Reverse Engineering to Create High Quality Polymer Parts Using Additive Manufacturing

by

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Abstract

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Reverse engineering is a process of recreating parts for which the tools no longer exist, reducing the cost of an original part by manufacturing it in-house or redesigning and improving the original part's function. This research demonstrates two methods to reverse engineer a part using Polyworks software, having it printed using an SLS printer and checking the accuracy of the printed part to the original scan. The part is first scanned using a Faro-Arm laser scanner to obtain the point cloud data. The two methods used to recreate and extract the STEP file are:

- Exporting NURBS.
- Exporting Features and Sketches.

The results show the accuracy and difficulties of the two methods. Not only the NURBS generation is complex to recreate, but the CAD generated had a rough and noisy surface which is a bad result when accuracy is the primary aim, the latter method shows better accuracy on recreating the CAD and provides the reference to edit if required. The material used to print the part is Nylon 12 in standard white colour, but this work also compares different materials and printing methods which can be considered depending on the requirement.

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Chapter 1

Introduction

There has been significant growth recently in the field of additive manufacturing specially in the aerospace and automotive industries, which demands more robust, more durable, and lighter components. The area of applications includes rapid prototyping for concept designs to end-use parts. Reverses engineering can be used to recreate a very old part for which all the design data has been lost. It also provides freedom to redesign the part, either to increase its efficiency or to manufacture using a different method. Additive manufacturing provides freedom to the design engineers, but the design rules and considerations are different when the designed part was manufactured using traditional subtractive methodology. The report will discuss steps taken to create high quality parts after reverse engineering them and having it printed using additive manufacturing. The basic approach of the entire process is shown in the flow chart below.

The primary phase of geometric reverse engineering can be divided into digitization, shape reconstruction, and CAD modelling and these stages are usually iterative. The digitization and shape reconstructions cover areas like Point clouds, the Polygonal model, B-spline and NURBS, and how they play a critical role in reverse engineering. Once the editing is done the next step would be to generate CAD model, the report covers two different methods of reverse engineering a part. It is necessary to recreate a CAD model of the existing part if the original design is no longer available for analysis or further modifications, which would help improve the piece. The CAD models cover a significant portion of the market. Moreover, compared to decades ago, 3D digitization devices have become more affordable.

Type of fabrication and materials are also discussed further in the report, thought the focus is mostly on the Selective Laser Sintering as that was the method used to recreate the part. Lastly the evaluation as the we plot points on the scanned surface of the printed part in reference to the CAD model generated. The appendix section covers in detail each point that clear the set limit for tolerance. The conclusion gives a brief overview of both type of CAD generation method and discuss the possibility of what additionally can be done which was not achievable in this report.

Chapter 2

Background

In today's manufacturing environment, the operation starts with the design and ends with machine manufacturing. This chapter discusses the steps to reverse engineer a design and manufacture a component using additive manufacturing while maintaining optimal quality, different methodologies to acquire the data using specialized software, creating CAD file and the deviation results of the printed part from the original scan. It also discusses the suitable method of polymer AM and the best material suitable for the process.

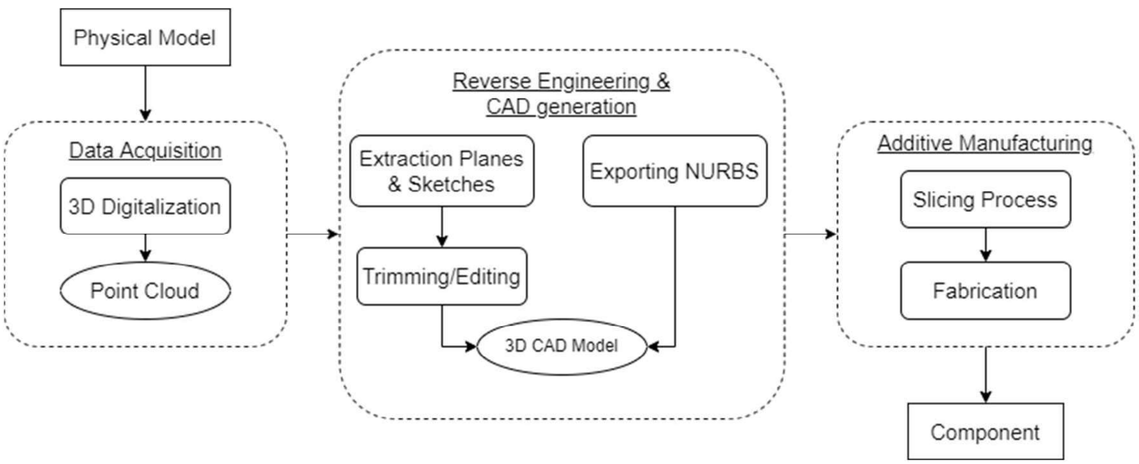


Fig 1: General overview of the process

2.1 Data acquisition: The data acquisition which is the primary step in reverse engineering can be broken down into following categories, shown in **Fig 2**.

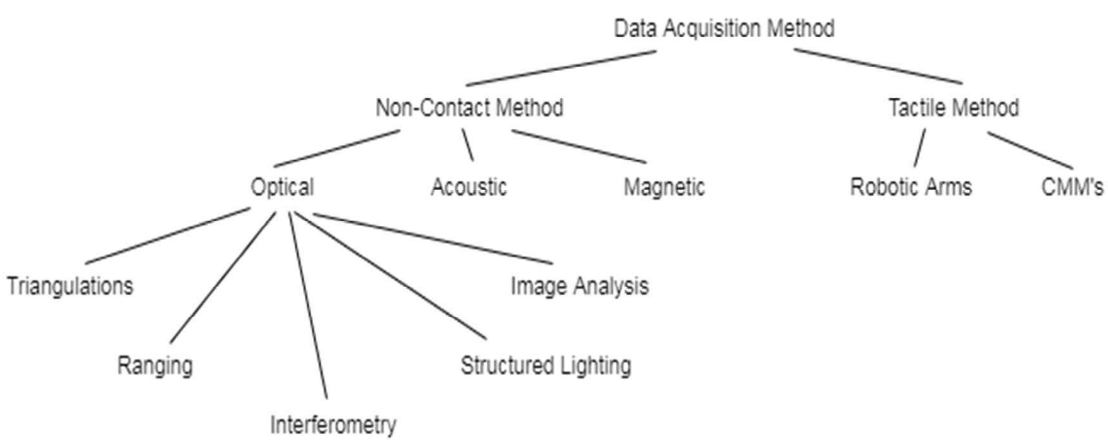


Fig 2: Classification of data acquisition methods

2.1.1 Non-Contact Method: In the non-contact method, the scanned part is seen from the orthogonal direction to create the image. Since orthogonal viewpoints are considered for creating the part, it creates 2D projections and transfers the data set to the CAD/CAM package, which is further digitized using contact probe guidance, and the surface is generated. It involves two processes, edge detection and vectorization. The initial process detects potential edge points while the latter fits the appropriate curve from these boundaries, and a mathematical description of the edges can be transferred to the CAD system [15].

2.1.1.1. Optical System: In the optical method, the source of light is created with the help of a flash tube which is collected, focused, and then directed to create a concentrated strip of the light onto the part. It is achieved with the help of a concave reflective mirror that uses the upward light beam, optical condensers, sharp edge band slits, adjusting mechanisms and a pair of the projection lens. Several arrangements are required before optimal results are obtained using this data acquisition method [17].

