In reverse engineering there is another term introduced the Computer Aided Reverse Engineering (CARE) that is the opposite of CAE. Using 3-D scanning technology, designers can produce a 3-D model of an existing object in order to duplicate it or improve it without the need to redesign it from the beginning using the traditional CAE.

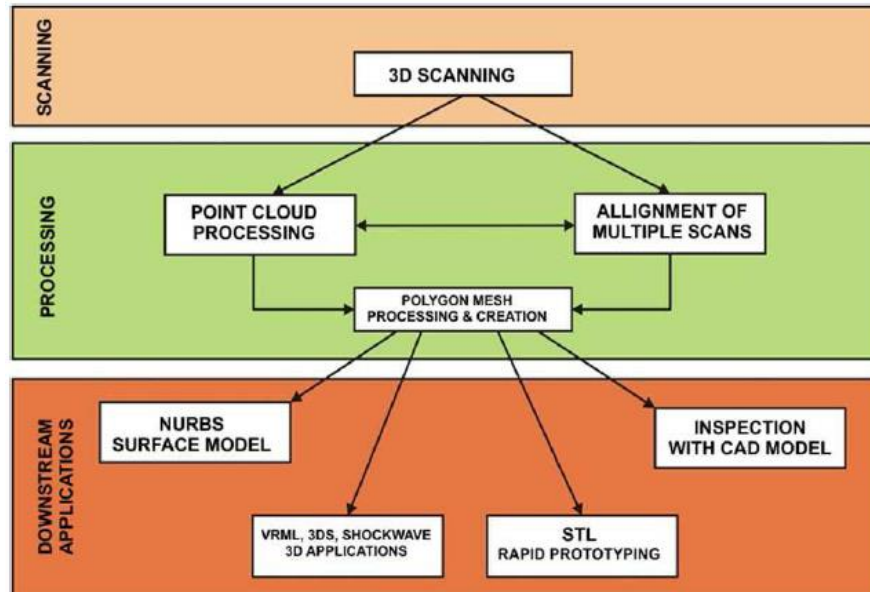


Figure 2.1 - Reverse Engineering process. (Bilalis, 2013. Page.17)

Reverse engineering is explained by the picture above. The first step is to scan any object using 3-D scanning device. It may take more than one 3-D images to capture before proceeding to the next phase. The second phase consists of the processing of the 3-D images. Point processing refers to the processing of any individual scanning point captured by the 3-D scanner. For example, by processing separately any pixel of the scanned points, you can transform it to another pixel. As an example, colors can be enhanced in order to highlight a scanned area. Other abilities that are available are alignment and noise reduction in order to have a drawing. The third phase converts all data from the processing to any format that is suitable for the designer. (Raja, 2010).

2.2.2. Contact and noncontact method

In a previous paragraph we separate the scanning methods for collecting 3D data in noncontact and contact methods. The first one is performed by a machine, which is based in Coordinate Measuring Machines Technologies, that uses a specific equipment to follow the shape and the curves of the surface.

Even if their tolerance range is few microns, they have quite a few disadvantages that make them users unfriendly. The time of scanning depends from the size of scanning surface and the probes need to deviate to register a new point in it. Furthermore, the user of the scanning machine has to assure the contact of it with the scanning surface, constantly. (Bilalis, 2013)

The second method and the most common is the noncontact method which consists of laser, optics or waves scanners. Laser scanner, a broad used machine, can scan a large number of points fast and accurately. Additionally, their small size makes them competitive to the noncontact scanners, the operator can carry it almost everywhere.

2.2.3. Laser scanning Triangulation

Triangulation is the procedure/method that the laser scanners use in order to scan any object by emitting a high energy light at a specific angle on a object's surface. Looking closely at the image below (Figure 2.2) and considering that length (L) between the mirror of laser's light source and the lens of the photosensitive device, the values of angle θ , the focal length F and point P are known, point P_i can be calculated. It is crucial to notice that point P_i will be in camera's coordinate system. (Park and De Souza, 2005).

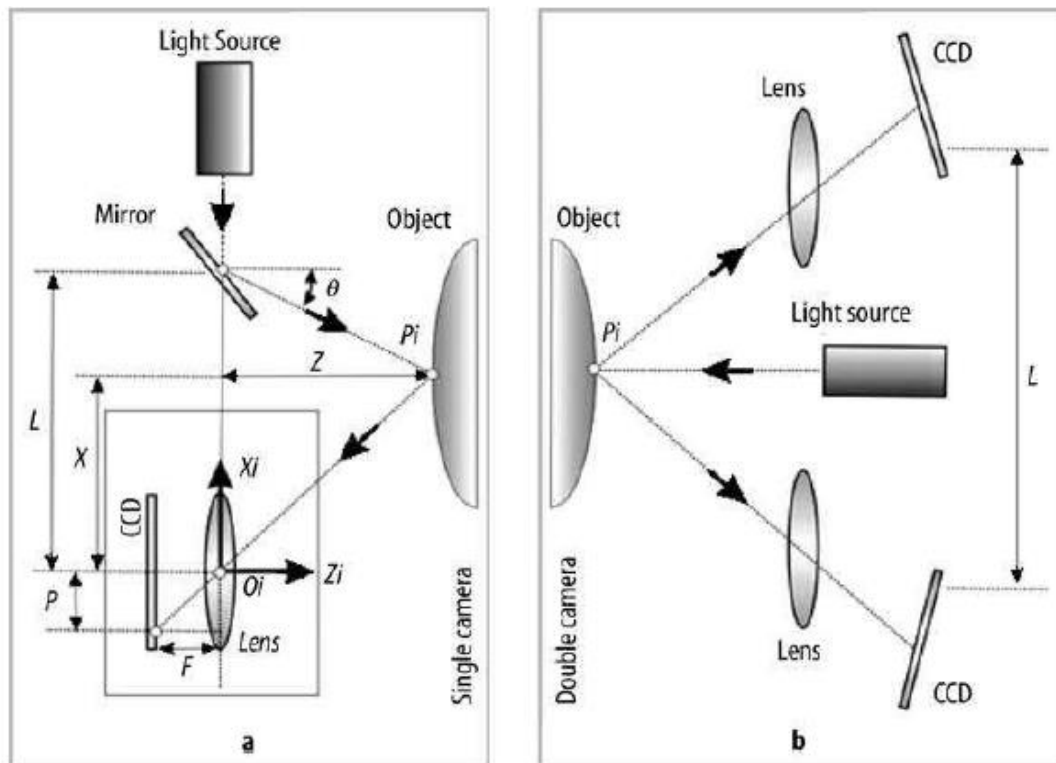


Figure 2.2: Triangulation Methods

2.2.4. Surface representation – Cloud of points

Point cloud is the total number of points that can represent the external scanned surface. Each point is described by three coordinates (x,y,z); point cloud, as well.

Although, point cloud can be used for creating 3D CAD models is necessary to transformed it to “Mesh of Surface” model before we could edit the scanned data.

One way to do this is the known method of “Delaunay Triangulation” where the vertices of the scanned object will create a network of triangles. This network will constitute a face, a face is the simplest form which is described by three vertices, each one with different coordinate. The total number of faces of the specific object will be a polygon. (Figure 2.3)

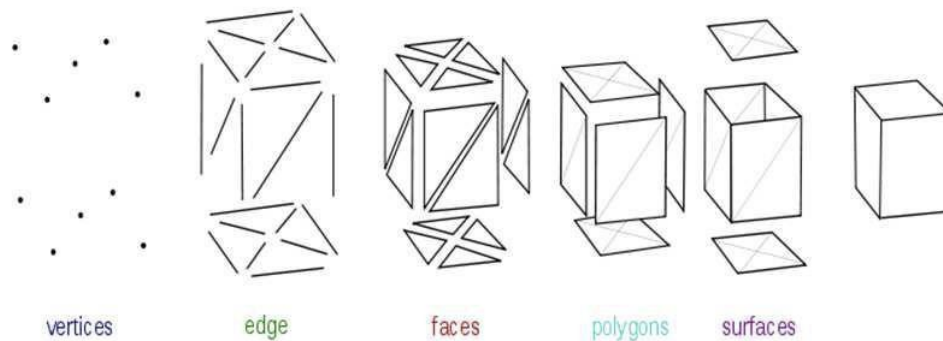


Figure 2.3 Vertices, edges, faces, polygons, surfaces, https://en.wikipedia.org/wiki/Polygon_mesh

Surfaces, also called smoothing groups, are used to group smooth regions. A better explanation is given with the below example. As per the image (Figure 2.4) three groups/surfaces are consider, the first group is the one where all the surfaces point horizontally from the center, and the other two where the surfaces point up and down from the center.

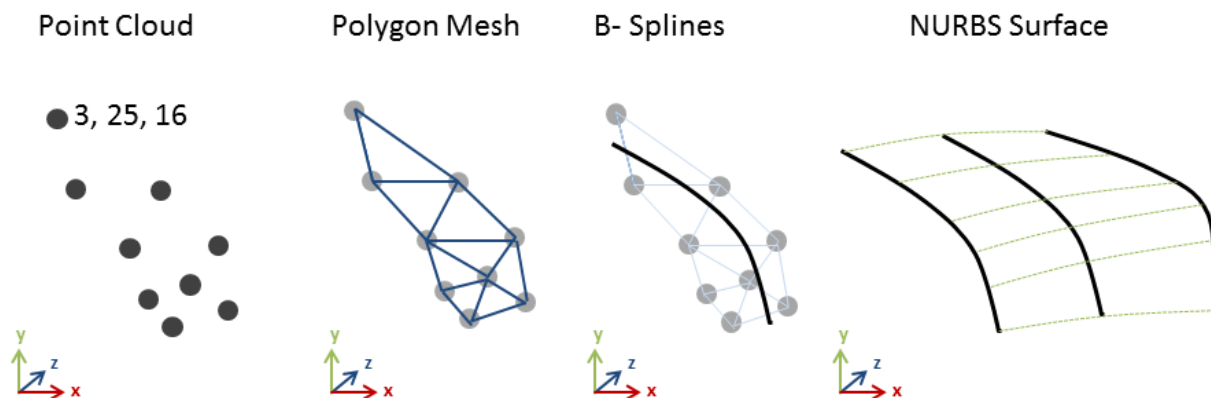


Figure 2.4

Below is described the four phase of Reverse Engineering data process with their Reverse Engineering operations that need to be completed step by step in order to consider the object scanned and ready for process. (Figure 2.5)

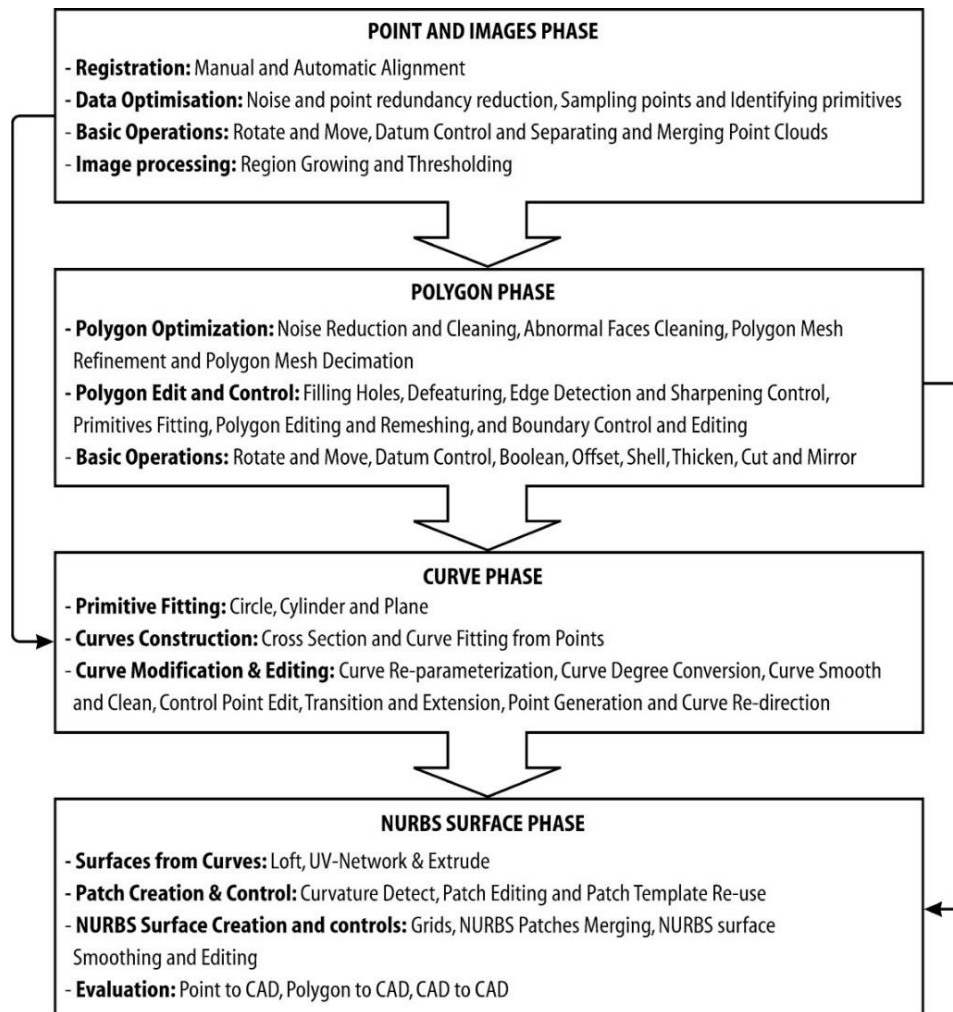


Figure 2.5 Phases of Reverse Engineering process (Raja, 2010. Page 54)

2.2.5. File Types

The file and the formats which used to elaborate the scanned data are listed below:

ASCII – x,y,z point cloud

PWK – Polyworks Workspace File

IGES – Initial Graphics Exchange Specification

SLDPRT – CAD format for SolidWorks

3. Systems & Software Description

3.1. Laser Scanner & Reverse Engineering Software

For the 3D scan & further processing of the point cloud data Laser Scanner of the company QCONTROL Ltd. located in Kallithea Athens were used. The specifications of the Laser Scanner are the following:



The Romer Absolute Arm 7-Axis "SI" series with integrated laser scanner delivers the convenience of a fully integrated 3D scanning solution. The scanner is permanently incorporated into the seventh axis, and weight balanced with ROMER's Zero-G counterbalance feature for ergonomics and ease of use. The feature pack contains the scanner interface, so no external controller box is required. Single button automatic laser power control allows scanning of different surface types.

ROMER Absolute Arm with integrated scanner is the first portable arm system in the market that is factory calibrated and certified to B89 specifications.

Figure 3.1

Technical Specifications

Model3	Measuring Range	Max. Point Acquisition Rate	Stand off	Points per line	Scanning System Accuracy	Arm Weights
7325SI	2.5 m .	30,000 Points/s	150mm ± 50mm	1000	±0.084mm	8.6 kg

Operation

The scanner is collecting data of the geometry as points through a laser line. The movement of the scanner is manually. The Part shall not be moved during the scanning procedure. The scanner is manually driven over the surfaces which have to be scanned. Through the optical scales, in the arm where the scanner is integrated, the system recognizes the position of the scanner and the angle to the part.

The Reverse Engineering Software used for the data collection and the data acquisition is the following:
Innovmetric Polyworks - Standard reverse engineering package.

- Fully supports all high-density point cloud 3D digitizers
- Includes mesh generation and editing
- Includes curve and NURBS surface generation
- Includes parametric 2D sketching tools
- Imports IGES and STEP files and includes CAD reconstruction technology

The reverse engineering software is divided in 3 parts.

1. IMAlign – Collecting and Editing the Point Cloud
2. IMMerge – Creating the Polygon File
3. IMEdit – Edit the polygons & Creating the Curves & NURBS
4. IMInspect – Measuring Software

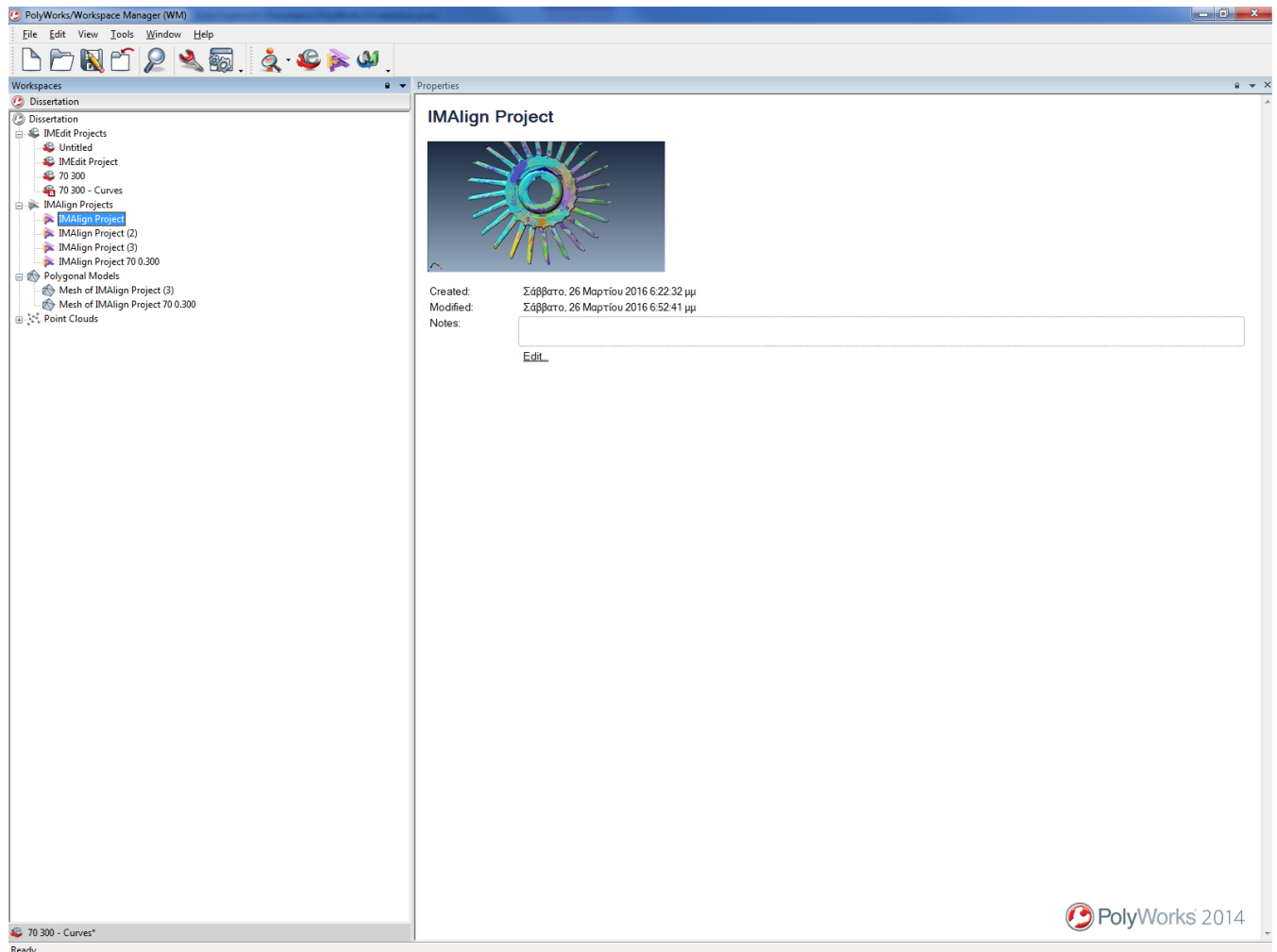


Figure 3.2

3.2. 3D CAD Design Software

The CAD Elements (Polygon Surfaces & Curves) created by the Reverse Engineering Software are exported in native cad formats files. These elements are imported in a 3D CAD Design Software in order to create a parametric 3D CAD model. Afterward this 3D CAD model can be used for the following operations:

1. Re-design & Optimization of the Scanned Part
2. Simulation in other software
3. 3D Printing
4. Production with CNC machines, Casting, Injection Molding etc. or
5. Creating Measuring Programs in a Measuring Software for inspection.