2.1.1.2. Acoustic System: A major advantage over other existing designs is that it serves as a system synchronizer that provides the continuous signal to each of the sub-systems. For example, when all the sub-systems are ready, and image is in focus, it gives commands to other systems and takes pictures from which it gathers data sets by capturing the reflected sound wave from the surfaces. The distance is then determined by knowing the speed of sound from the source to the surface [17].

2.1.1.3. Magnetic System: It employs sensing the magnetic field strength of the source. In this data acquisition method, magnetic touch probes are used, which senses the orientation and location of the probe within the field. A trigger is also attached to the systems, which helps the user gather specific data points near the point of interest [1].

2.1.2 Tactile Method: In the tactile method, the data is acquired by employing a probe. A 3D model can then be gathered using the force-sensitive tactile sensor and the proprietary software, which will help stitch the data sets obtained from various views. The computational model of visual attention uses geometrical information to identify the surface area. Since the tactile method requires local contact with the part, the procedure of moving and positioning the sensor can be very extensive [16].

2.1.2.1. Robotic arm: This process uses a probe attached to a robotic arm. The probe is moved over the part's surface and gathers the data points with their x, y, and z coordinates. To gather accurate results, the contact is maintained with the surface throughout the scanning process. It is the most widely used tactile method for scanning parts.

2.1.2.2. CMM: The coordinate measuring machine, where the preprogrammed machine follows the path of a surface while collecting specific data sets, which does not contain any noise. It is the more specific option when compared to the robotic arm, which uses a probe to determine the coordinates for the data set.

2.2 Reverse engineering and CAD generation: It is an evolving discipline covering various processes. It is used to make models out of an existing part, which is useful when the original drawings are missing or if the component must be re-engineered into a new, improved product. To achieve this, a 3D scanner is used, which captures raw data from the object, and a computer further interprets this to generate a model. It also extracts the knowledge of the shape, which can help derive new shapes, make variations, quickly analyze properties, and determine the characteristics such as the surface area and the volume of an object [1].

Once the data is gathered, we assume it to be a dense set of cloud points that are digitally created on the critical surfaces of the object scanned; the overall goal is to create a higher-level representation of the object in the form of a surface. Segmentation is a process where the original set is divided into subsets, which further contain the sampled form of the natural surface. Surface fitting is where the surface type (i.e., cylindrical, or planar) is used for the subset points, finally fitting the best surface type to the selected subset points [2]. Once all the editing is done, the file is then exported to CAD software (SOLIDWORKS), where it can be further edited or directly printed depending on the method of reverse engineering.

2.3 Additive Manufacturing: It is the process that produces physical objects layer-by-layer. AM processes, places, bonds, and transforms volumetric elements of material and provides the final part. The shape and size and the bond strength between the layers are determined by the material used, the manufacturing equipment (e.g., the build platform precision, nozzle geometry, laser beam wavelength), and the process parameters (e.g., the nozzle temperature, light or beam intensity, traverse speed). In addition, the tool paths, projection patterns (digital masks) help determine the overall part geometry [4]. AM systems can be categorized in terms of material feedstock, energy source, and build volume. The manufacturing systems can be divided into three broad categories, which are briefly described as follows:

2.3.1. Powder bed systems: The powder bed systems have a general build volume of units less than 0.03 m3. A part is created by raking powder across the work bed. The energy source is programmed to sinter the powder into the desired shape. The new layer of powder is raked across the work bed, and the entire process is repeated until the desired 3D component is obtained. The advantage of this system includes its ability to produce high-resolution features, internal passages and maintain dimensional control [15].

2.3.2. Powder feed systems: In powder feed systems, a build volume is generally higher, more than 1.2 m^3. This system lends itself more readily to build volume scale-up when compared to the powder bed units. The powder is conveyed through the nozzle onto the build surface. A laser then melts the powder into the desired shape, creating a substantial 3D component. The two dominant systems currently used are where the workpiece remains stationary, and the deposition head moves. While in the second type, the deposition head remains stationary, and the workpiece is moved. The advantage of this type of system includes its larger build volume components [15].

2.3.3. Wire feed system: In this system, the feedstock is in the form of a wire, and the source for these units can include an electron beam, laser beam, and plasma arc. First, a layer of material is deposited on the subsequent passes, built upon to make the solid 3D structure. These systems are well suited for high deposition rate processing. The manufactured product can usually require more machining in post-processing when compared to powder bed or powder fed systems [15].

2.3.4. Fused Deposition Modeling: This system is also known as the Fused filament fabrication (FFF) process belonging to the extrusion family. In this the material is melted to glass transient temperature and deposited layer-by-layer in a predetermined path which is created by a slicer software. The material is mostly in the form of a filament and extensively uses thermoplastic polymers. It is probably the first type of AM process the people are exposed to.

2.4 Reliability: AM is revolutionizing the aerospace industry, with the use of AM for prototype hardware designs being iterated into the design stage from the beginning with minimum cost and schedule impact. It is expected that by using AM processes, many companies will be able to create parts readily available in matters of a few days compared to months. However, before looking at the gains from the AM, robust quality control and qualification procedures are needed, more importantly for parts where the possibility of fracture is very critical [10].

2.4.1. Part Quality: Many additively manufactured parts producers would be required to fabricate parts that meet their customer's quality needs, but at an industry level, it requires standards. These requirements can be dimensional, surface finish, or mechanical properties. The resolution quality depends on the AM technique used and deposition rate. The surface finish of the parts produced via AM has a rougher surface than the casting counterparts, and the degree depends on the process condition used. The most crucial consideration would be residual stress and build failure; since the material is deposited and solidified onto a substrate, there is potential for significant residual stresses in the AM build cycle. It can also influence parts geometry, performance, and AM can also affect the likelihood of a build failure as the part gets distorted during the build. To avoid this issue, we use the building layout and support structure, as it is highly critical to any build success.

2.4.2. Part Evaluation: If we are to ensure a defect-free part to be manufactured via additive manufacturing, nondestructive techniques need to be applied post build on an AM part. It is a most critical section of quality control and is often dictated by the part's requirements. A full description of this topic may be out of this report's scope, but there are some essential key points that we should be aware of. Firstly, the incoming powder characterization is critical and helps ensure the input materials consistency and the quality. The particle size distribution, flow rate of the powder, the chemistry of the compound and morphology are essential, and these should be measured and kept track with different material lots.

2.5 Design for additive manufacturing: Once the measured data are acquired, the process of recognition and model building can begin. If the part was initially manufactured using traditional methods, we can look at additive manufacturing and the benefits it offers. When the CAD file is generated using the reverse engineering process, we can edit the part further to better suit the AM process. When describing design for additive manufacturing (DFAM), it is the method where the part is developed considering AM and compromises equally the process of designing the part and the method of fabrication. The design freedoms from various processes, currently for creating parts out of AM allow for new flexibility when deciding the parts geometric design [11]. Hence it is difficult to design a part that entirely takes AM capabilities without first understanding the limitations the process offers. The various methods that are currently being used in the development of additively manufactured components are:

2.5.1 Topological optimization: Topology optimization (TO) has always been an engineer's tool to reduce the material amount and strain energy while maintaining a part's strength characteristics. Topology optimization is a mathematical method which helps the design engineers by providing them critical load paths in the component and optimizes the material allocation within the design domain. Most proprietary TO software broadly available are paired with FE-based techniques. The solver keeps evaluating the structural stress distribution constantly while removing material and provides the result, and these results sometimes require a human element with experience that assesses the design and moves forth with it.

2.5.2 Part integration and repair: This process is not new when structural fabrication is concerned, but in the context of AM, it integrates components and subassemblies using the additive manufacturing material as a medium. The integration of components is application dependent, but a public benefit is using the process to reduce the assembly issues or labour by integrating separate parts using AM. Other operations such as drilling and tapping holes on a curved surface with accuracy is quite challenging, and since the materials, especially in the aerospace industry are superalloys, it further increases the difficulty of machining such operations. It should be recognized that the process is not only limited to insets, but it can be used to add bearings, sensors, bearing journals, inspection ports [11].

Chapter 3

Methodology

The chapter discusses the methodology, the challenges faced, and steps taken to reverse engineering and generating a CAD file. The reverse engineering is done using Innovmetric Polyworks, which is a 3D digitizer. The data is first acquired using a Faro Arm laser scanner, which captures the points representing an object's surface. Although the resulting point clouds represent the physical object, their accuracy can be affected by the colour of the material, or the glossiness of the surface being scanned. Once the CAD file is generated the fabrication options are discussed. Lastly the evaluation procedure is reviewed to check the overall surface deviation of the 3D printed part and the CAD model. The flowchart below gives a brief overview of what the chapter discusses.

But before we start with the data acquisition, we must first understand the limitation of 3D digitizing a part. If we were to imagine an ideal scan, the part should be floating in air making it accessible from all directions. The data acquired from a coordinate system is of outmost accuracy, there is no noise, no overlap, no misalignment errors due to deviation, and more points are easily collected from highly curved surfaces. Unfortunately, such characteristics are not available at present. Many practical problems can affect the usability of the data collected when using a 3D scanner, the major ones being:

- Calibration.
- Accuracy.
- Accessibility.
- Occlusion.
- Fixturing.
- Multiple views.
- Noise and incomplete data.
- Statistical distribution of parts.
- Surface finish.
- Colour.

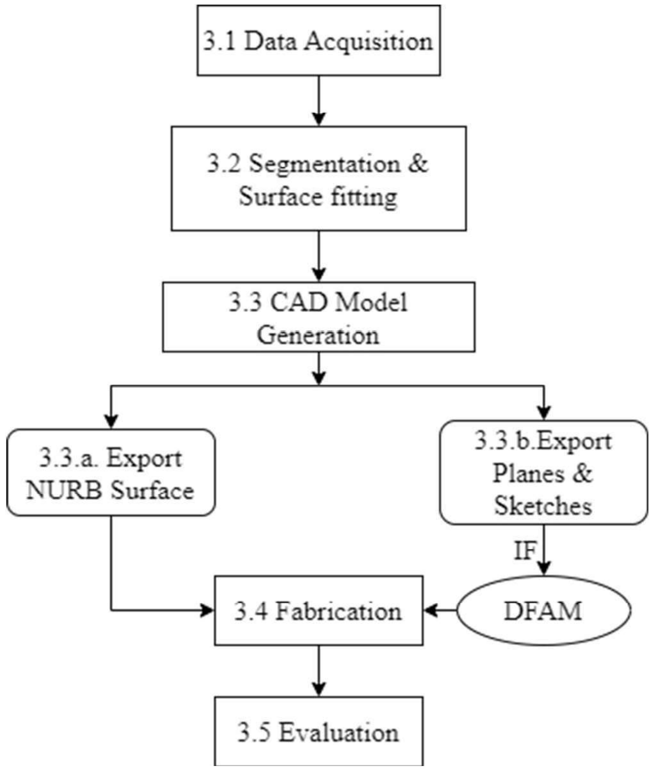


Fig 3: Overview of process for reverse engineering

3.1 Data Acquisition: The data acquisition in our case is a machine vision approach used to capture a 3D image of a part by using a laser as an illumination source and a camera to capture the target. The **Fig 4** is an essential representation of the entire process which is also called laser triangulation.

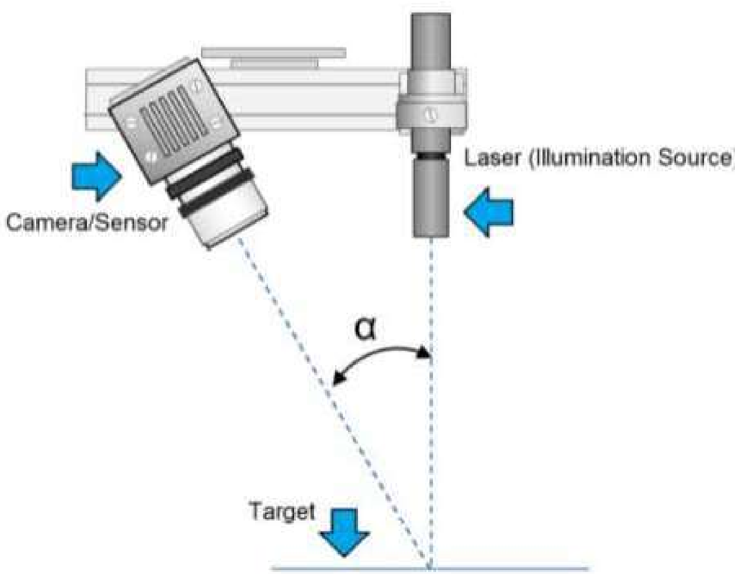


Fig 4: Laser Triangulation [19].

In the above image, alpha is the known angular offset between the laser and the camera, which with the help of trigonometry, measures the depth difference from the target being scanned.

The location where the reflected light hits the sensor's surface, depends upon the offset distance between the target and the laser/camera assembly. So, a minimal change in the vertical length of the target produces a proportionally significant shift of position at the sensor, making the variability of the target position limited. Conversely, when a slight change in distance from the laser to the target produces a broader sweep at the sensor, one exceeds the physical sensor size for depth variability when scanning the target. To differentiate between depths depends on the ability of the sensor to detect the measurable difference concerning reflected laser light. If there is no measurable change at the sensor with the change in the target distance, then the change is not within the systems resolution limit [19].

In our case the data is gathered using a faro-arm present on campus. There is a touch probe on the robotic arm and there is an attachment for laser and light scanner working on the principle discussed above. Once the scanning attachment is connected to the arm, it needs to be connected to the laptop which has the Innvometric software installed in it.

Fig 5: Faro-arm Scanner at UTA

Once Faro-arm is connected to the Polyworks via plugins available, all the joints of the arm must be moved for it to be calibrated. To begin the scanning the software provides options where the type of operation and the quality of the scan can be preselected, (Note: the higher quality of the scan generates more point cloud data which tends to slow down the software and the system on which it is being run).

The three scanning options would be:

- **Freeform Scanning:** It freely scans the surface and tends to scan the background or the surface on which it is placed.
- **Scanning the Surface and Boundary/Edges:** This option distinguishes the edge of the scanned part and the boundary and only scans the surface within the edge of the part.
- **Scanning just the Boundary/Edges:** The final option only scans the edges of the part and does not scan the surface.