The 3D CAD Design Software used for the data collection and the data acquisition is the SOLIDWORKS Student Edition Software. SOLIDWORKS software provides an intuitive 3D development environment that helps maximize the productivity of the design and engineering resources to create better products faster and more cost-effectively.

SOLIDWORKS is a powerful 3D design solution for rapid creation of parts, assemblies, and 2D drawings. Application-specific tools for sheet metal, welding, surfacing, and mold tool make it easy to deliver best-in-class designs.

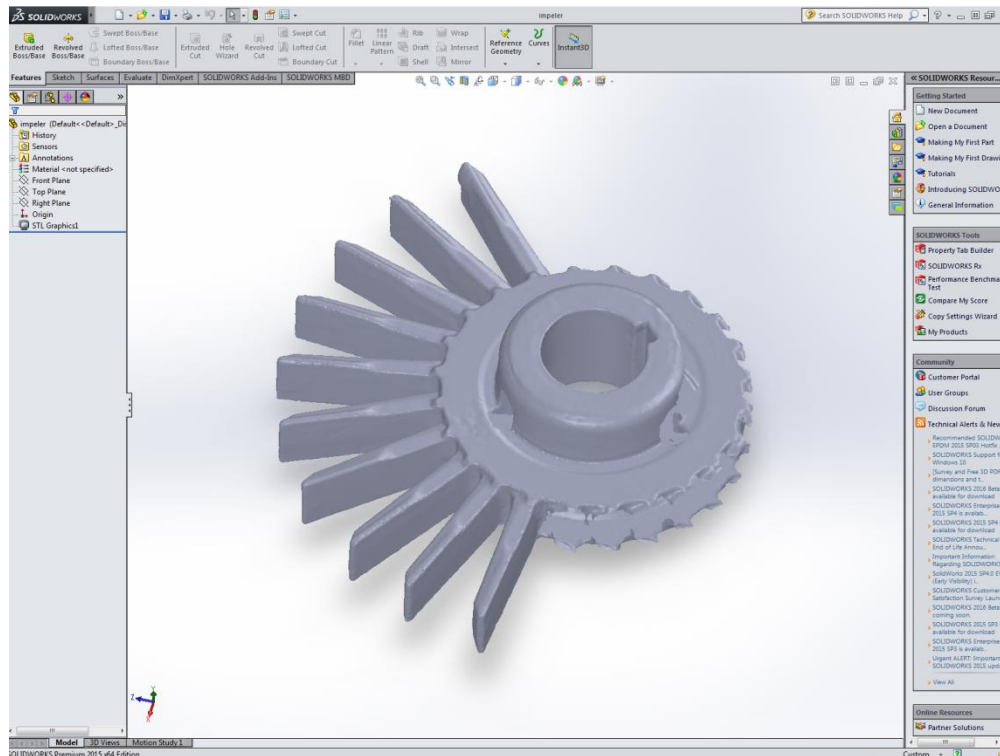


Figure 3.3

3.3. Coordinate Measuring Machine & Measuring Software

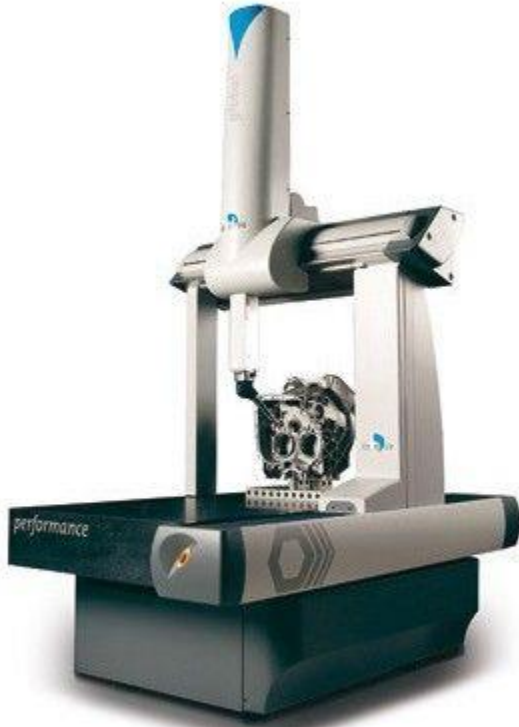


Figure 3.4

For the evaluation of the used methodology a system with a higher accuracy is required. With this system we will measure the deviations between the created 3D model and the real object.

For the choice of the measuring system we followed the “Rule of Ten” or “one to ten” which is that the discrimination (resolution) of the measuring instrument should divide the tolerance of the characteristic to be measured into ten parts. The measuring instrument should be 10 times as accurate as the characteristic to be measured. The whole idea here is to choose an instrument that is capable of detecting the amount of variation present in a given characteristic.

Since the certified Scanning System Accuracy of the Laser Scanner is $\pm 0.084\text{mm}$ the measuring system used for the evaluation should offer a system accuracy of $\pm 0.009\text{mm}$.

For measuring the object and perform the CAD to Part comparison we used the coordinate measuring machine (CMM) DEA/ Brown & Sharpe/ Mistral/ PH10M/TP200 Renishaw Head of the Rapid Prototyping & Reverse Engineering Lab of the National Technical University of Athens

- Measuring Range: 700mmx 700mmx 500mm.
- Measuring Accuracy according to ISO 10360 – 2 / VDI/VDE 2617: $E = U3 (\mu\text{m}) = 2,5 + L(\text{mm})/250$

A coordinate measuring machine (CMM) is a device for measuring the physical geometrical characteristics of an object. This machine may be manually controlled by an operator or it may be computer controlled. Measurements are defined by a probe attached to the third moving axis of this machine. Probes may be mechanical, optical, laser, or white light, amongst others. A machine which takes readings in six degrees of freedom and displays these readings in mathematical form is known as a CMM.

The typical 3D "bridge" CMM is composed of three axes, X, Y and Z. These axes are orthogonal to each other in a typical three-dimensional coordinate system. Each axis has a scale system that indicates the location of that axis. The machine reads the input from the touch probe, as directed by the operator or

programmer. The machine then uses the X,Y,Z coordinates of each of these points to determine size and position with micrometer precision typically.

A coordinate measuring machine (CMM) is also a device used in manufacturing and assembly processes to test a part or assembly against the design intent. By precisely recording the X, Y, and Z coordinates of the target, points are generated which can then be analyzed via regression algorithms for the construction of features. These points are collected by using a probe that is positioned manually by an operator or automatically via Direct Computer Control (DCC). DCC CMMs can be programmed according to a CAD model to measure specific parts geometries and to compare the deviations of the measured dimensions to the nominal dimensions.

Following, with the measuring software PCDMIS CAD++ which is the software interface of the CMM, the operations were performed by the following schema:

1. Import of the created CAD model,
2. Writing the measuring program
3. Run the measuring program
4. Dimensioning
5. Reporting

PC-DMIS is the world's leading measurement software, with over 60 000 seats in place worldwide. Its powerful capabilities enable users to measure everything from simple prismatic parts to the most complex aerospace and automotive components. PC-DMIS leads the way in revolutionizing measurement, pioneering technologies such as:

- Use of CAD models in the inspection process
- Directly linking CAD systems and measurement software through its Direct CAD Interface (DCI) technology
- Implementing a full set of sheet metal measurement routines tailored for the automotive industry
- Digitally simulating measurement in an offline virtual CMM environment
- Easily aligning complex contoured parts using breakthrough iterative alignment technology

PC-DMIS comes in three basic configurations, Pro, CAD and CAD++, with optional modules available to fine-tune for specific needs. It is also available in an offline version for virtual programming.

PC-DMIS CAD extracts part data directly from the models. Inspection routines are simplified and error-proofed by pointing and clicking on those models of the parts. This virtually eliminates mistakes related to bad data entry or misinterpreting hard copy blueprints.

PC-DMIS CAD adapts CAD capabilities to inspection. This doesn't mean that PC-DMIS CAD is a CAD system - it's a powerful metrology software that fits CAD to the job of inspecting and evaluating parts.

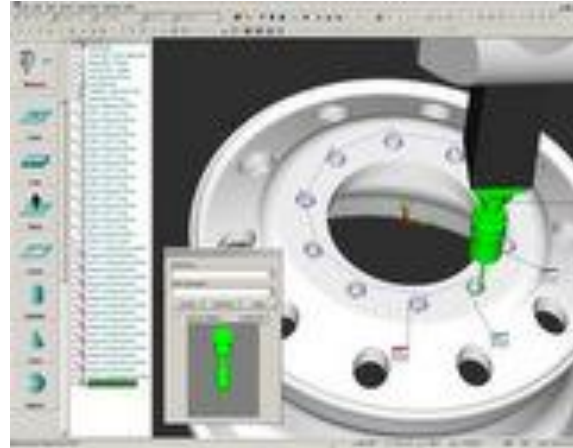


Figure 3.5

The software lets you graphically test and debug your inspection routines before they run on the machine. PC-DMIS CAD animates probe paths and lets you edit them on the fly, it includes accurate kinematic modeling of most CMMs, and, when working with solid models, it automatically detects probe collisions with parts and fixtures.

PC-DMIS CAD supports multiple protocols for linking to CAD. It can be neutral like IGES or STEP or it can be CAD system native like UG or CATIA or something in between like DMIS. Whatever the format, PC-DMIS CAD has a solution to handle it.

Built into the baseline packages are pre and post processors supporting widely recognized standard formats like IGES, STEP and DMIS. Translators tailored to specific CAD systems like UG and CATIA are available as options. For the most demanding applications, there are Direct CAD Interfaces (DCIs). DCIs link directly to the CAD database and let customers work directly with their models from PC-DMIS with no translation. No other metrology software comes close to giving users this kind of versatility and flexibility in linking to CAD.



Figure 3.6

4. Scanning Procedure

Firstly the part has to be firmly fastened on a surface area within the range of the Scanner in such a way were all the side geometries are accessible for the scanner. Areas of the part which are used for the mounting should be limited to a minimum since they will not get scanned. For our work we placed the impeller on the side of the granite table the scanner is mounted and stabilized with a blue tack adhesive slice.



Figure 4.1

For digitizing the part and for collecting the cloud of point's data with the Romer Absolute Arm 7325SI laser scanner, the software Polyworks IMAlign were used. A plug-in in the software enables the direct use of the laser scanner and the real time visualization of the digitalization of the scanned part. This helps to coordinate the speed, distance and angle position of the scanner for the optimization of the point's collection without noise and gaps.

4.1. Scanning Parameters.

- a. The laser density is adjustable according to the part's surface color and gloss. This is done automatically by pointing the scanner to the part and pushing simultaneously the two side buttons. Immediately the system auto adjusts the parameters of the laser according to the surface.
- b. In this Software the data of the cloud of points is organized in a grid. The space between the grids is set by the parameters Max edge length and Interpolation Step in the options menu. The smaller the grid size is set, the more details will be captured. The disadvantage of using a high detail is that the scanner has to be moved very slowly in order to capture the required details. Due to the fact that for the impeller the details geometry is simple and high accuracy is not requested, I used 0,300mm for the interpolation step. For the parameter the max edge length is set at the 10x the interpolation step.
- c. By moving the scanner over the part the angle of the camera to the part is continuously changing. In order to scan some surfaces which are not directly visible by the camera (e.g. at the compounds of the blades with the core) the part is approached sideways. This leads to reflections of the laser that are recorded by the camera as noise in the point cloud. To eliminate this effect the maximum angle parameter is adjusted. This parameter ignores the collected points recorded over the requested angle. By running several test scans with different set max angle parameter we observed that the points collected with an angle of 70 degrees are sufficient enough to recreate the surface without noise.

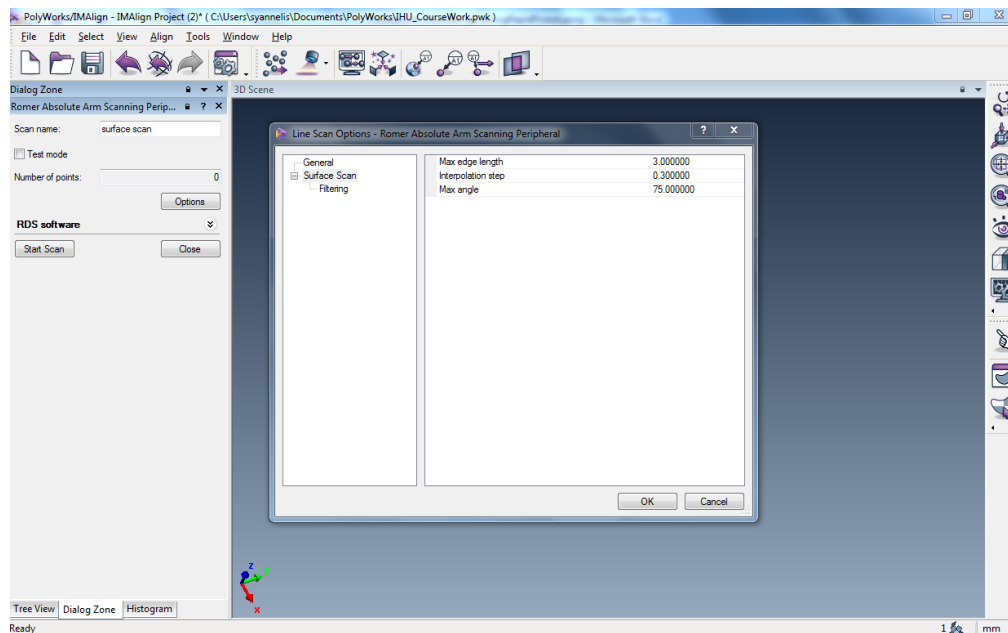


Figure 4.2

4.2. Data Collection – Point cloud creation

In order to collect the data with the laser scanner and to create the cloud of points the scanner is moved manually over the part. The movement is similar to the movement of a brush paints a wall.

The scanner is collecting data of the geometry as points on the laser line. The part shall not get moved during the whole scanning procedure. Through the optical scales of the arm where the scanner is integrated, the system recognizes the position of the different scanning positions and the angle to the part.

The distance between the laser and the surface should be approx. 5 to 10 cm. In order to control the distance to the part a laser pointer is used (fig. 3.3). The laser point is moving away sideways of the laser line if the distance is too near or too far. The viewing angle of the scanner to the part cannot exceed the 70°, adjusted in the parameters. In case this angle is exceeded the software will show holes in the scan data.



Figure 4.3

The outcome was several clouds of points which are highlighted in the software with different colors. Since only the upper part of the impeller was totally visible for the scanner the scanned data includes several holes. The not closed scans are illustrated with blue surfaces, these are the scanned surfaces from the inner side.

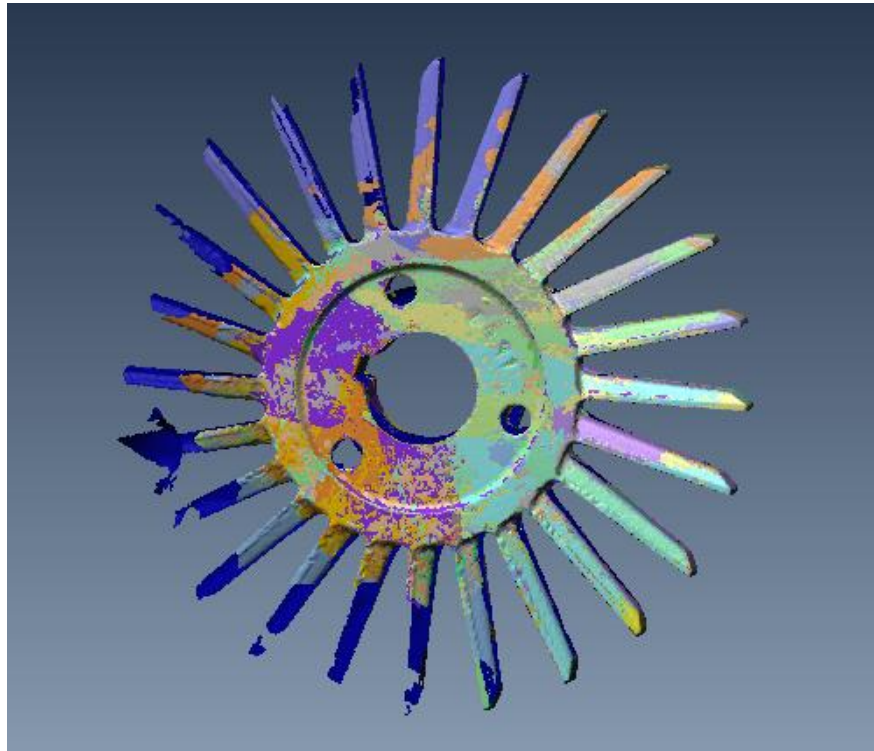


Figure 4.4

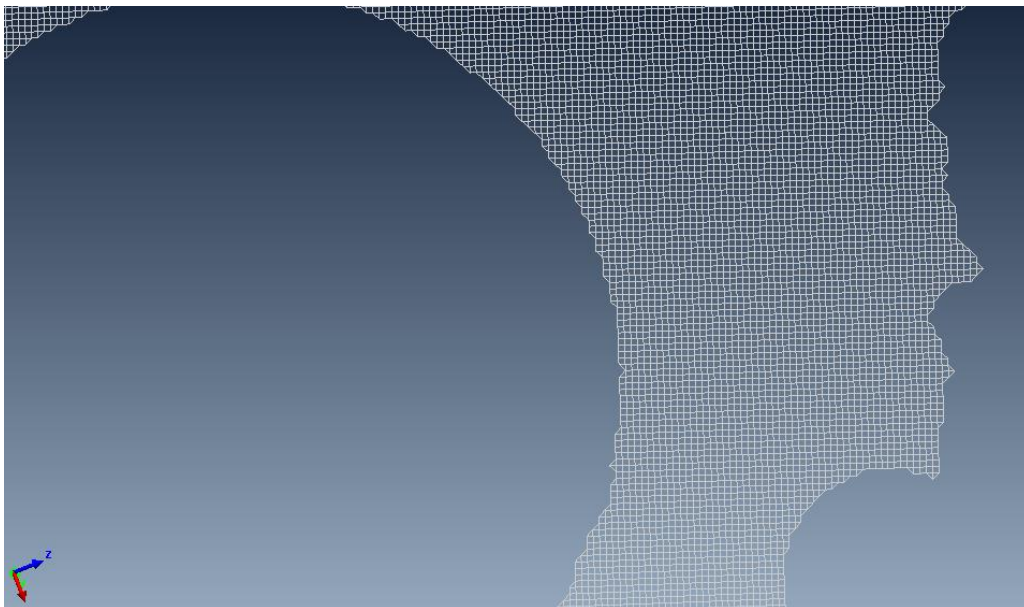


Figure 4.5 shows the created grids of the clouds of points

4.3. Processing of the point cloud

4.3.1. Best fit Alignment of the scans

The created cloud of points is a cluster of different sub clouds. Every time a new start point were used a new grid of the points was created. This is used in order to log the different scan directions which is helpful for the further point processing. These several scans are overlapped in several areas.