For our operation the second option was considered, as it gives us the optimal result and saves time that would be spent deleting unwanted background surface. Now the scanning can begin, but it is recommended that we consider our scanning path and placement of the part before hand as the arm has restriction, which can hinder the scanning process either by the scanning a miss-alignment or the arm reaching its limit. Now hold the scanner and gather as many data points as possible by moving it around the part, the Polyworks software also has preset option which when selected provides indication at real time on how much data is being gathered and if some region is still missing data or would require more info, that region would be highlighted blue in colour.

3.2 Segmentation & Surface fitting: Before we dwell into the steps required it is necessary to discuss the four phases of reverse engineering. The four phases are Point Cloud, Polygonal Mesh/Model, b-Splines and lastly NURBS as shown in **Fig 6**.

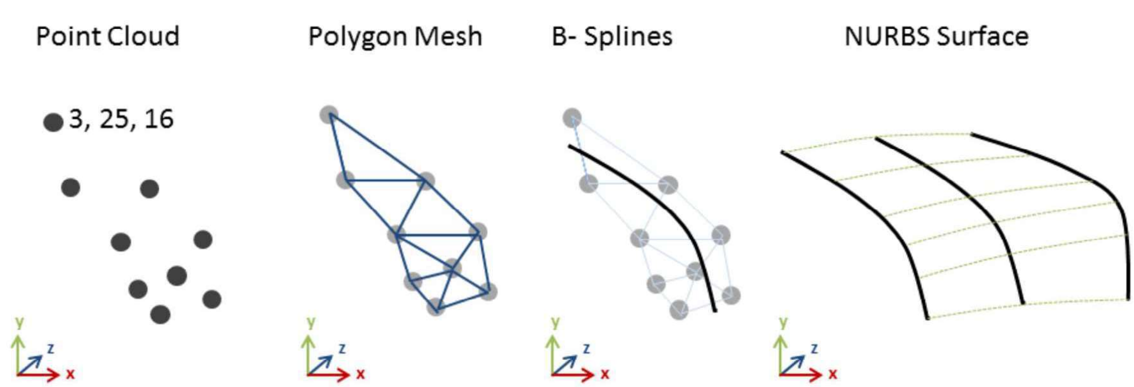


Fig 6: Four phases of Reverse Engineering [26].

When the part is scanned it is in the form of point cloud, which is the total number of points representing the external scanned surface. Each point is defined by x, y, & z coordinates. It is mostly used to create CAD models, but first it needs to be converted in polygonal mesh/model for it to be edited as required, because the point cloud doesn't infer much information. It can be done by a method known as 'Delaunay Triangulation', where a network of triangles is created from the vertices of the scanned surface, this is done in the backend of the software. When a polygonal mesh/model is generated mesh refinement can be done to reduce the noise in the scan and clean abnormal faces. It also helps select regions and fill holes if the data is missing in that region, these can be achieved by the smoothing tool and fill hole tool.
B-Splines is the generalized form of Bezier curve; hence it also shares similar properties. In b-spline the curve is defined by n+1 control points and the order of curve. Unlike global propagation properties of Bezier curve, the b-spline curve has local propagation. i.e., if one of the control points is moved to a new location not all the curve segments are affected. It can also be used to define both open and closed curves. It also helps fit complex shapes. When the mesh editing has been done and you are satisfied with the set results, we will add these anchoring curves across the part and have it divided into as much sections as possible, usually it is recommended to have more sections on the curved surfaces. Lastly, the final phase is the NURBS; it is a type of curve modelling that can mathematically represent 3D shape from lines, circles, or curves. Once the grid is created using the curves, the NURBS patches are merged onto the model, smoothing and further editing can be done. The evaluation can be done by exporting these NURBS patches directly as an .STL file or to CAD software (SOLIDWORKS).

3.3 CAD Model Generation: There are two methods with which a parametric CAD model can create from the polygon surfaces:

a) Export NURBS.

The software provides additional tools for creating NURBS, if the surfaces are very complex and cannot be defined by curves. These surfaces are tangent on the polygon mesh and can be exported directly into the CAD software. To create the NURBS, the curves must be generated across the polygonal model. The curves will indicate the borders of the surfaces. Each NURBS patch shall have at least four curves to create it. The curves are then fitted according to the deviation of the tangency of the NURBS patch (Polygon Mesh).

Once the NURBS has been generated across the part, we can select all the NURBS patches from the tree on the left side and have them fit to the part surface. It is necessary to fit the NURBS after which it can be exported as .IGES file**.**

b) Export planes and sketches.

In this method, the planes and sketches are created with reverse engineering software. The software offers several tools for extracting these features from the polygon surfaces. These tools are easy to use and accurate, contrary to the cad software's use of several points. The features can be created by selecting sections of surface and the software tries to attach that section of the surface with the pre-select plane. Polyworks offers cylinder, sphere, flat planes which can be attached to surface. The sketch section works on the same principle, where you pre-select the sketch type either circle, line, ellipse, square or point and then select the point clouds where you want to create these features. Once the desired planes and sketches are created, these can directly be exported as a .IGES file.

3.4 Fabrication: First we will explore the SLS process which is what we selected based on availability. In this AM process an object is manufactured one layer of powder at a time using a laser beam. A 3D CAD model is converted into 2D slices. A thin layer of powder is deposited, and a laser beam is used to fuse selected regions of the powder layer and create the layer as defined in the 2D slices. The platform is lowered, and a new layer is deposited. The powder is then fused to the bottom layer in pre-defined points. This process is then repeated, and complex shaped parts can be constructed as defined by the 3D CAD model. The layer-by-layer nature of the SLS process, can produce objects that can be complex in shape and geometries in bulk, porous or cellular form with potential application not only in aerospace but also in medical and automotive industries. The process is simple and is great for small volume productions. A wide range of materials can be used in this process. It has remarkably high heating and cooling rates of 103 to 106 K/s associated with the SLS process providing the conditions for producing non-equilibrium phases with fine-grained microstructures in these polymers, resulting in better properties [14].

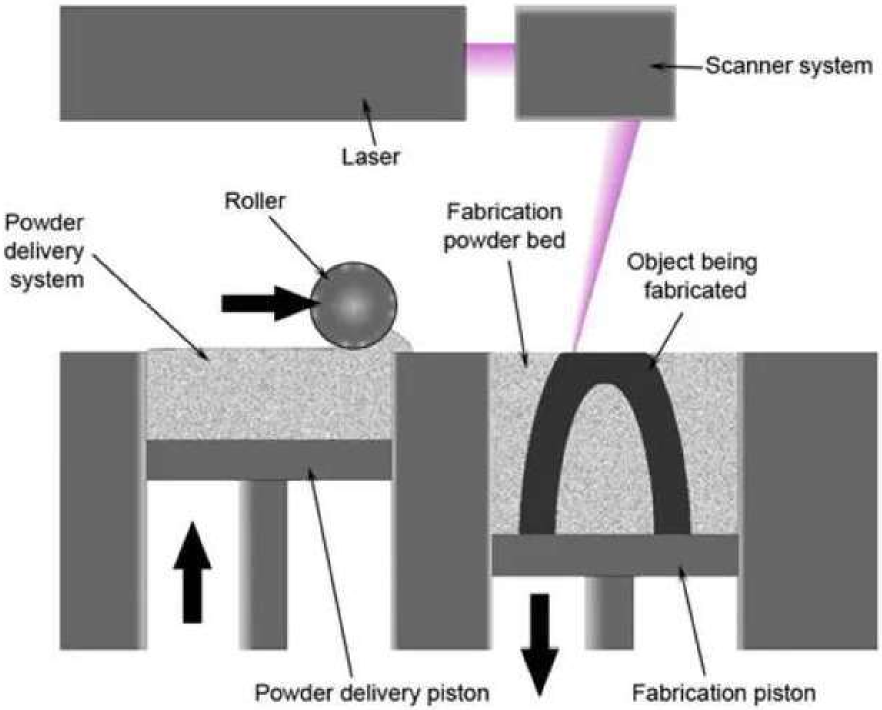


Fig 7: Schematic of SLS printer[20]