For the scan of the impeller 84 scan clouds were created.

Since, due to the accuracy and the different positions of the laser scanner, there are small spaces in between the scans, a best fit alignment is performed which automatically aligns the scans on the overlapping areas. A histogram indicates about the quality of the alignment of each scan. The form of a good alignment has to be bell shaped since it should be a normal (Gaussian) distribution. From this histograms scans with big outliers can be recognized in order to be corrected or erased.

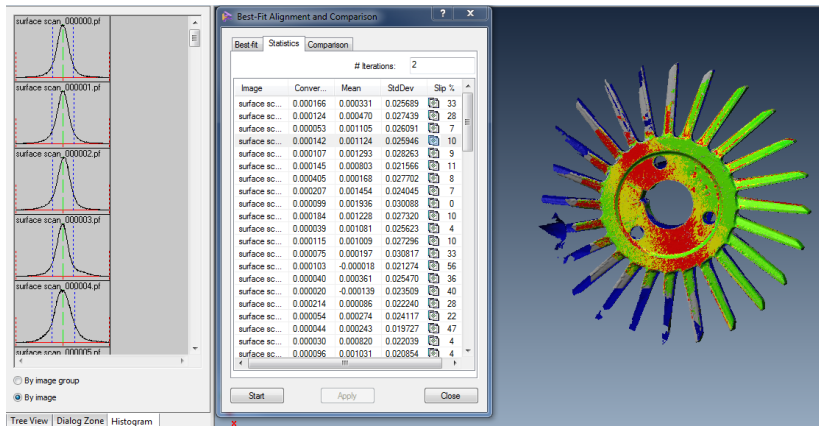


Figure 4.6

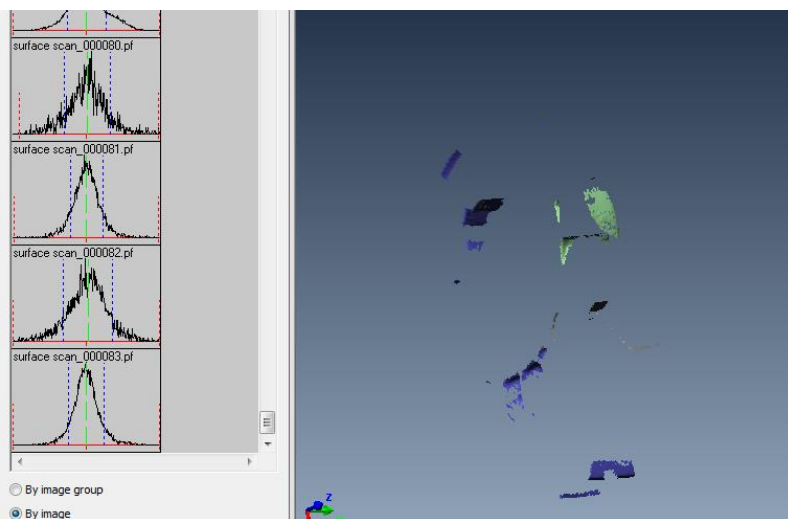


Figure 4.7

4.3.2. Cleaning of the point cloud

Next action required is to remove eventually captured noise from reflection & fixtures and points which are not required for the further processing. The software offers some simple tools for selecting points and afterwards to delete or split them. By using these tools the down part which was not totally scanned were selected and removed.

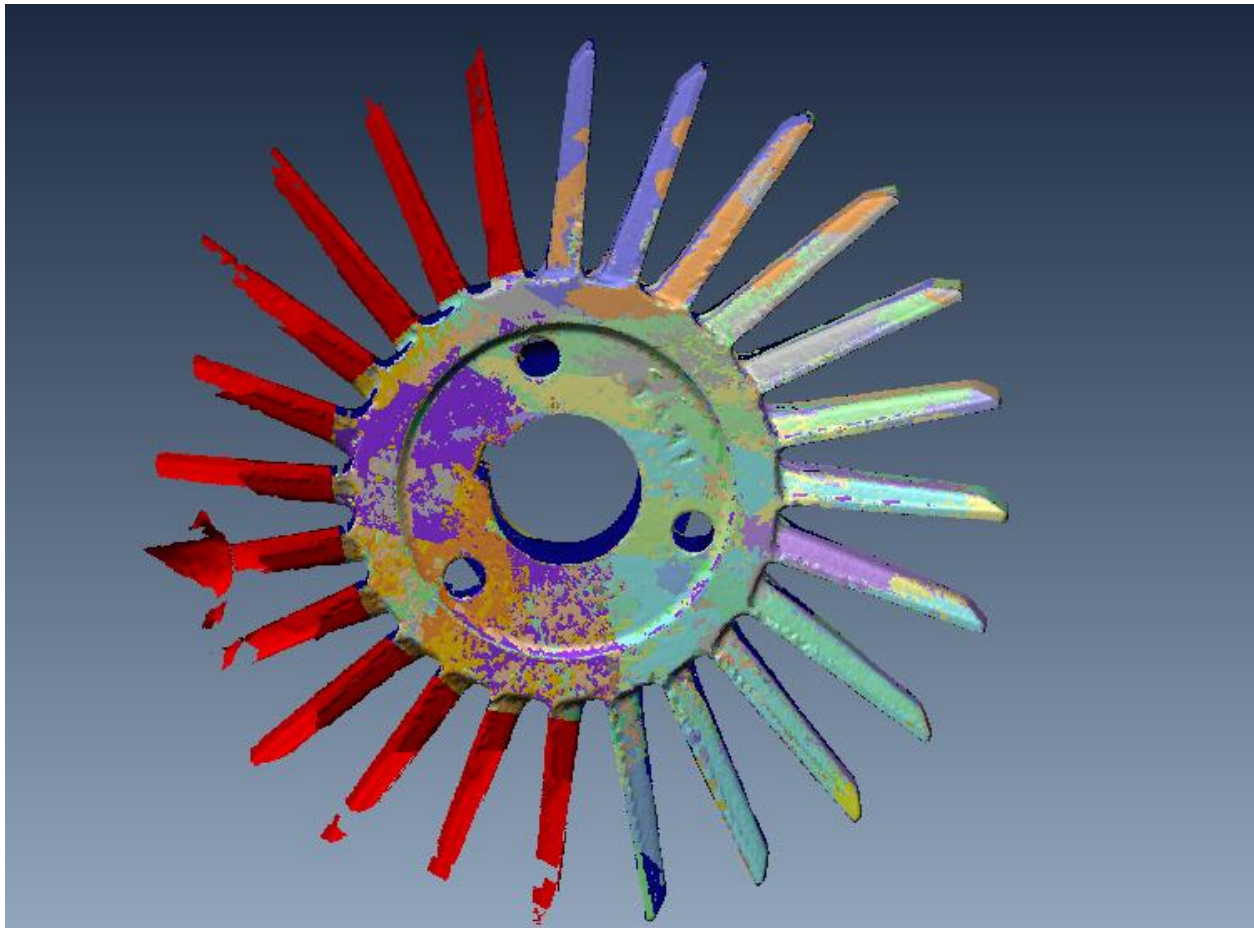


Figure 4.8

4.3.3. Reduce the cloud data

For creating the polygon- mesh and proceed with the cad creation it recommended to reduce the size of the file. The IMAlign software reduces the cloud of points by reducing the overlapping points and by keeping only two (2) overlapping clouds of points in areas where the scans are joining together.

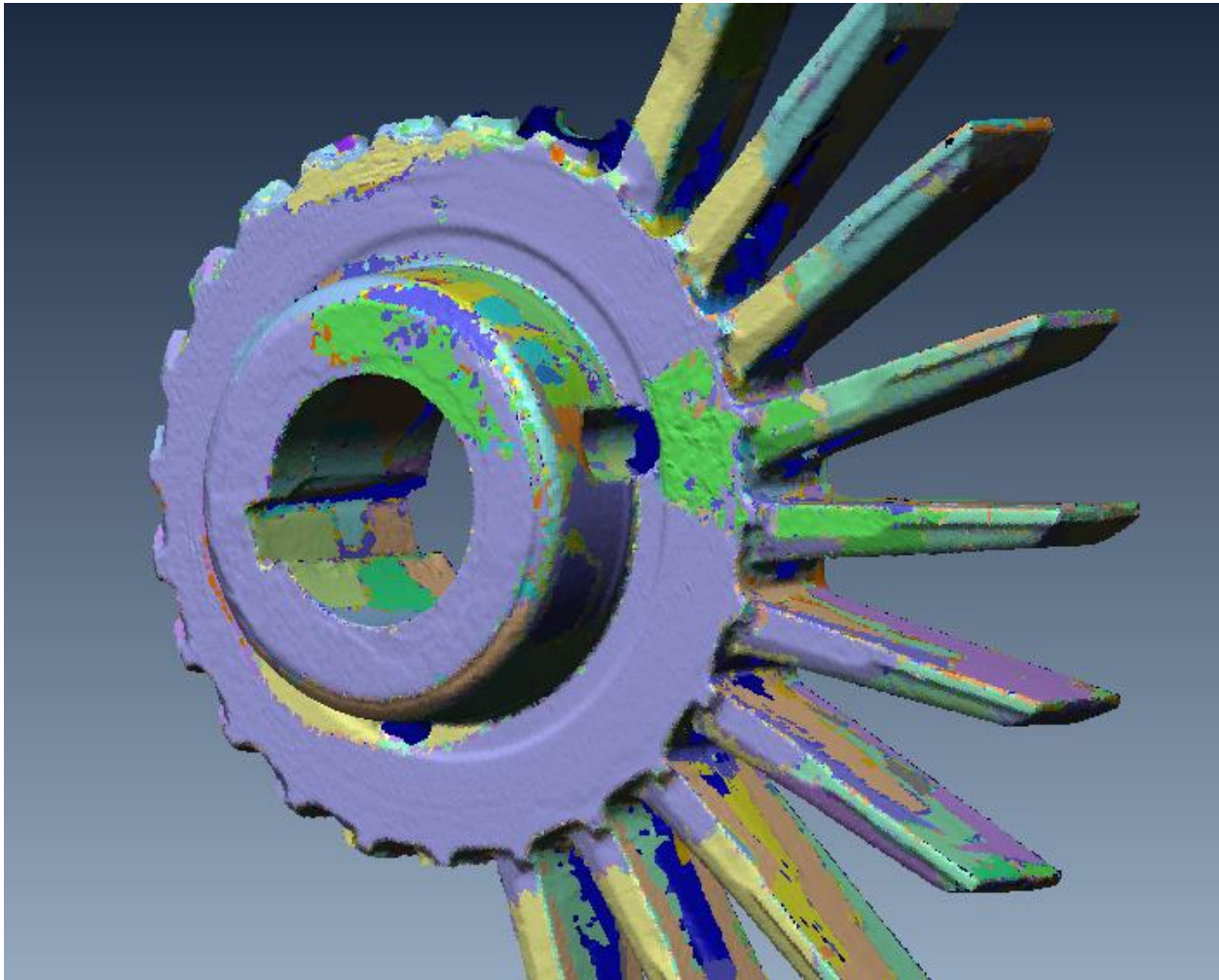


Figure 4.9

The file is saved in the workspace of the Polyworks software and in order to be processed the second part of the reverse engineering software IMMerge.

5. Procedure of creating & processing the polygons (stl)

For creating the polygon file from the point data the second part of the software IMMerge is used.

5.1. Creating the Polygon Mesh

The procedure is made automatically and the parameters are predefined by the grid settings. This means that the polygon files will look exactly like the scanned data if the parameters are not changed. Nevertheless, in case where the result is not acceptable, we can repeat the procedure with different parameters.

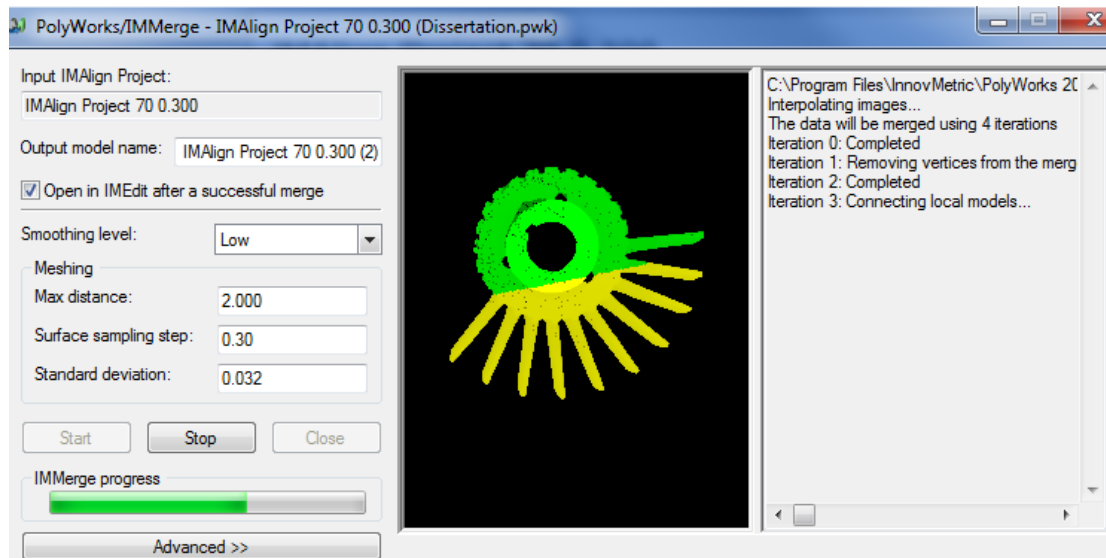


Figure. 5.1

The created polygon-mesh is represented fig. 5.2.

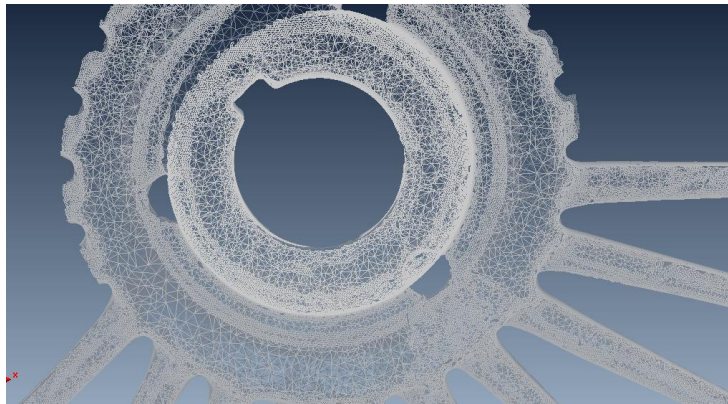


Figure 5.2

5.2. Processing of the Polygon mesh

For further elaboration the data is opened with the third part of the software IMEdit. In this software it is possible to optimize, smooth and reconstruct the polygon mesh as well it is possible to reconstruct surfaces in order to close the holes.

In the process of transforming the point clouds into polygonal surfaces, holes appear from the deficient scanning. By changing the parameters of the initial process this effect could be limited but consistently also the surfaces would be varied. In order to avoid deviations it is preferable to create the surfaces untreated by filters and to work with the included tools.

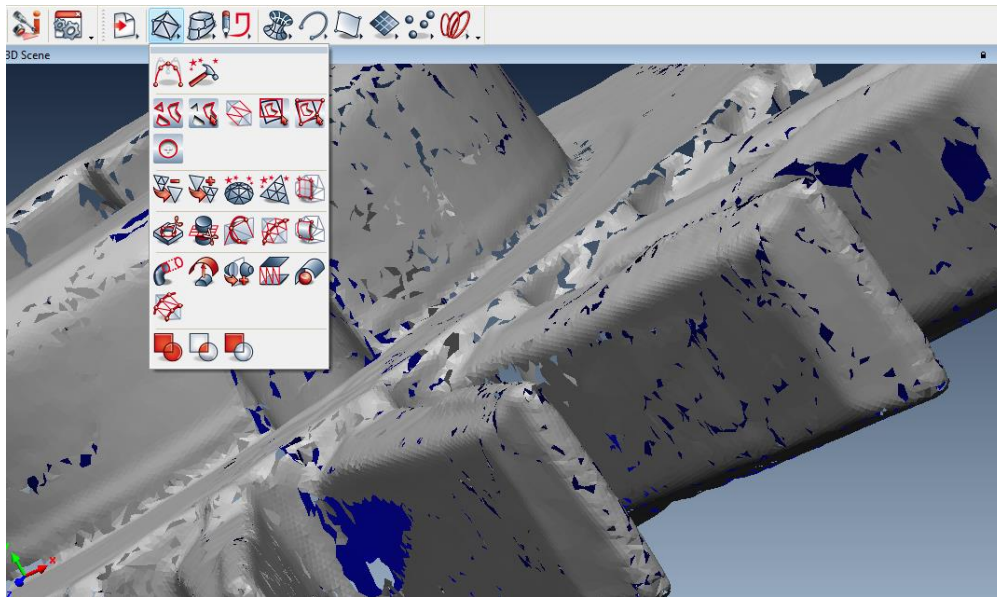


Figure 5.3.

5.2.1. Optimize the Mesh

First it is important to reconstruct the polygons in such a way were the angles, the sizes and the vectors are as uniformly as possible. For this reason the software offers the following tools:

1. Optimize Curvature – for the polygon size optimization
2. Improve Equiangularity – for the polygon angle optimization
3. Smooth – for smoothing the vertices
4. Reconstruct Surfaces

Since the tools Smooth and Reconstruct are changing the initial surface data, there were not used for the purpose of this work.

5.2.2. Automatic Hole Filling

For the small holes the software is automatically calculating the curvature based hole filling without changing the surfaces. Then every hole should be evaluated by the user and the outcome can be changed or confirmed. The parameters used are the max size of the holes and if the filling should be Curvature based or Flat.

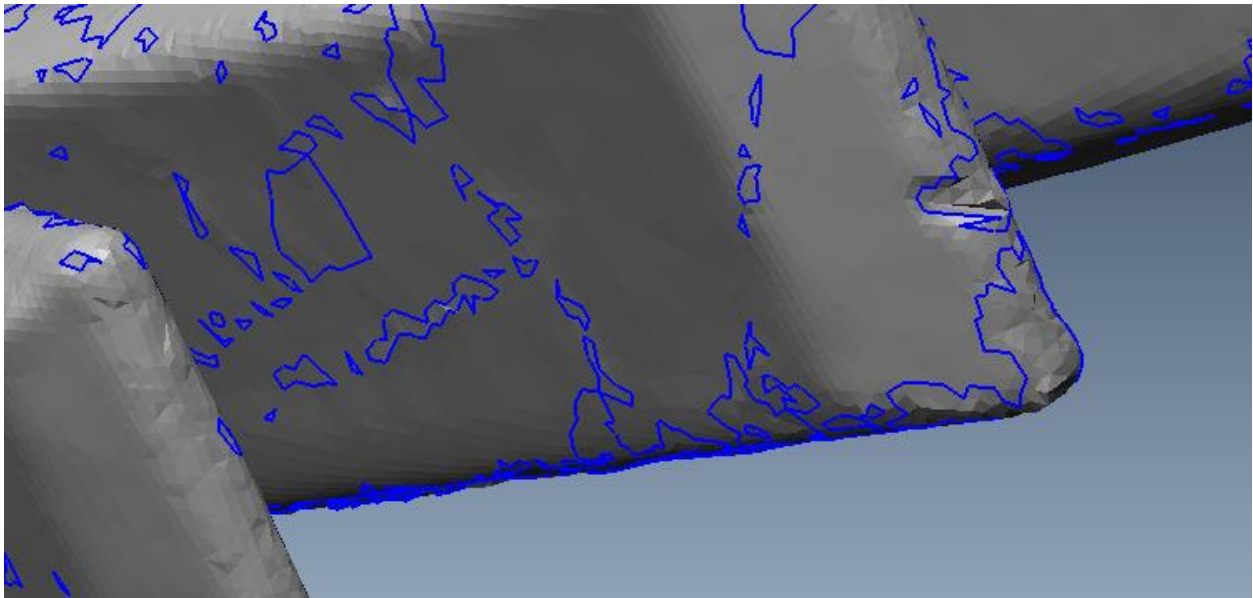


Figure 5.4.

5.2.3. Interactive hole filling

For larger holes the mathematical formula used by the automatic hole filling tool is not working. The reason for this is that more curvatures are forming the surface. In order to close these holes the software offers several tools for the partial filling.

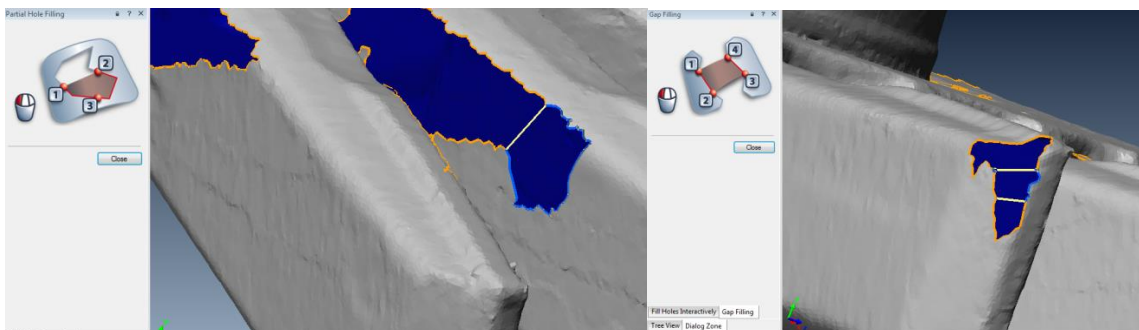
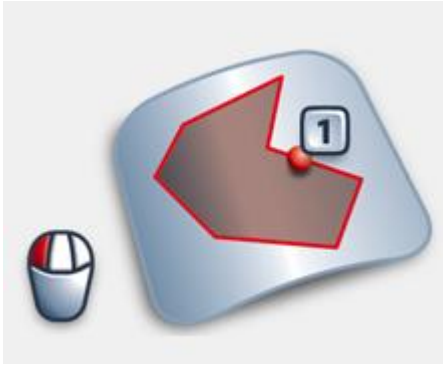


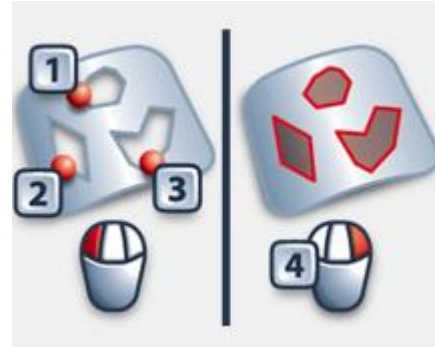
Figure 5.5

The offered tools are the following:

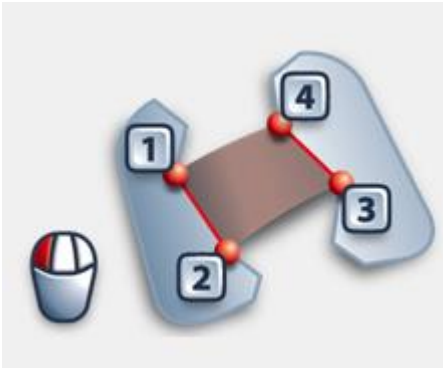
1. Single Boundary Filing



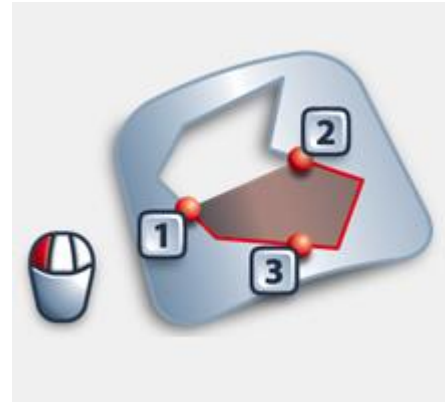
2. Multiple Boundary Holes



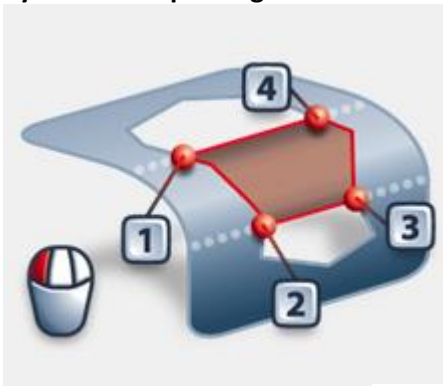
3. Gap Filling



4. Partial Hole Filing



5. Cylindrical Gap Filling



6. Fillet and Surroundings filling

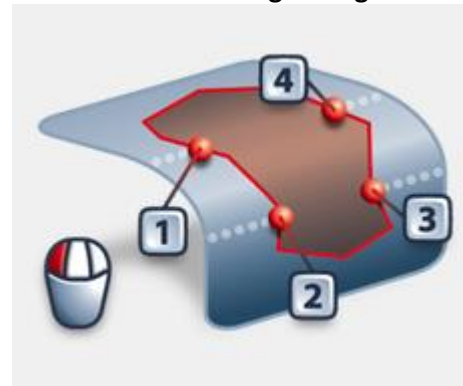


Figure 5.6

With these tools a watertight mesh is created which is suitable for 3D printing or for manufacturing with CNC machining through a CAM software. For the scope of this work, further processing will be required in order to create the curves adapted on the polygon surfaces.

6. Procedure of creating the Curves (B-Splines)

6.1. Reconstructing Options

In order to reconstruct a parametric CAD model from the polygon surfaces, several practices can be applied.

1. Export the polygon surfaces into a CAD software.

The part is designed from scratch based on the scanned model. In this method only the tools of the CAD software are used to create the features on points of the polygon surfaces. The disadvantage of this method is that the tools of the CAD software's are not as sophisticated as the tools of the Reverse Engineering Software's.

2. Create the Curves and Export them into a CAD Software.

In this method the curves and features are created with the Reverse Engineering software. The reverse engineering software offers several tools for extracting the curves from the polygon surfaces. This tools are easy to use and accurate since the created curves are tangent to the surfaces. Contrary to the cad software's were a number of points are used.

These curves can be imported in any cad software and used directly to extract the features of the cad model.

3. Create NURBS surfaces and Export them into a CAD software.

If the surfaces are very complex and cannot be easily described by curves the reverse engineering software's provide further tools for creating NURBS surfaces. This surfaces are tangent on the polygon mesh and can be exported into a CAD software. In order to create the NURBS surfaces the curves have to design like in the second method. The curves will indicate the borders of the surfaces. Each NURBS surface shall have at least four (4) curves in order to create it. Then the curves are adjusted by the software according to the deviation of the tangency of the NURBS surface - Polygon Mesh and not according to the tangency of the curves - selected polygon surfaces.

Furthermore this surfaces are not handled by the CAD software's like features of parametric models. For the further processing special plugins in the CAD software's are required for surface modeling.

For this work, the method No.2 create the B-Splines is chosen. We consider that it is sufficient enough to recreate the impeller by the curves created by the reverse engineering software. This decision was made since the part is a mechanical part and was initially designed in a CAD software.

6.2. Creating the Curves (B-splines)

For creating the curves from the polygon surfaces the IMEdit software continues to be used. There are two toolbars offered by the software:

1. Curves
The curves are created in a three dimension environment
2. Sketch
The curves are created with projections on planes. The created curves are similar to the parametric CAD software sketches and easier for the further processing.

6.2.1. Sketch

The sketch tool is guiding the user step by step in order to create the curves needed for the CAD software.

1. Select or Create the plane for the sketch
To create the plane three points are selected on the polygon surface. The plane becomes visible and shows the tangent to the surface which can be adjusted with an offset until the bulk of it is covered.
According to the offset the cross-sections are created which will be used for the curves creation.

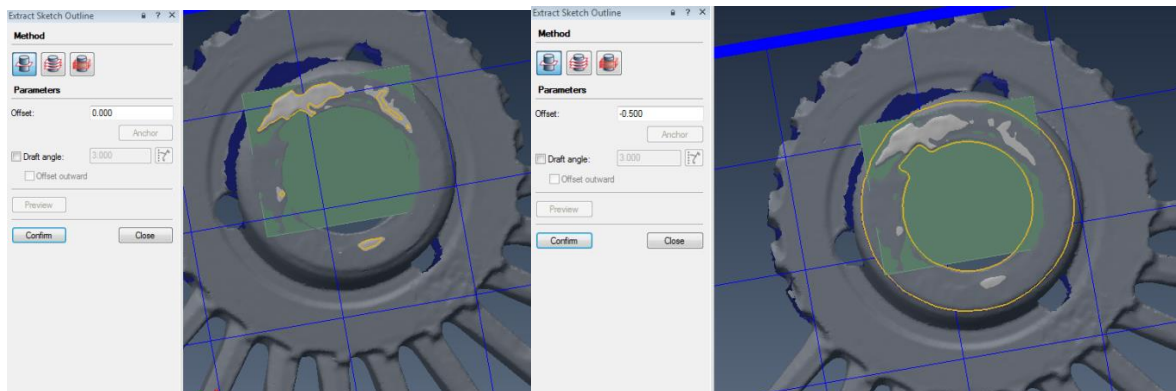


Figure 6.1

2. Creating the curves from the Cross sections
In order to create the curves four options are available:
 - Geometrical Features: Lines, Circle, Arc
 - Freeform Feature: Splines

For the Holes and the Wedges the geometrical features are used in order to create the curves which describe the model.

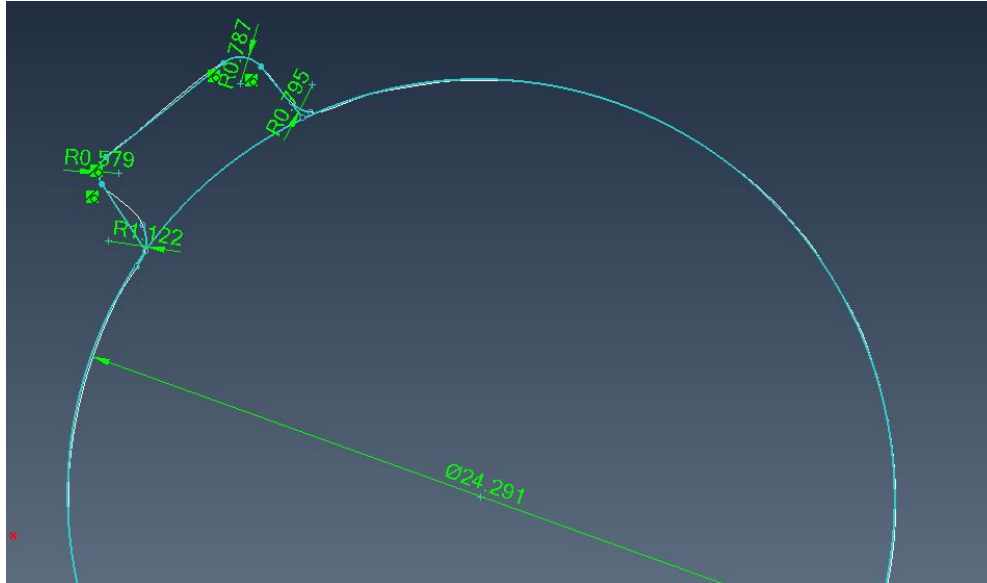


Figure 6.2

For the blades the freform features are used in differend level in order to get all the required information for the the design of the model.

We choosed one blade for the recontruction and not all of them. We choosed one which seems to have the less decay. In the cad software the rest of the blades can be created with a circular pattern.

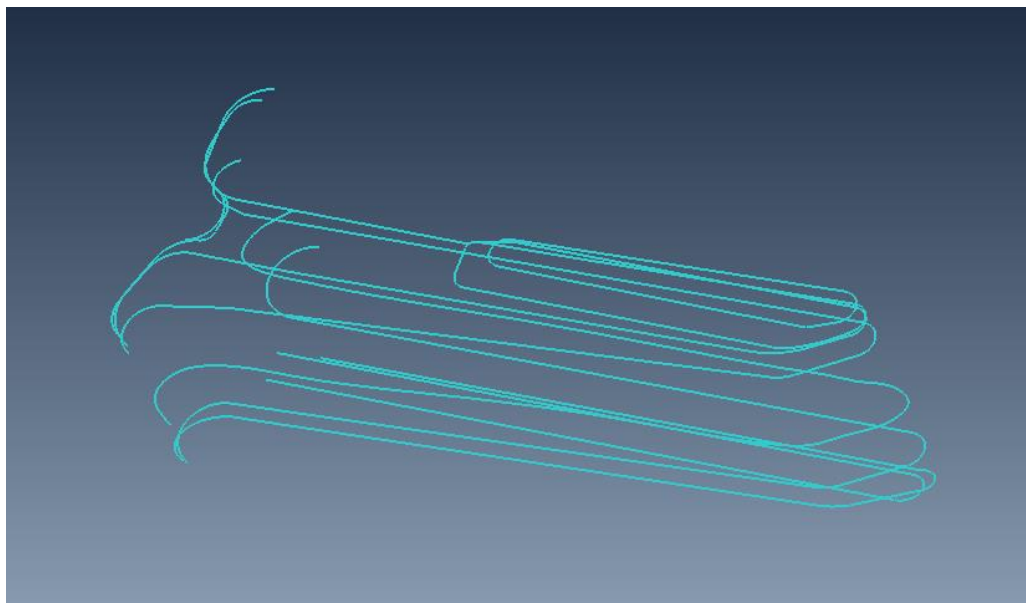


Figure 6.3

All the created sketches are exported as an iges file which is an universal file format and can be imported in the CAD softwares.

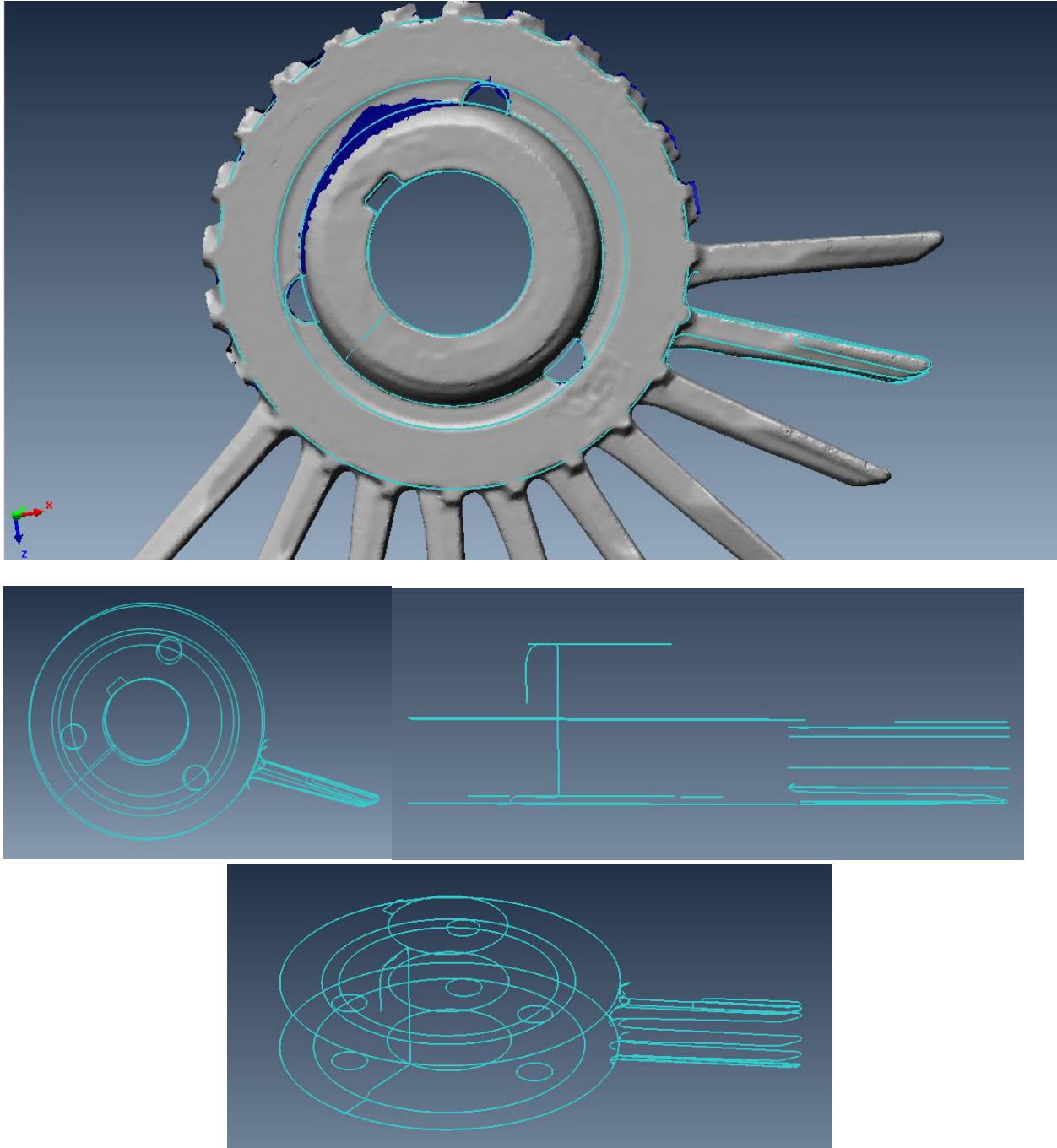


Figure 6.4

7. Procedure of parametric modeling with the Curves in a CAD software

Like in the most cases where reverse engineering of a spare part is required, also the impeller scanned and designed for this work has signs of deterioration from the operation of the machine (pump). This has a consequence that the outcome of the scanning procedure is not suitable for immediate recreation of the mechanical component. In order to design a fully functional part or even to improve the functionality of the part the CAD model created should be customized by the designers and the engineers.