The final step of a polymer based additively manufactured part is post-processing. When the term 3D printing is used, one will quickly manufacture a finished part, making the 3D CAD model tangible with just a push of a button. However, in most AM applications, this is not the usual case, which most of the AM manufacturers are realizing, the primary process of printing itself is but a small portion of the task needed to make a part using AM. The post-processing in AM includes a significant portion of the overall cost required to manufacture the part in the first place and hence must be given equal importance and attention. When evaluating for post-processing the key things to be considered are removing the powder efficiently; it should not be entrapped in the final part. To minimize the post-process machining cost by adequately orienting the part and seeing to it that the design requires a minimum number of supports. Lastly, heat treatment, as most AM parts require this to either reduce the residual stresses from the build, to improve uniformity of the microstructure or to enhance other microstructural/mechanical properties. However, the most important thing to be considered when conducting this operation is to consider the cooling rate according to the application as it can distort the parts.

The table below discusses the different manufacturing methods which can also be considered based on the parameters listed.

Parameters	Injection Molding*	Selective Laser Sintering**	Stereolithography***
Undercut	Possible (requires expensive tooling)	Possible	Possible
Negative Draft	Not Possible	Possible	Possible
Interior Features	Not Possible	Possible	Possible
Tooling	Required (which can be expensive)	Not required (affordable for small production 1-1000 parts)	Not required
Wall Thickness (inches)	0.197	0.027 – 0.079	>0.016
Sharp edges and corners	Not Possible (it produces parts that have ±0.4mm radius on all corners)	Possible	Possible
Shrinkage (%)	Up to 6.5 if the percentage of tolerance from dimension is 10%	3 - 3.5	0.2 – 1, Depending on material
Draft Angle (°_)	Minimum of 0.5°, but bigger the better	Not Required	Not Required
Warping	Can occurs when Thickness changes	When printing Large flat Planes	When the geometry is thin, long and has no support
Radii at Edges	Helps increase greater material flow	Helps relieve some stress when radii is greater than 0.08 inches	Helps reduce stress

Source for Injection Molding*:https://www.3dhubs.com/guides/injection-molding/#design-for-injection-molding

Source for SLS**:https://www.3dhubs.com/knowledge-base/how-design-parts-sls-3d-printing/

Source of SLA***:https://www.hubs.com/knowledge-base/how-design-parts-sla-3d-printing/

3.5 Evaluation: The final step would be to evaluate the quality of the printed part and check for surface irregularities. To do this we need to scan the printed part again and generate point cloud and once we got the point cloud the next step would be to import the reference into the Polyworks, which would be the CAD file generated using reverse engineering. We will then mate the point cloud and the CAD reference using the Best-fit-to-reference. Once mated the next step would be to evaluate the surface deviation results by plotting the colour map, setting the tolerance limit and creating a set report by anchoring points onto the surface of the part.

Chapter 4

Results

In this chapter we will look on the results we got after attempting the set methodology discussed in the previous chapter. As mentioned in section 3.3 of chapter 3, the CAD model can be generated by two methods, here we will look at the results we got from each method. Method 1, Reverse Engineering by exporting NURBS had issue of missing sections as seen in **Fig 18**, and since the surface recreation was not of great quality the process was not pursued any further. Method 2, Exporting planes and sketches showed great results and the CAD file was fabricated using SLS method of additive manufacturing. The chapter consists of fabrication, material used, the final part being printed and deviation plot after scanning the printed part in reference to the CAD generated using reverse engineering first for the method 3.3.a and then 3.3.b.

4.1 Exporting NURBS: The method of exporting NURBS was first selected to test the CAD generation. For this, end cap of a pipe was taken as a test sample to get familiar with the process of reverse engineering using the Polyworks software.

Fig 8: End cap to be RE using method 1

4.1.1 Data Acquisition: Top and bottom of the end cap were scanned multiple times using the Faro arm in the Polyworks Inspector. The scans were then imported again in inspector and unwanted points were cleaned from the elements.