The reverse engineering software is suitable in order to collect the data of the scanner and to create replicas with some interventions in order to improve the surfaces. But it is not a design software. The model types created by the reverse engineering software 1. Cloud of Points, 2. Polygon Mesh are not suggested in order to be further processed. The Nurbs surfaces and Curves are usual CAD elements which can be imported and processed by any CAD software.

7.1. Importing the data in a CAD Software Solidworks

The igs file is an universal CAD file format which can be opened by any CAD software without any problems. The software offers some diagnostics in order to find any trouble spots which are corrected or deleted.

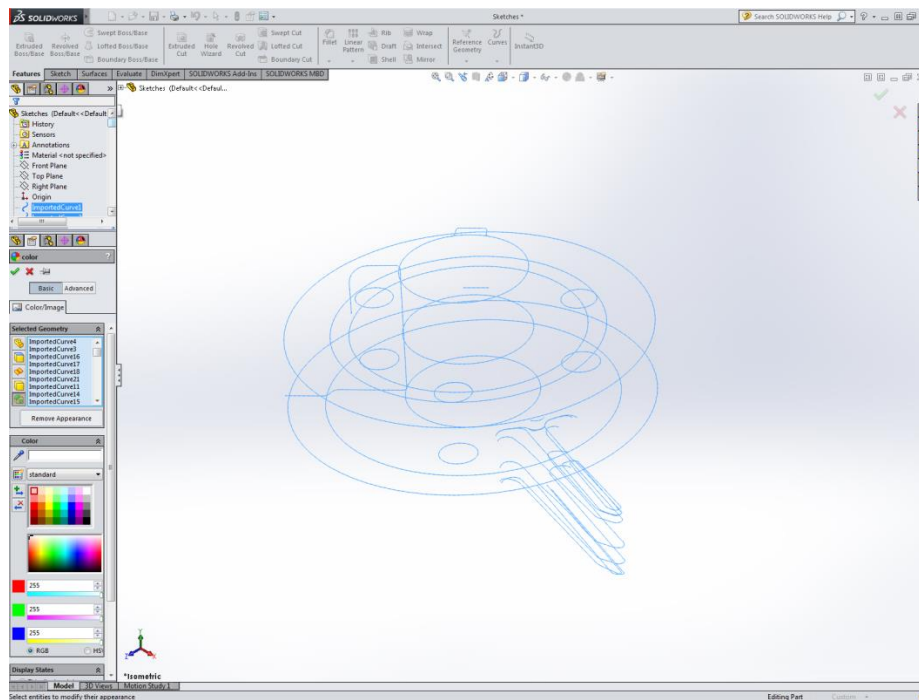


Figure. 7.1

7.2. Design of the cad model

In order to design the 3D Model the same procedure is followed like in the case a part is designed from scratch. Planes are created on which the sketches are designed. Then these 2D features are converted in 3D features by using the several offered CAD tools. The difference is that the sketches are not newly designed but the created with the reverse engineering software are used.

Hereunder the procedure to create is described step by step

For the design the part is separated in the two following segments:

1. Core Base – Geometrical Features
2. Blade – Freeform Features
- a. Creating the Planes

The reference geometries will be created by using points on the curves.

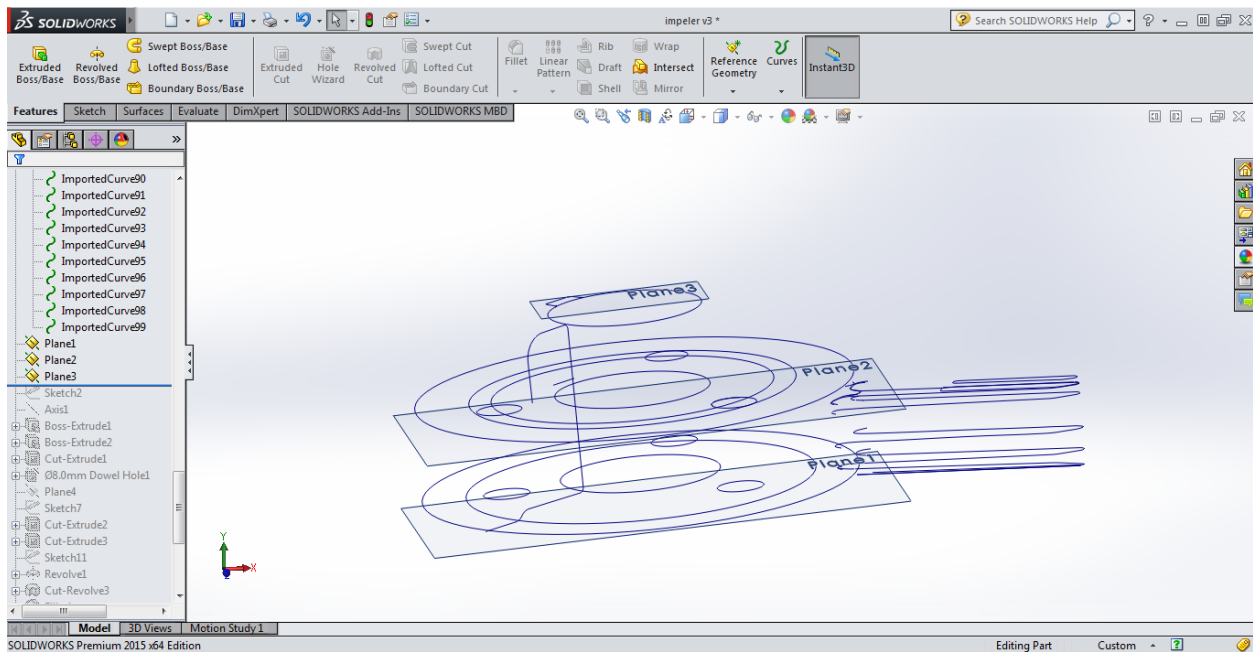


Figure 7.2

b. The geometrical elements are created.

Since the core can be described by the circles and a reference axis, the circles are designed by using the points of the imported curves. Then the axis is created with direction form the upper plane to the down plane and passing through the center of the circle.

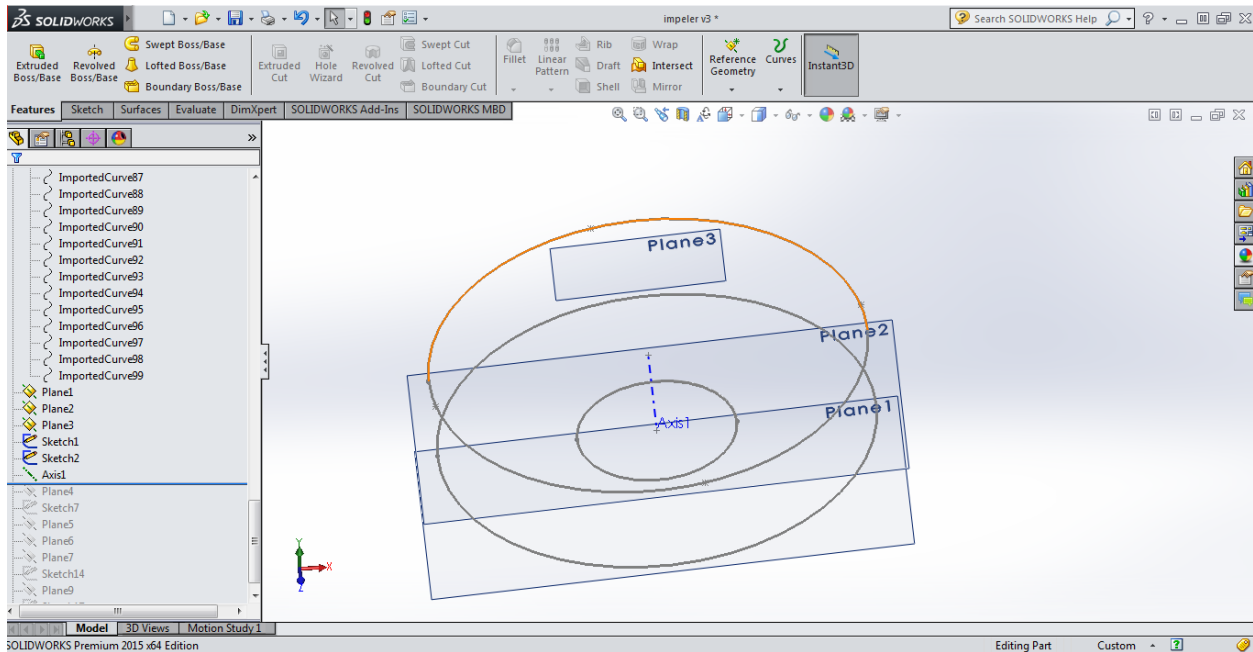


Figure 7.3

c. The 3D entities are created

With the circles and the axis the 3D object is created by using the extrude command

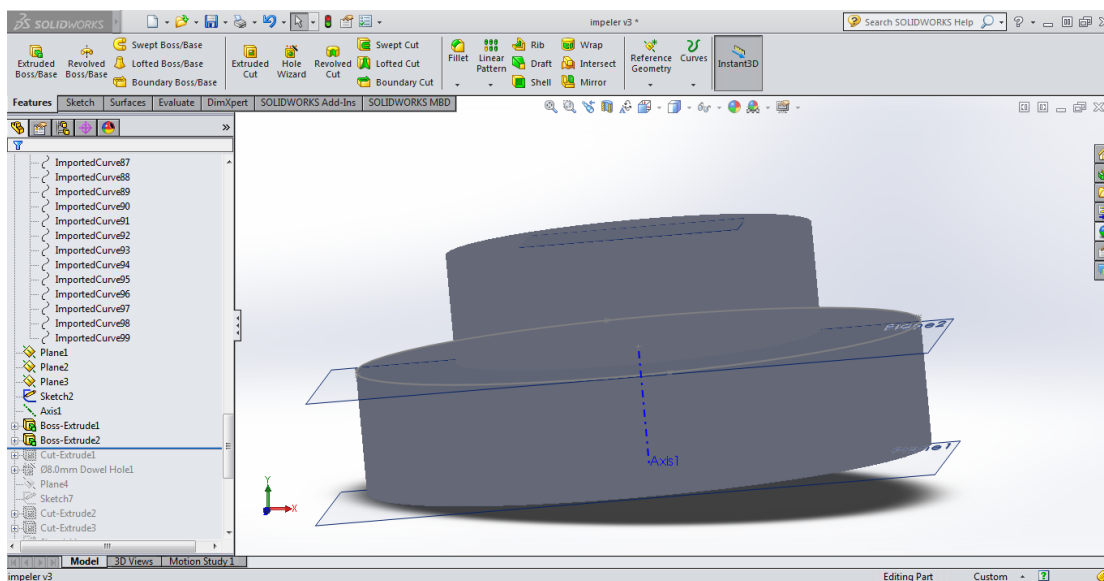


Figure 7.4

d. Creating the holes

By using the curves the circle elements of the holes are designed. Then several tools are used in order to extrude the holes on the 3D object

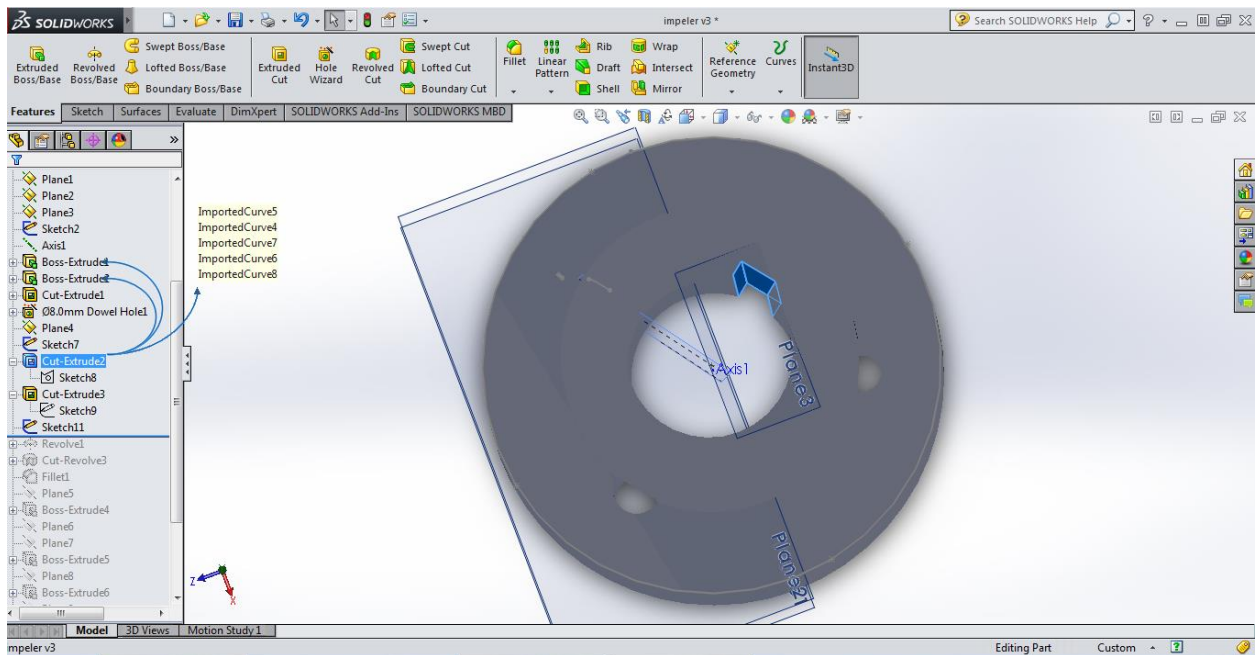
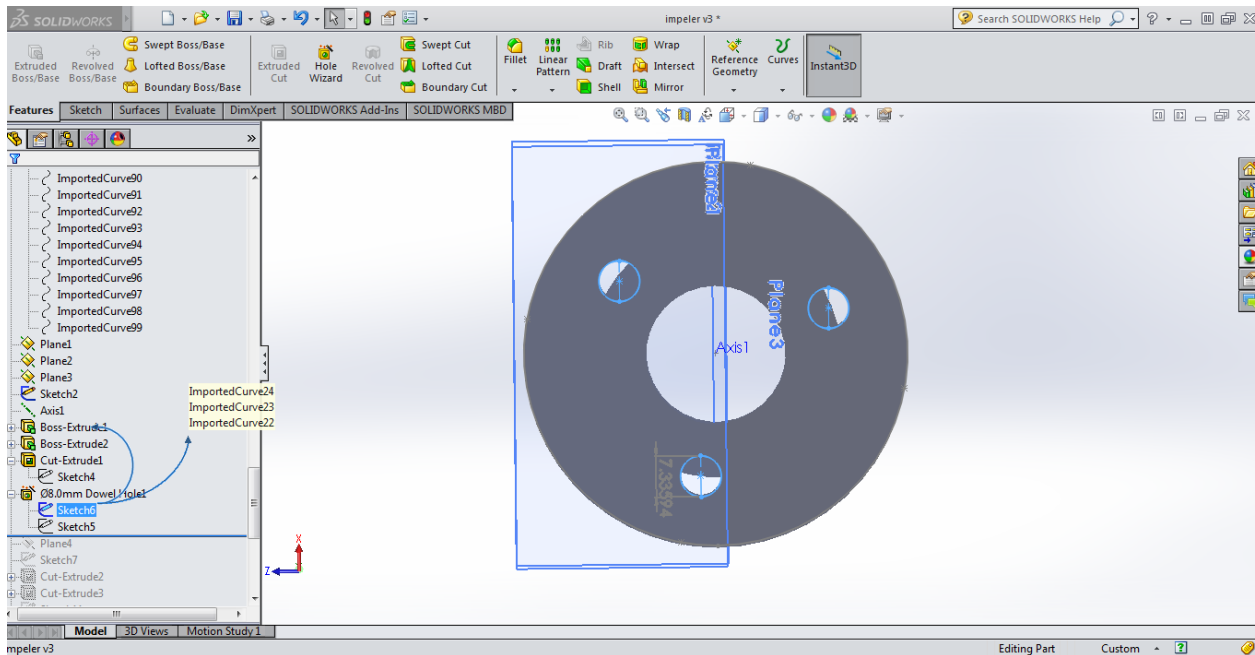


Figure 7.4

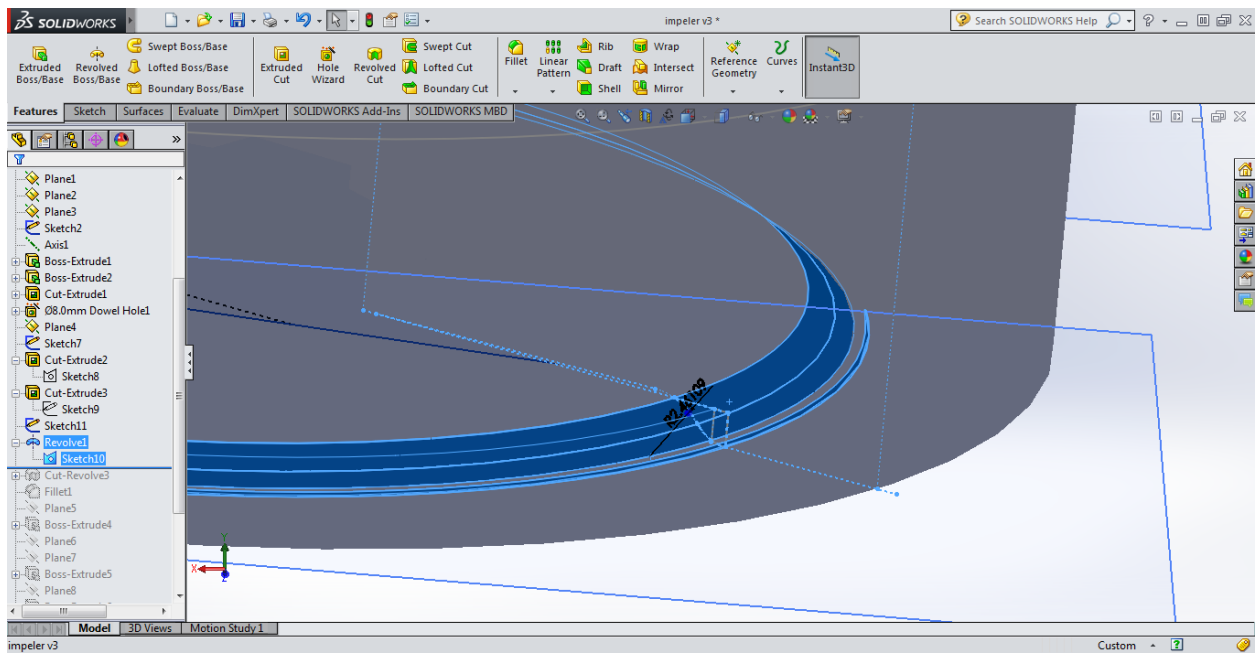
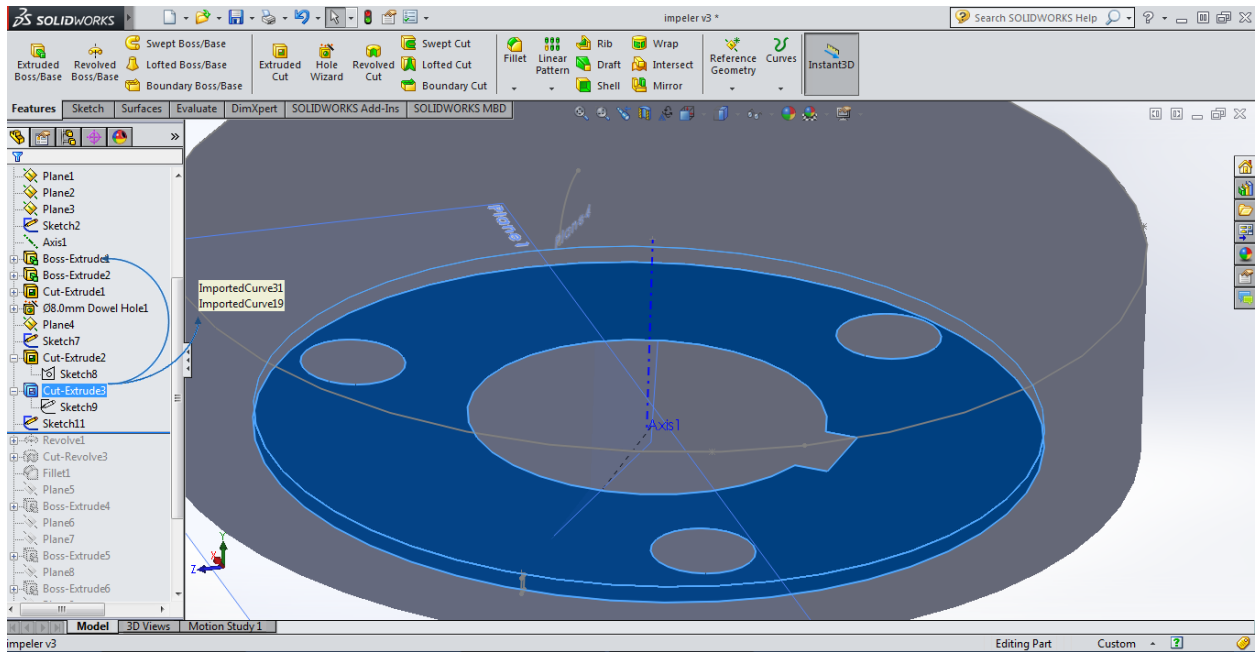


Figure 7.5

e. Other design entities

some 3D entities cannot be created by using directly the curves. In order to create the fillet of the upper part the value is approximately calculated from the curves and used for the used CAD command.

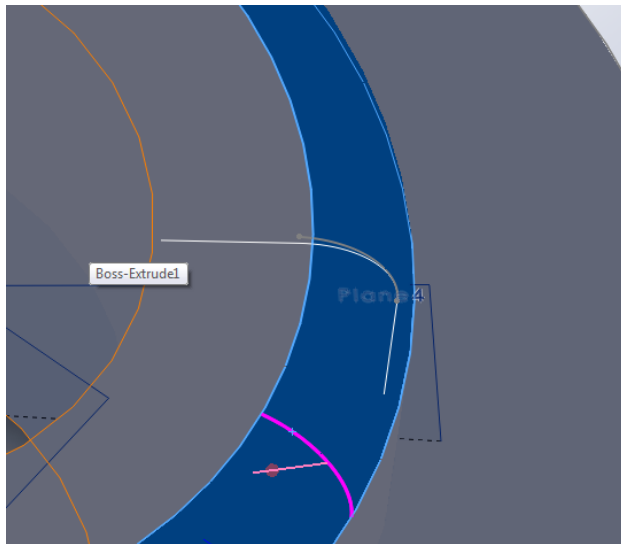
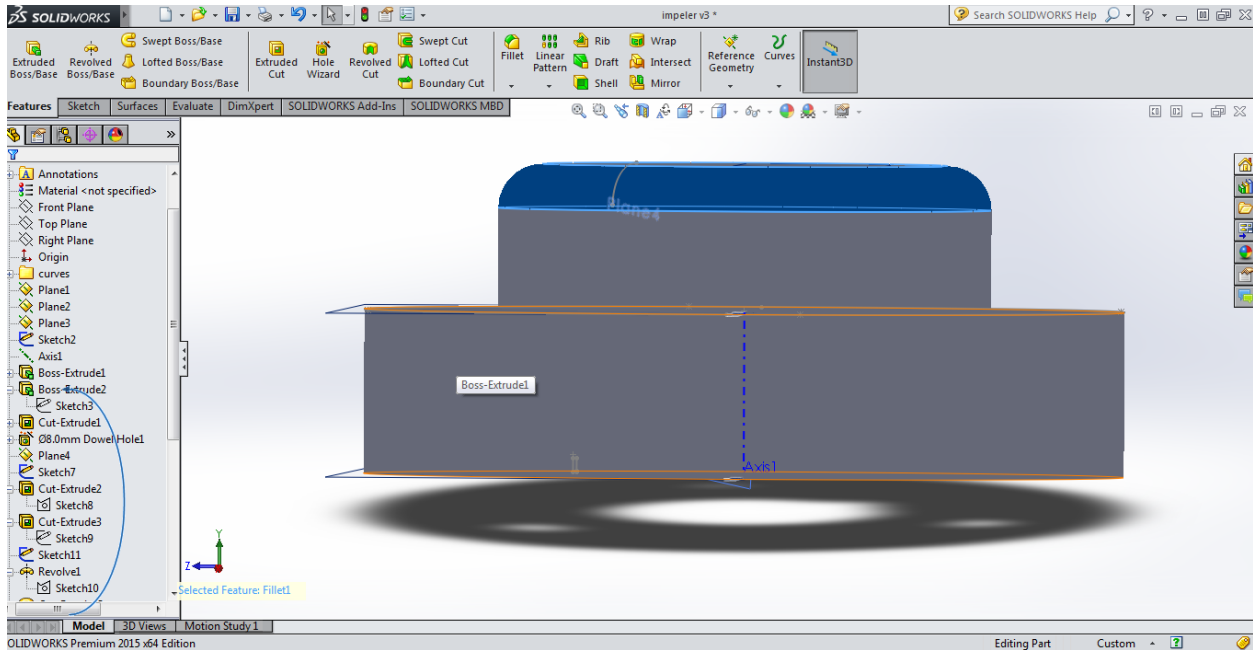


Figure 7.6

- f. For the blade (freeform surfaces) the same design approach is used. Planes - reference geometries will be created by using points on the curves. On these planes sketches of the curvatures are created. Then 3D entities are extruded.

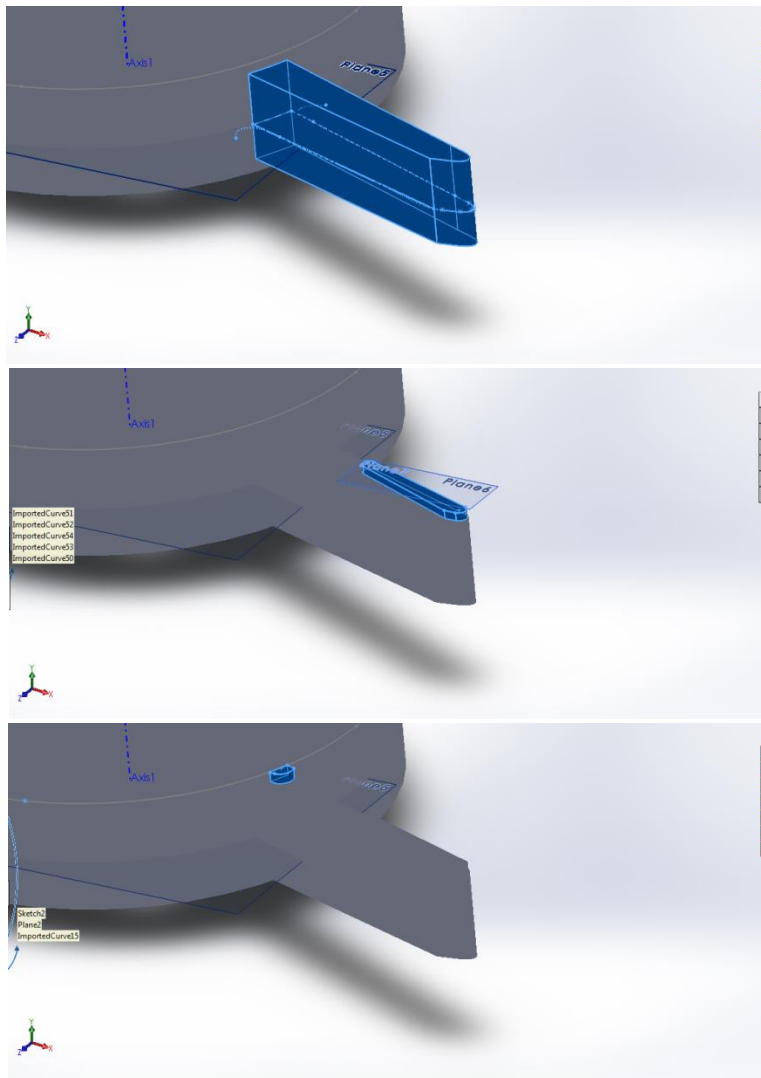


Figure 7.7

g. Circular Pattern

It is not necessary to repeat the whole procedure for the rest of the blades. The design software offers tools in order to create symmetrical in to an object components.

With the command circular pattern automatically the 24 blades are created around the initial axis

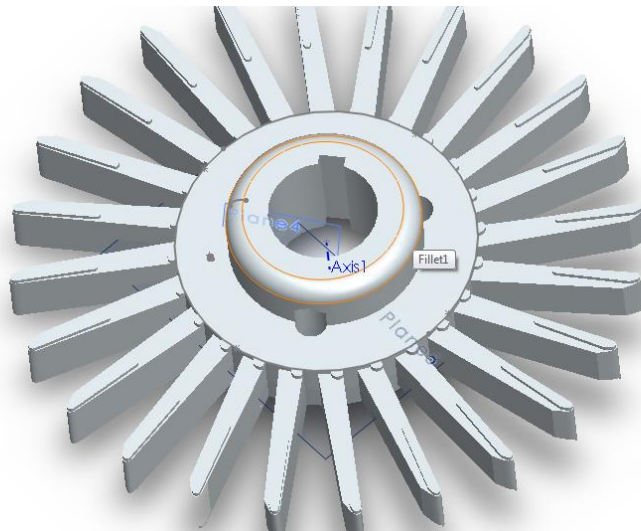
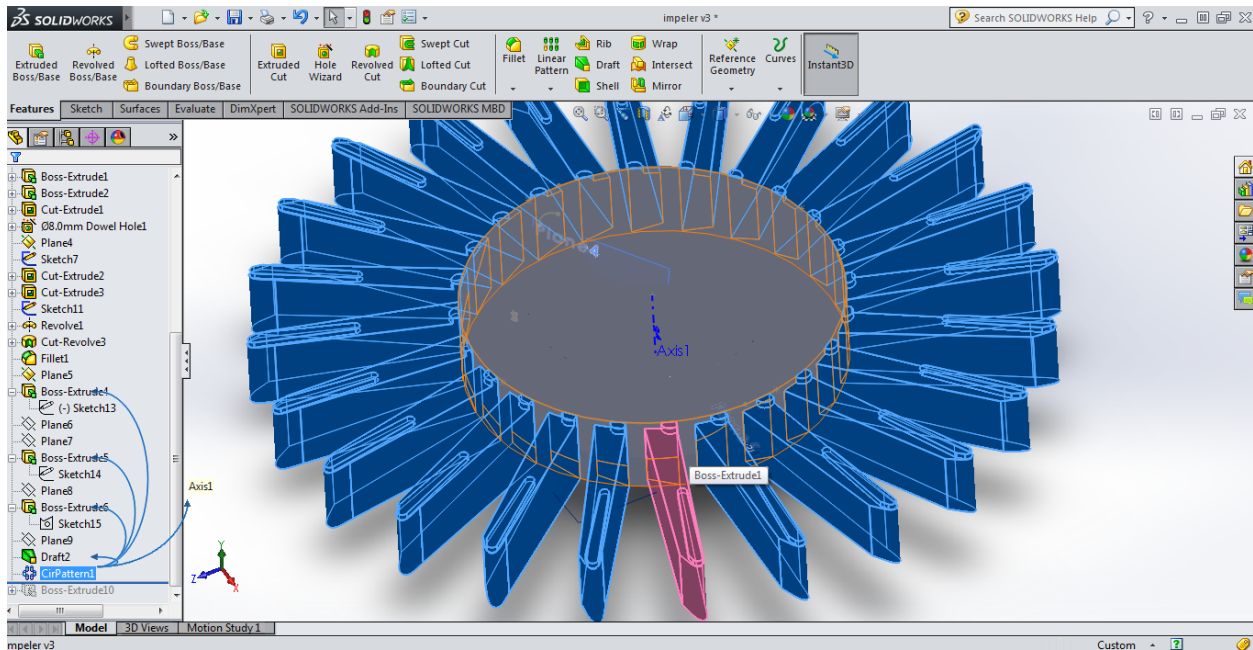


Figure 7.8

The 3D model is now created. On this model tests and corrections can be made.

For this specific work the item will again be exported as an iges file in order to import it for evaluation of the accuracy of the above described procedure in a Measurement software.

8. Measurements with a Tactile Machine

In order to evaluate the accuracy of the Reverse Engineering procedure the impeller will be measured with the Coordinate Measuring Machine described in chapter 3.3. This machine offers an accuracy ten times higher than the accuracy of the used Laser Scanner. With this machines points and geometries are directly measured.

The principle of measurements with a CMM by using a 3D model is that the coordinate system XYZ of the CAD data get aligned to the coordinate system XYZ of the part. By using a common coordinate system the features selected on the CAD model get automatically measured by the probe head. The measurement values will be compared to the nominal values of the CAD data. The tolerances are imported by international standards or by the design standards and the deviation is calculated.

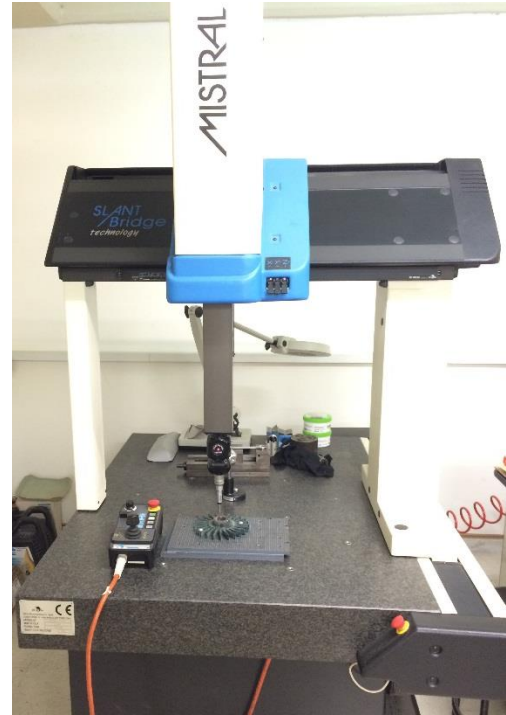


Figure 8.1

8.1. Importing the data into the Measuring Software

The measuring software PC DMIS is handling the cad data like any other cad software. The iges file is imported with a tool of the software. The elements are recognized and can be selected and used for the measurements. All the features can be extracted by using the offered tools. This features will contain the information regarding the nominal values of the point coordinates and the dimensions of the geometrical features.

8.2. Alignment of the CAD and the Part

To choose the right alignment of the coordinate system of the CAD model with the coordinate system of the part is a complex procedure. There are several international standards covering the procedures for Geometrical Dimensioning & Tolerancing GD&T such as the ASME Y14.5:2009 & the ISO 1101:2012.

For this work we cannot go further in this field and we will choose a simple coordinate system for the alignment. We understand that the error of the alignment will be transferred to measurement values and will take into consideration that this error exists.

In order to align the CAD and Part coordinate systems a 3-2-1 alignment will be used.

On this alignment 3 points are used in order to create a plane. The planes vector defines the Z-axis and the plane defines Z=0. 2 points are used to create a line. This line will define the X-axis and hence the Y-axis which is perpendicular to the Z and X axis. 1 point is used order to define X and Y (0,0).

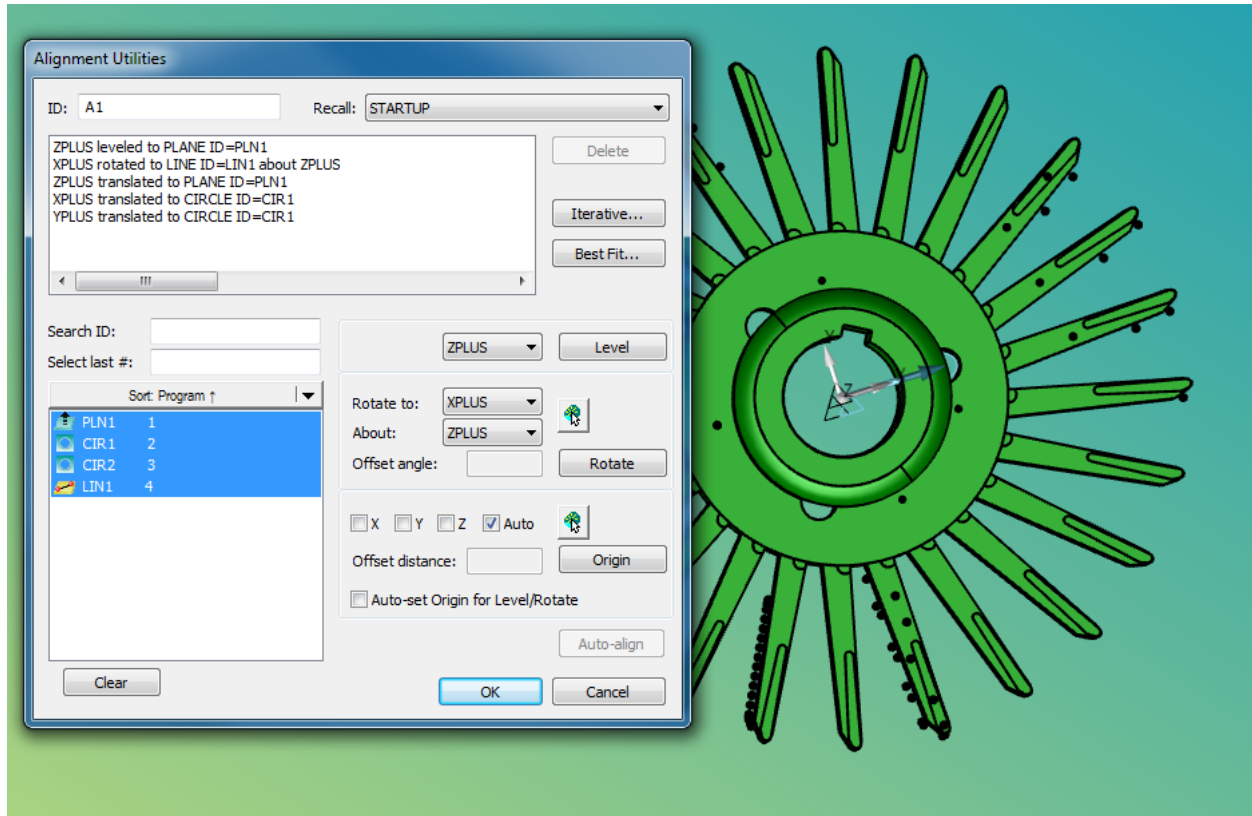


Figure 8.2

These features are created by selecting them on the CAD model and the coordinate system on the cad model will be created. Following the features will be measured manually on the part by using the joystick. This will create the coordinate system on the part. Finally the software will align the two coordinate systems.