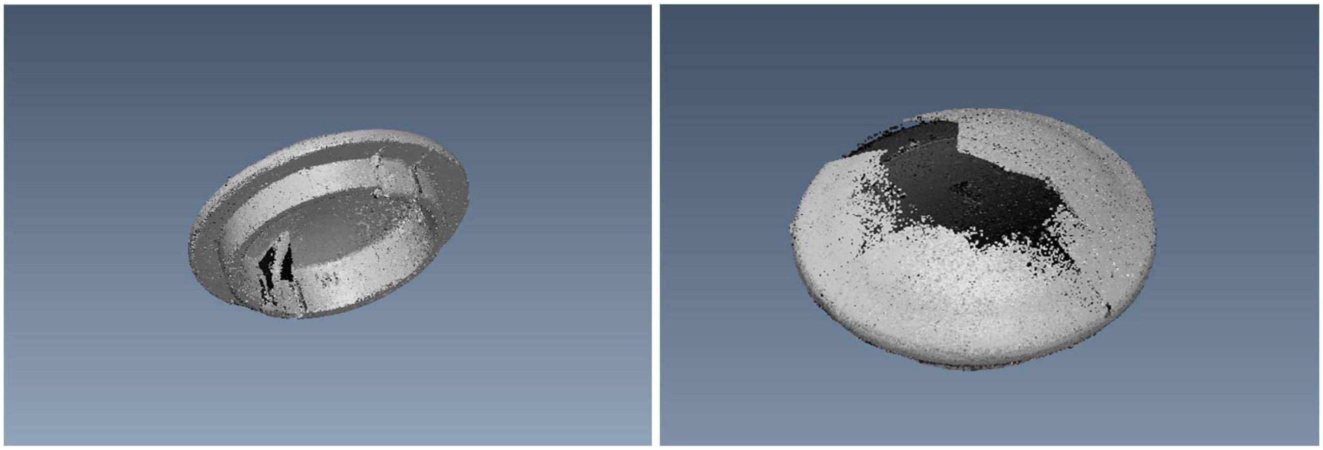


Fig 9: Bottom half of the scan

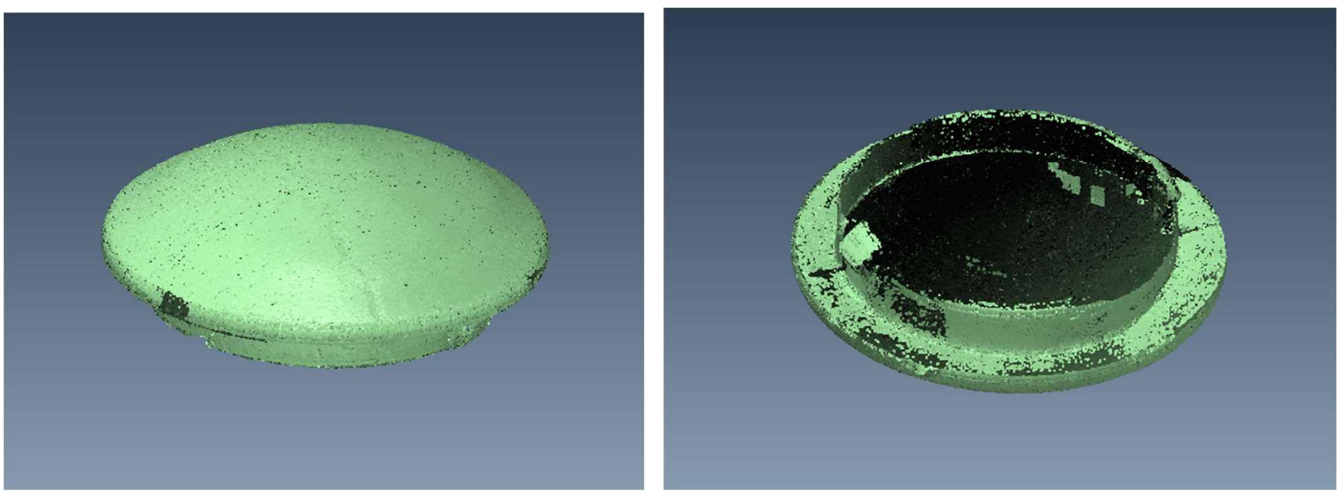


Fig 10: Top half of the scan

Once the unwanted elements were removed the next step was to align the two scans together, using the surface align feature under the IMAlign, the scans were mated together using the best-fit-alignment method, in which the points are picked on similar sections of each half to use as a reference for it to be mated. There are certain preset options that need to be fixed. In this case the max angle was deselected, the max distance was 0.322 mm, the number of iterations was set to 50, in the surface sections both halves are selected. Finally, the alignment process began which roughly tool 20 minutes, the following images are the result of the closest alignment we got.

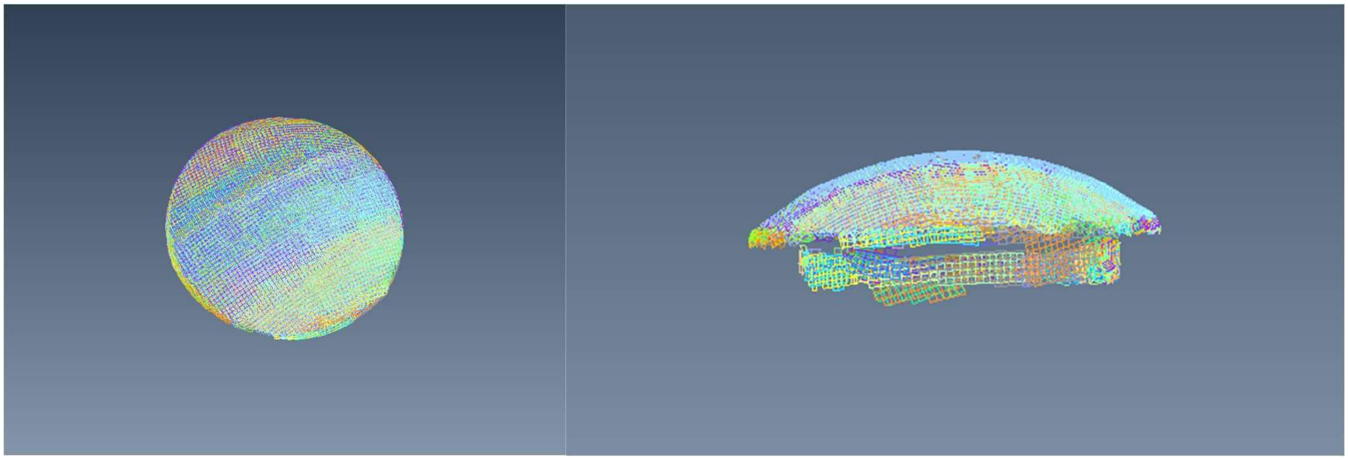


Fig 11: Scans aligned in IMAlign

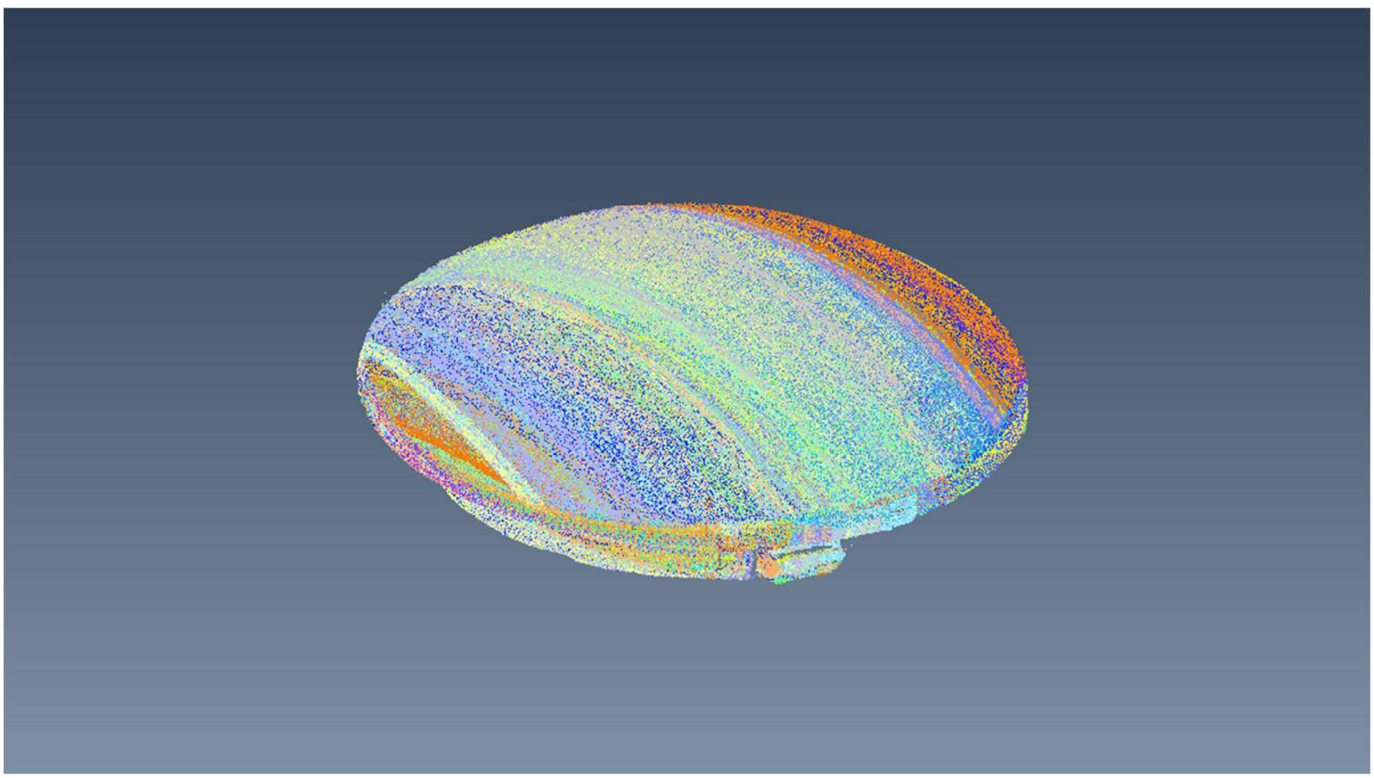


Fig 12: Aligned scan

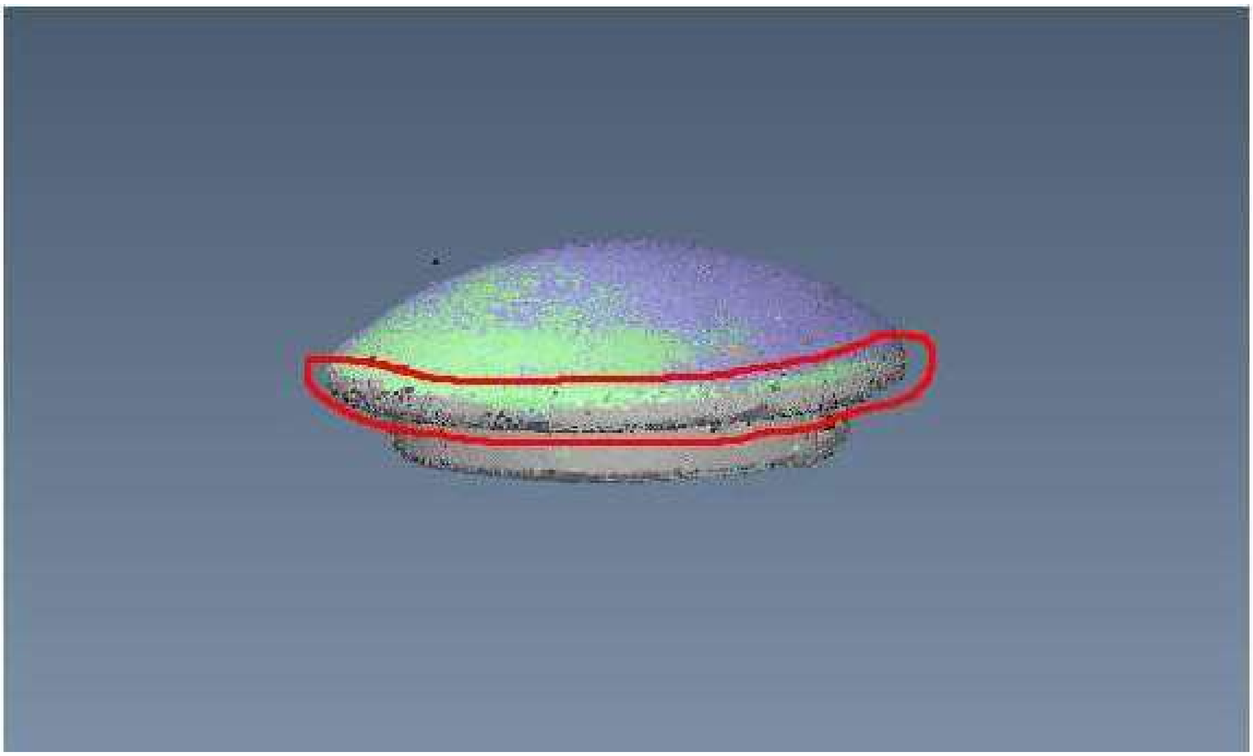


Fig 13: Noise at fillet

From the above image, when the multiple halves of the scans were aligned some of the points got overlapped causing it to create noise which can be seen in the highlighted section. As there was no way to get rid of the noise without compromising the mate. Hence it was left as it is for it to be treated in Polyworks Modelers.

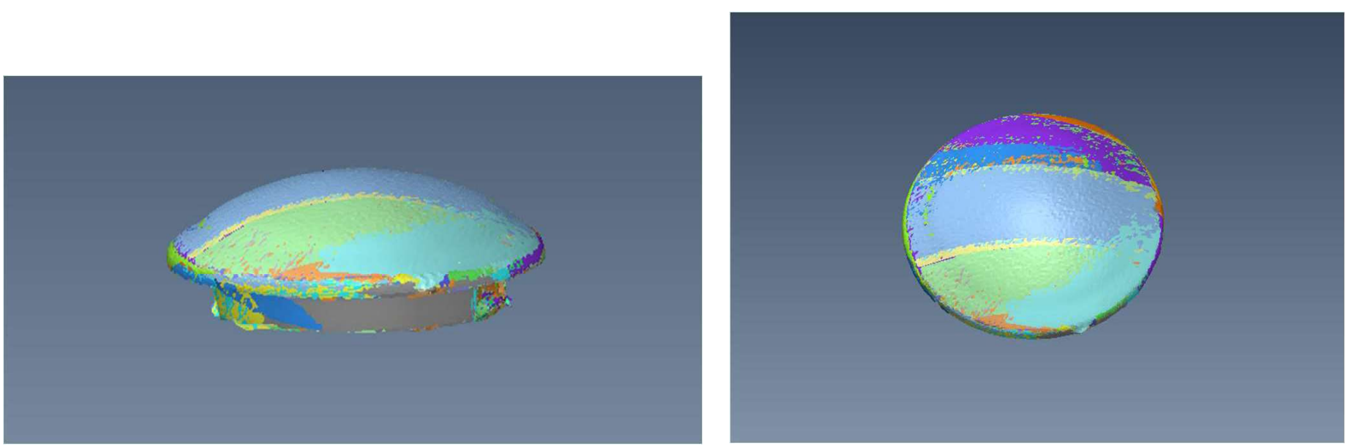


Fig 14: Point cloud converted into Polygonal model

4.1.2 Segmentation & Surface fitting: Once the polygonal models were generated, editing can begin firstly the entire surface was smoothen out. The next step was to fill holes, this could be achieved either by interacting with each hole separately or all the holes at once. For better results it is recommended to deal with each hole separately, cause when enough data is not present the software tries to create the surface which shouldn't exist. Once the holes are filled there could be surface irregularities like bump or dent, this can be fixed by using the reconstruct tool, first select the region to be treated and then hit SHIFT + R, an example of this can be seen in the images below.