For the alignment of the coordinate system of the impeller with the coordinate system of the designed CAD model we used the following elements:

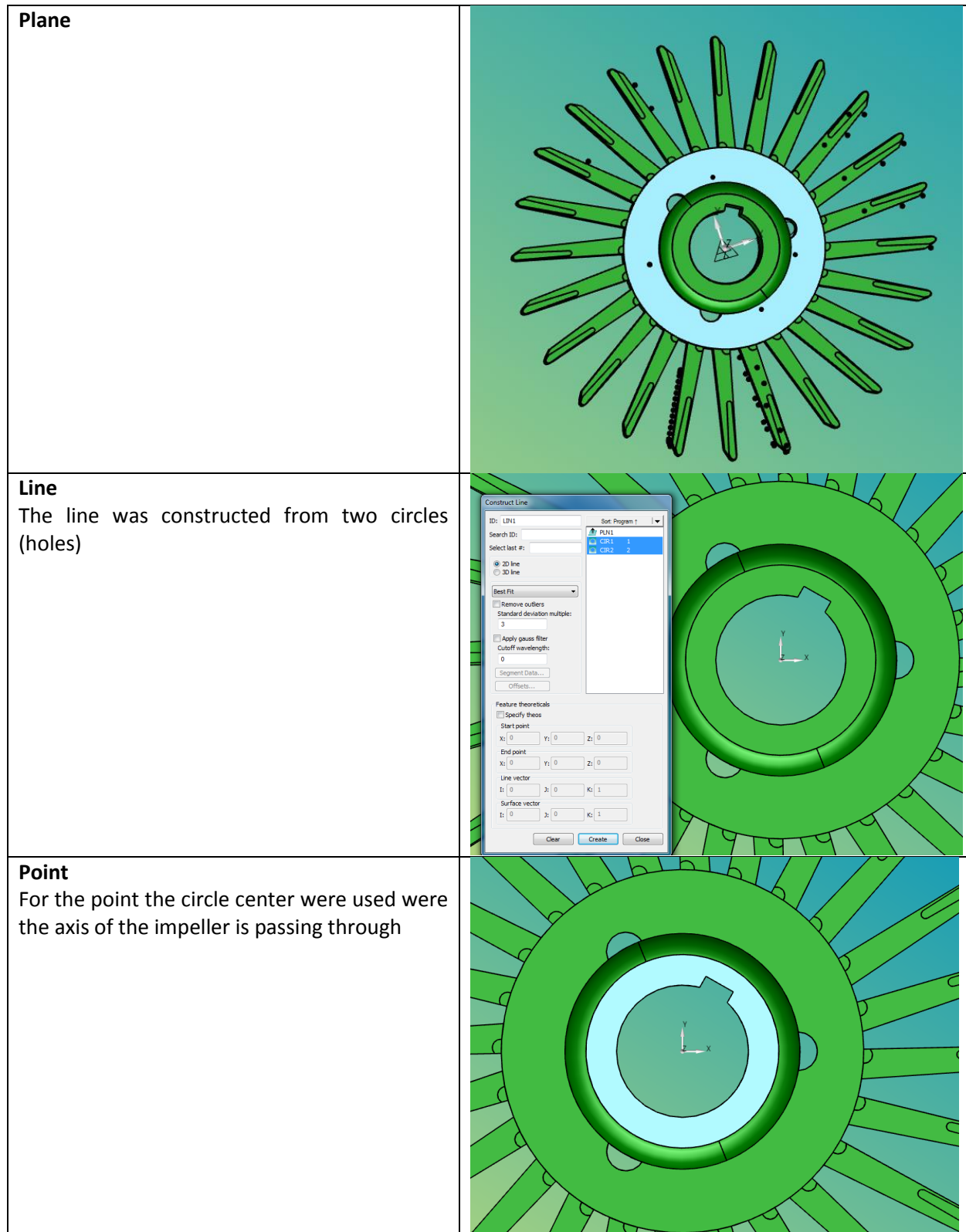


Figure 8.3

8.3. Measuring Procedure

Next the machine is set in DCC mode. DCC mode allows the machines to automatically take over the measurement of the measurement routine. From this point the joystick is not used any more. The features and the points are selected on the CAD model and measurements are taken automatically. The probe head is driving to the coordinates X,Y,Z of the selected feature which should be the same with the coordinates of the part feature. The real coordinates are recorded and the deviation is calculated.

In total we measured one cylinder feature and 87 measuring points. The measuring report is attached in the appendix and the data will be evaluated in the next chapter

The dispersion of the collected points are shown in the following picture.

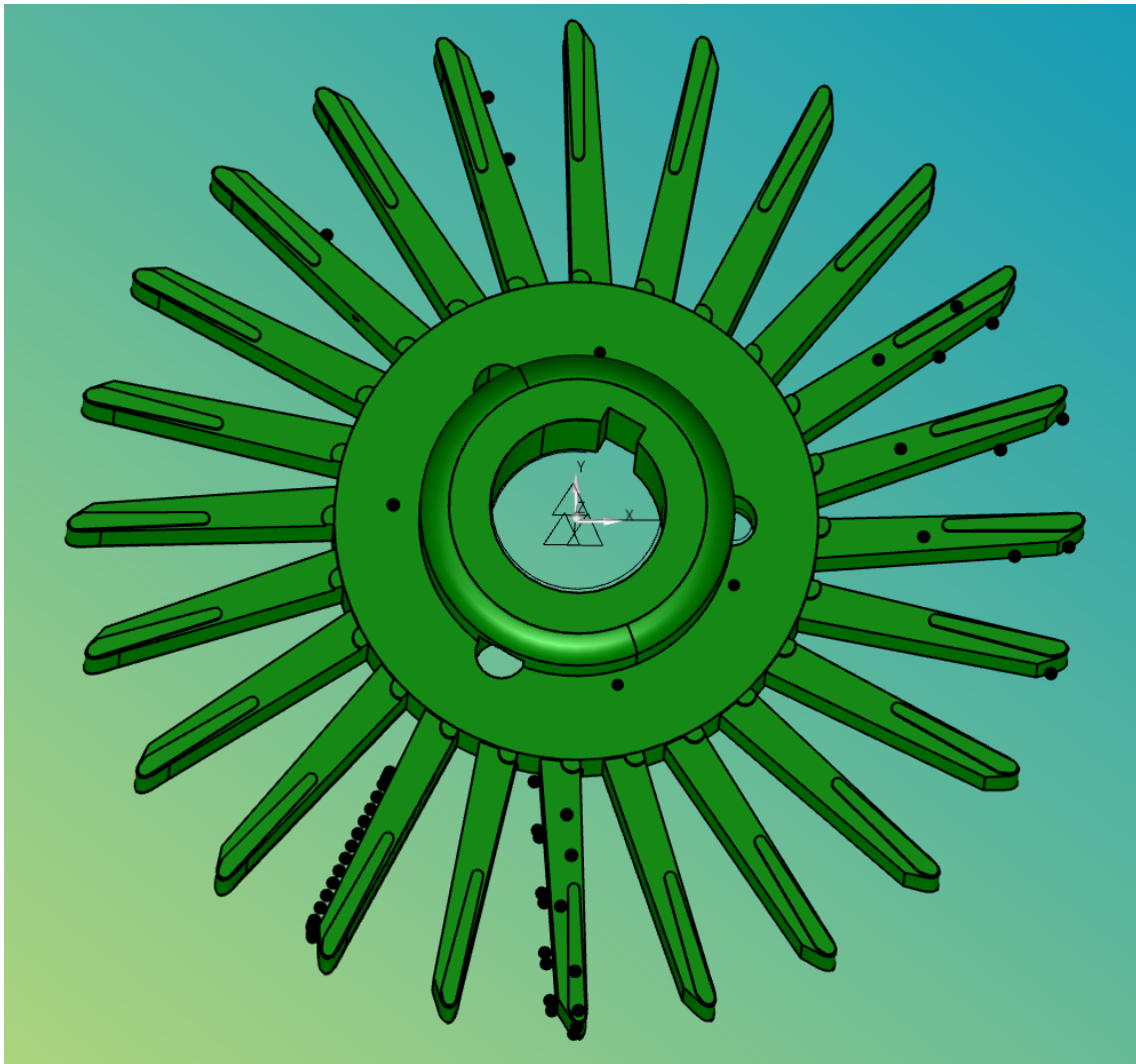


Figure 8.4

9. Measurements with a Laser Scanner

Second part of the evaluation the accuracy of the reverse engineering procedure is to compare the convergence with the initially laser scanner scanned data to the created CAD file. For this, the Polyworks software offers a measurement plugin named IMInspect.

In this software the CAD file and the cloud of points are imported and aligned to each other. Then the deviation of the scanned points to the surfaces is measured.

9.1. Importing the data into the Measuring Software

The IMInspect software is handling the cad data like any other cad software. The iges file is imported with a tool of the software. The elements are recognized and used as reference objects.

The cloud of points is imported easily with all the data since the software is using the same data format of the IMAlign software with which the points were created initially.

9.2. Alignment of the CAD and the Part

For the alignment of the points with the CAD a best fit tool is used. In this alignment the CAD file is locked on the imported coordinate system. The software shifts the points around the cad data and calculates the best fit.

9.3. Measuring Procedure

The software is calculating automatically the deviation of all the measuring points to the nominal data. Since the measuring points are thousands a spread sheet would be too complex for the evaluation. The software is visualizing the deviation on the cad screen. For this a color map scale is used with limits the max and min values of the measured deviation. Then the points are illustrated on the screen with colors according to the deviation value of the corresponding color map. Additionally points on the screen can be selected in order to show the deviation data.

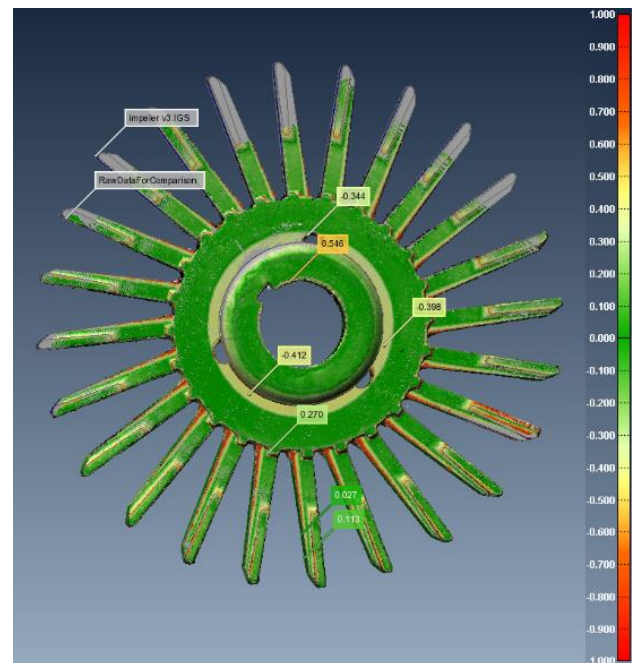


Figure 9.1

10. Data Analysis

The aim of this dissertation is to examine the accuracy of the reverse engineering procedure of creating 3D models from the scanned data for mechanical parts with freeform surfaces.

For this reason the measuring software's Polyworks and PCDMIS will be used.

During the Scan, Measuring and Design procedures the following data files were created:

1. Cloud of Points created with the Laser Scanner and the Polyworks Reverse Engineering Software
2. Measuring Features and points measured with the CMM and the PCDMIS software
3. 3D Model designed with the Solidworks CAD Software from the scanned data

Both software's are using the same principle, like described in the previous chapters the measured points with the tactile system or with the laser scanning system are compared to the nominal values of the CAD data.

In our case we applied the following measurements:

1. Comparison of the created 3D Model in the CAD software with the points measured with the Laser Scanner in the Polyworks IM inspect software
2. Comparison of the created 3D Model in the CAD software with the points measured with the Tactile system of the Coordinate Measuring Machine in the PCDMIS software

In the appendices are attached the Measuring Reports created the several methods.

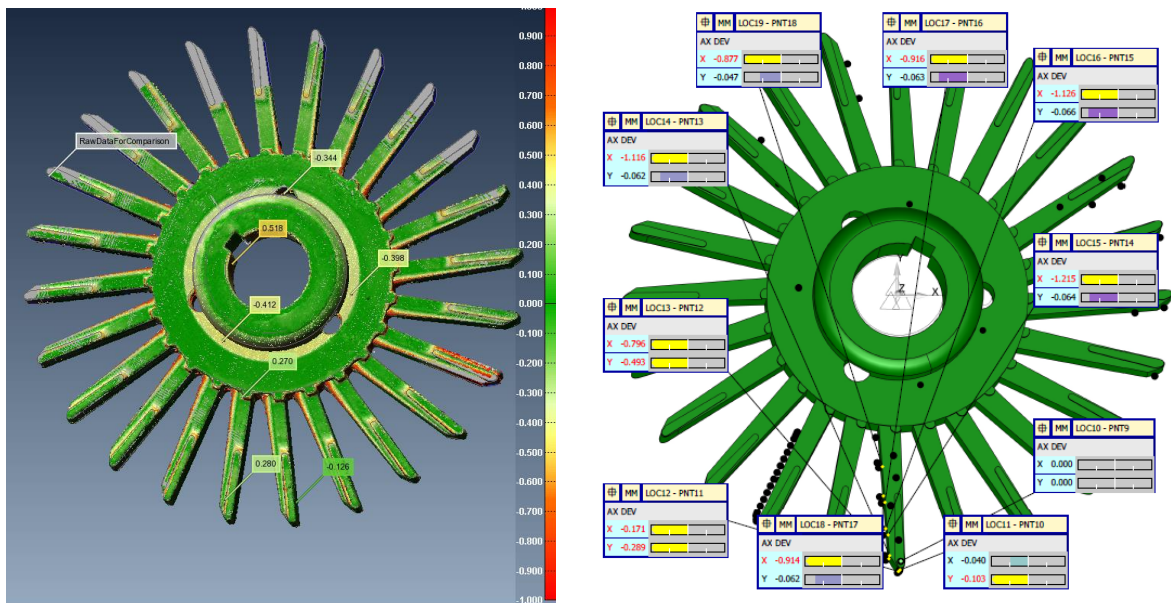


Figure 10.1

11. Conclusion – Discussions

With both measurement procedures we observe that the max deviations are up to 1mm. These deviations are mostly observed at the edges of the freeform surfaces

Even though the Reverse Engineering technology of Hardware and Software is continuously improving, the design process still generates errors. In any case the procedure has not been automated yet and the experience of the operators and the designers is crucial.

During the whole procedure and by evaluating the data with the several systems we observed that the errors are created by the following causes:

1. Laser scanning accuracy of $\pm 0,084\mu\text{m}$.
2. Unevenness of the impellers surfaces caused by the operation of the component
3. Errors created by the Mesh – Polygonal Model Creation
4. Errors created by the usage of the Reverse engineering tools for creating the B-Splines
5. Selected curves are not representative enough for the part
6. Errors made by the designer in the design software
7. Alignment Errors of the CAD data with the measured points of the CMM

The measurement results are an evidence that the technology is not ready yet to offer a solution for an accurate reverse engineering of parts when it is performed by inexperienced designers. It could be possible to redesign the CAD model according to the measured deviations but the outcome is questionable and should be further examined.

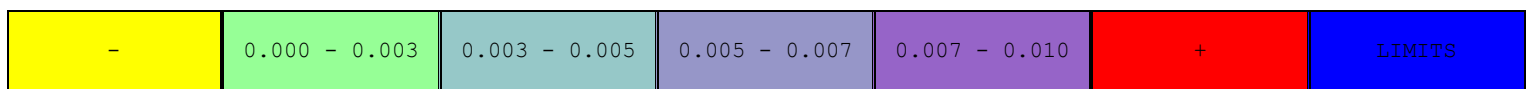
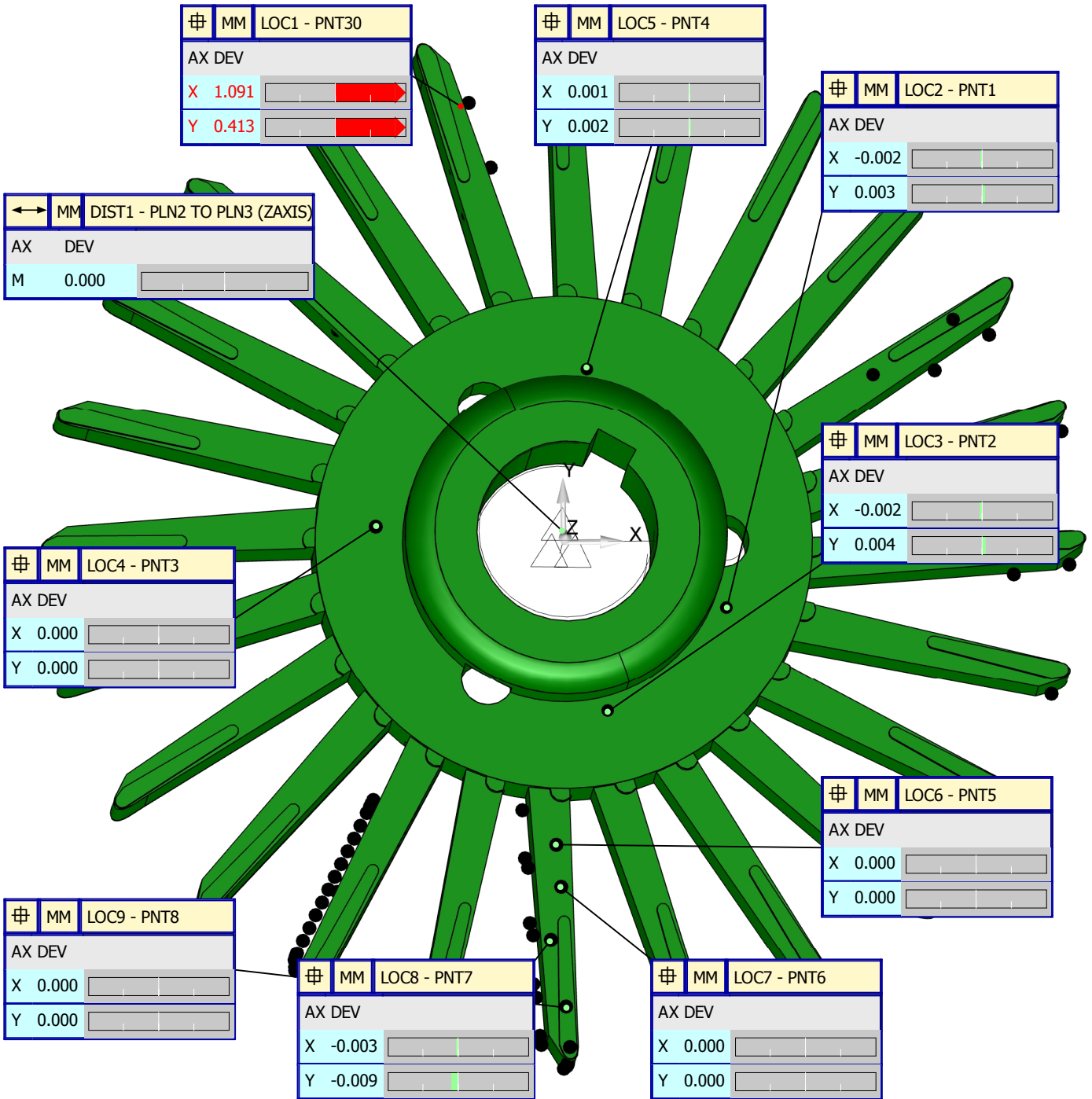
In any case, the technology provides certified accuracy of the performed measurements which can ensure the designer about the quality of the reverse engineering procedure.

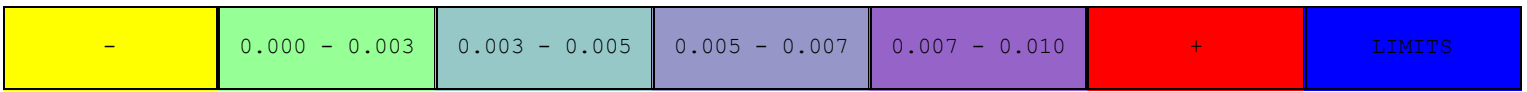
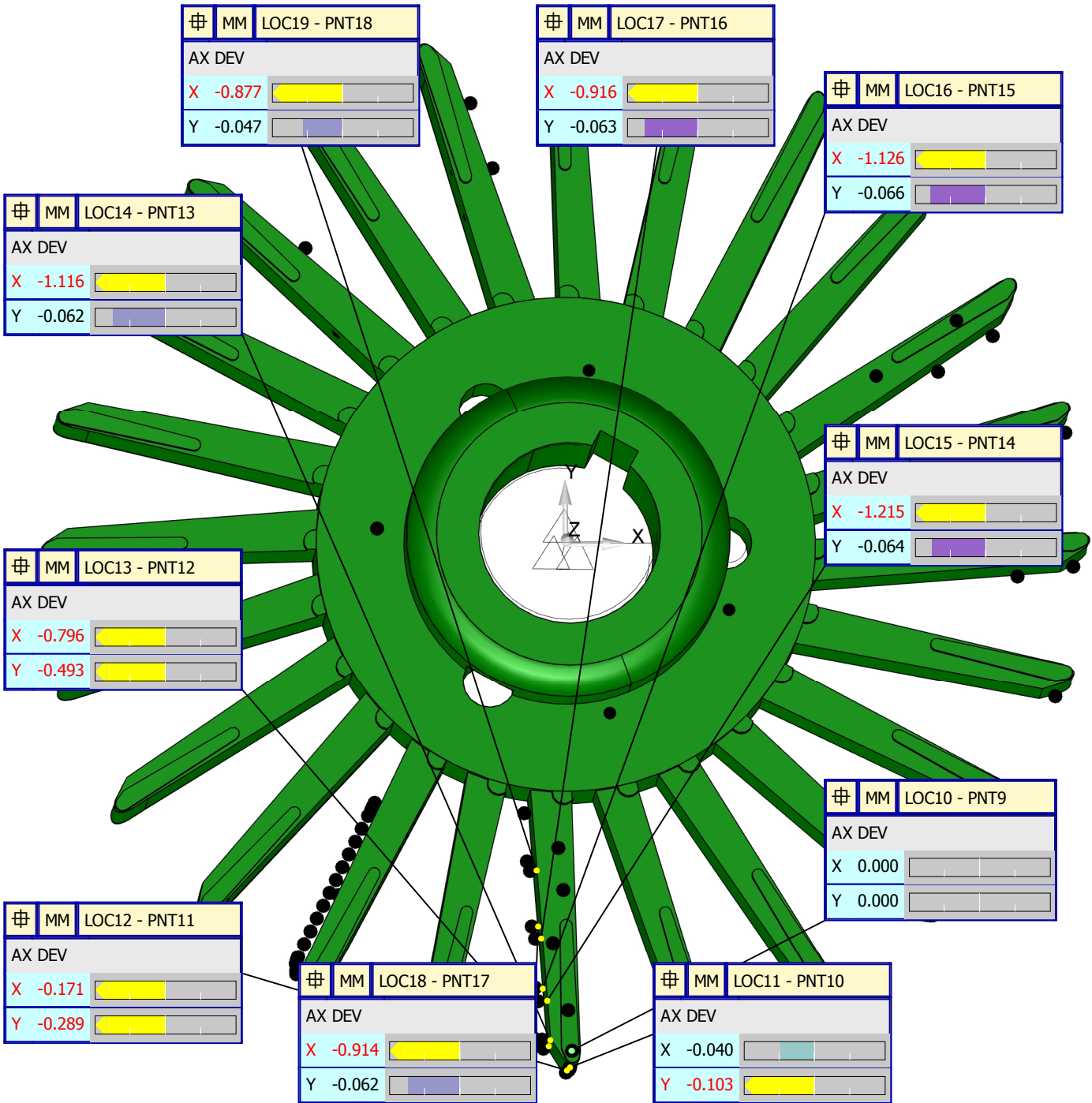
13. REFERENCES

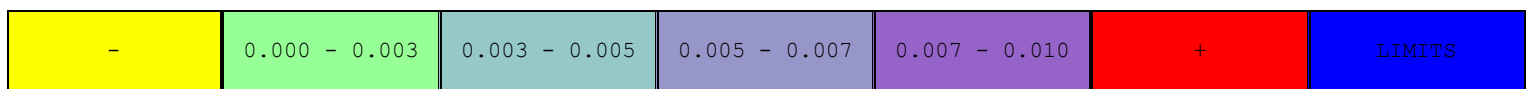
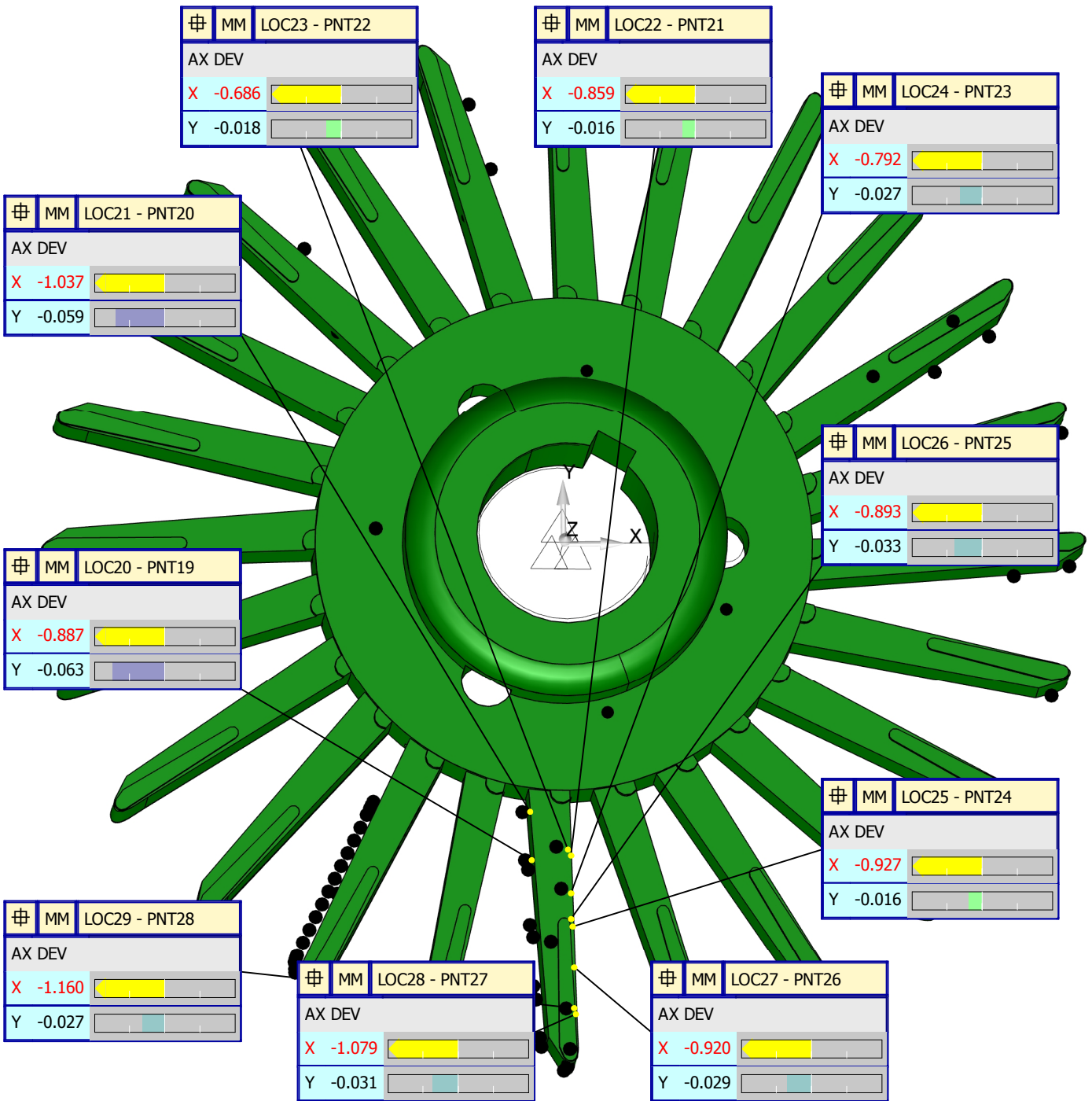
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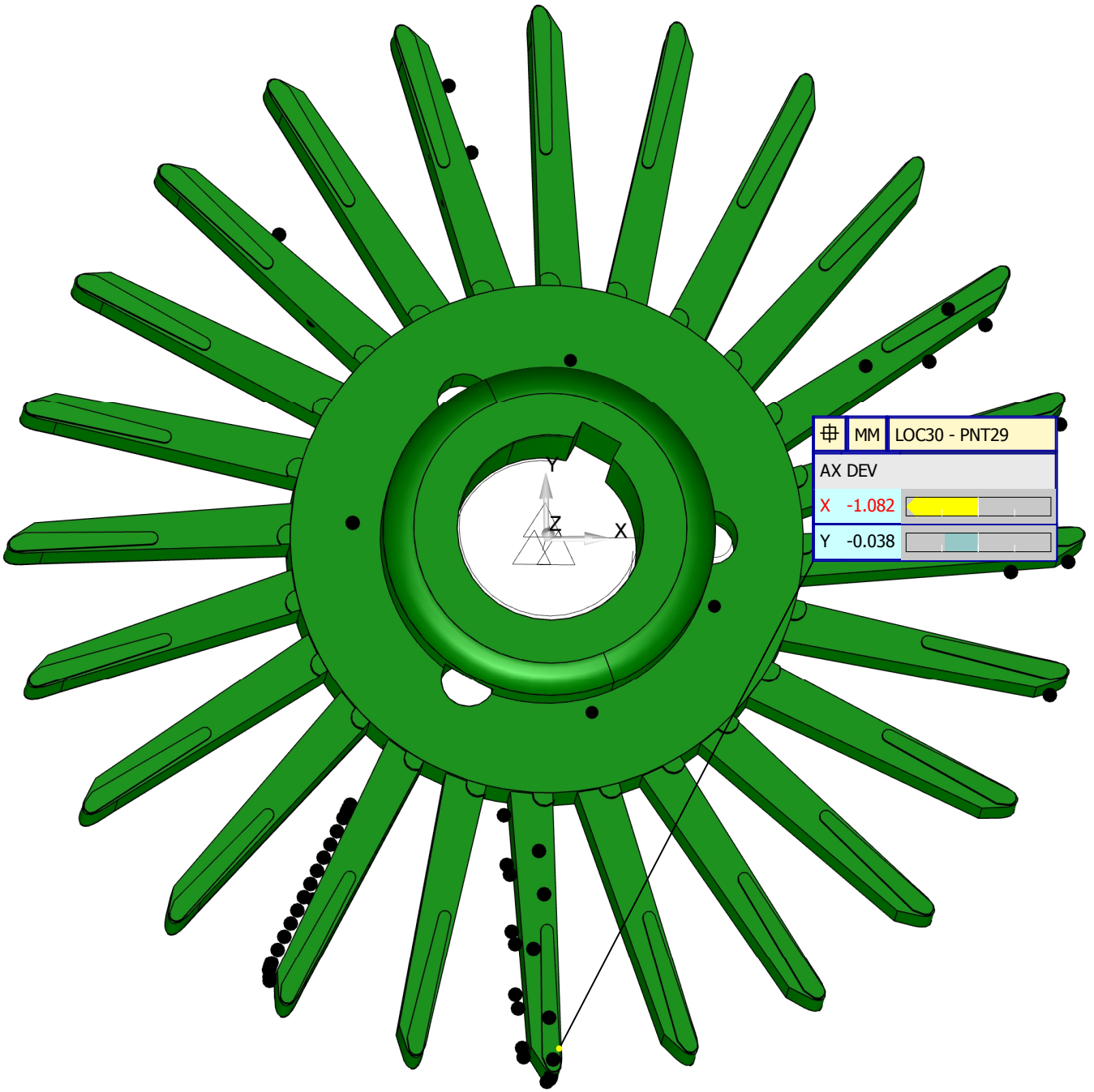
14. APPENDICES

1. PC DMIS Report
2. Polyworks Report
3. Polygon.stl
4. Curves.igs
5. Impeller.sdprt

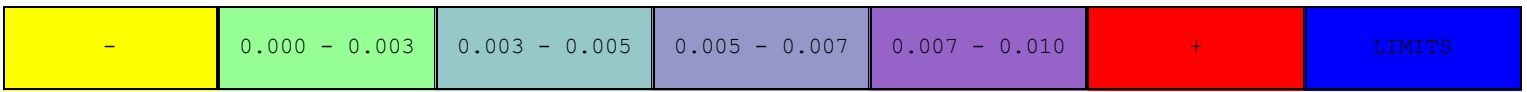


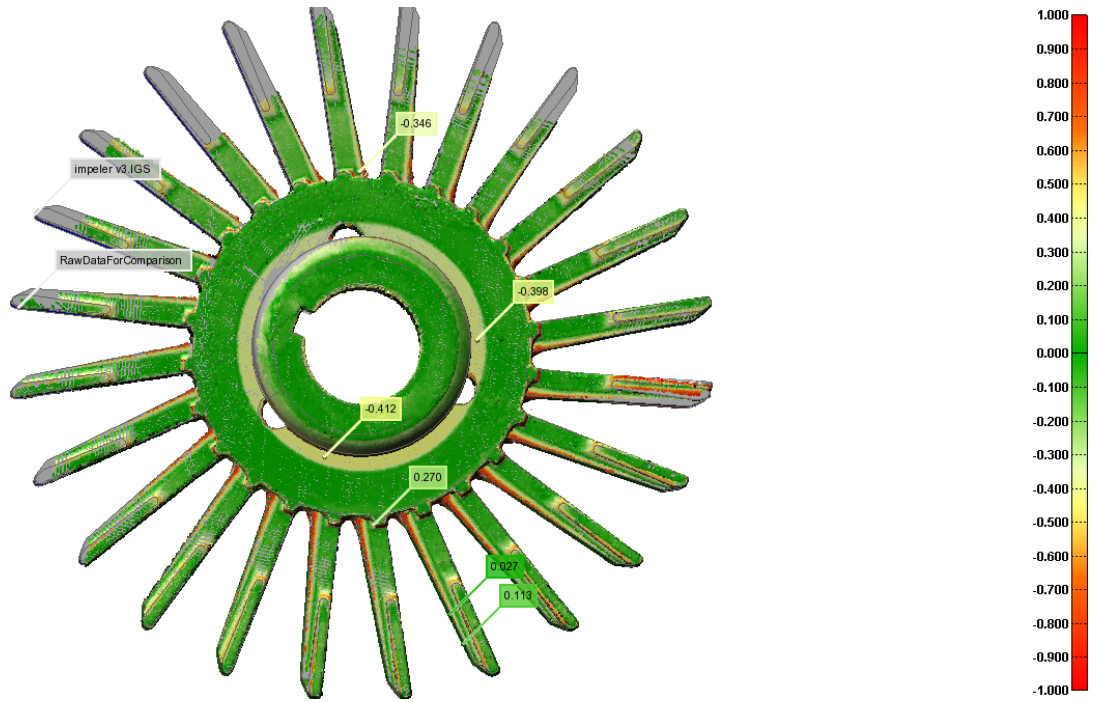






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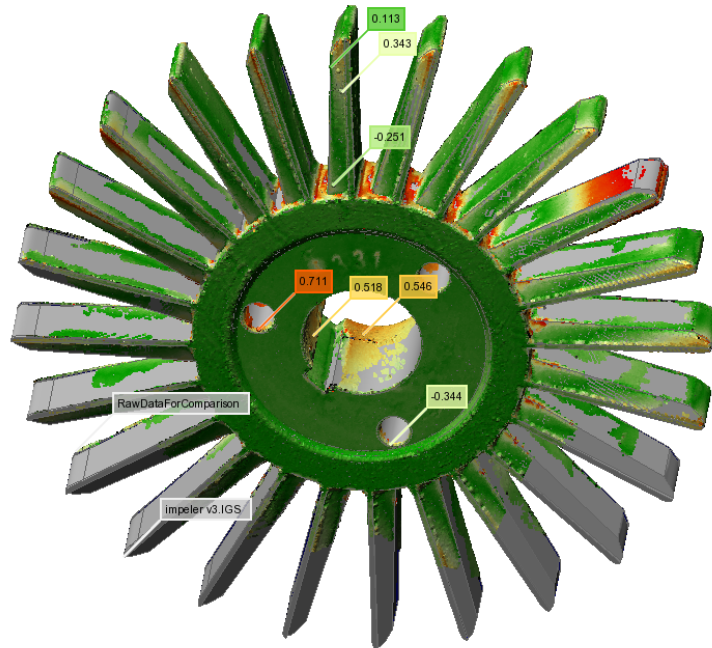
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