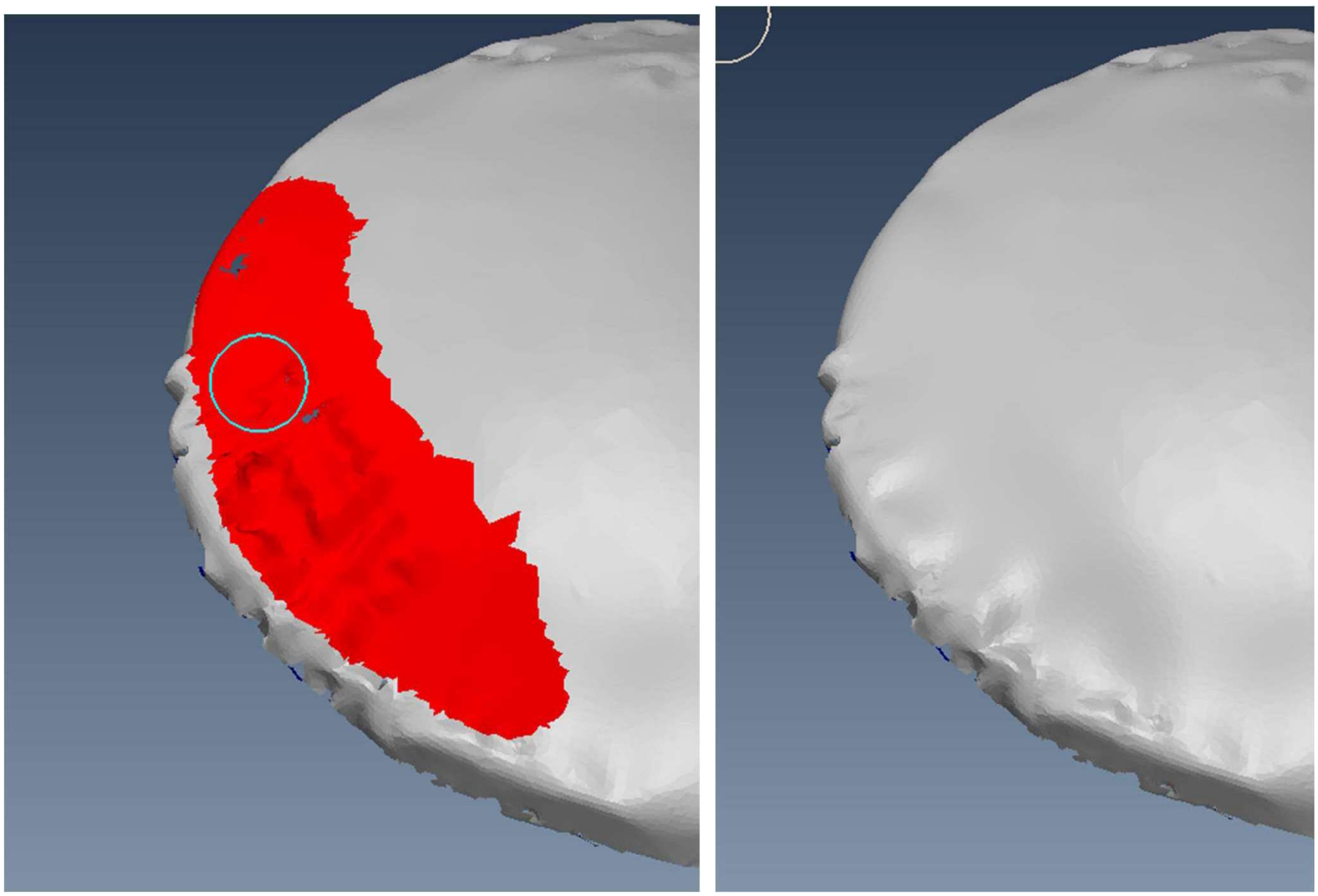


Fig 15: Surface being treated

Once all the treatment and surface editing has been completed, as shown in the images on next page. The next step of generating curves begin, the part is divided into multiple sections, the greater number of sections mean the better accuracy when generating NURBS patch. Once the curves have been created, select create NURBS with reference to curves from the drop-down menu in polygons.

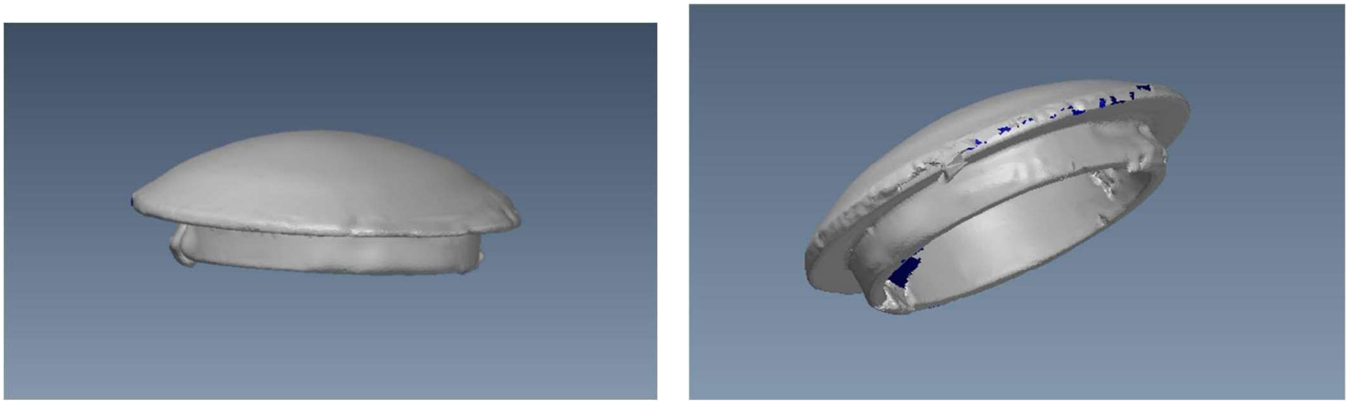


Fig 16: Polygonal Model Created

4.1.3 CAD model Generation: The result of the data sets is recognized. A CAD model is directly created using Unigraphics CAD/CAE/CAM software after processing of data format. There are currently two ways of creating CAD models using free-form data. The first one is called curve mode; the curve is generated using a data set, and the surface is generated from the mesh generated via curves; the generated surface is checked for continuity and smoothness. The maximum error can be within the range of 0.2mm [2].

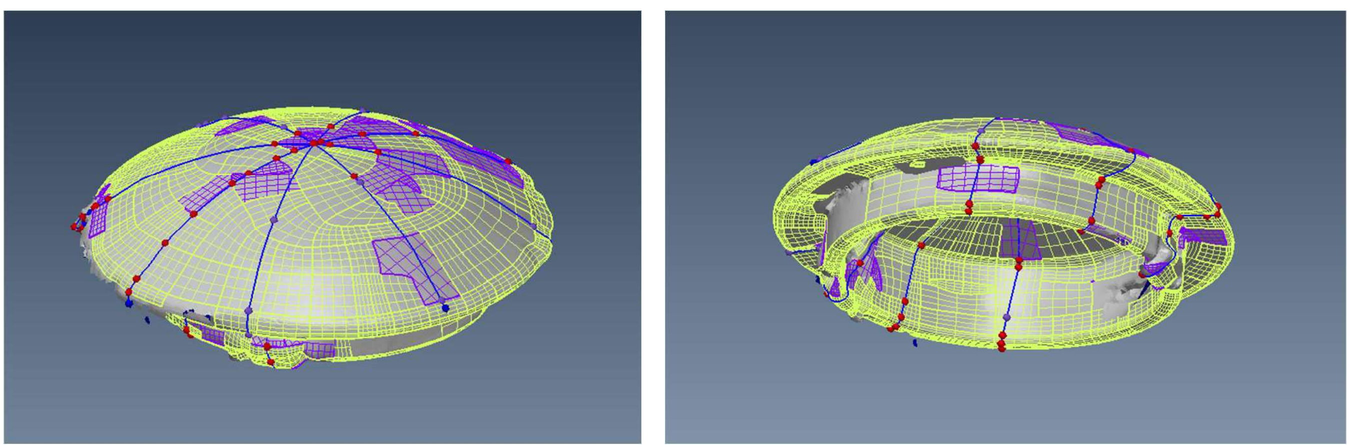


Fig 17: Curves created and NURBS applied

Finally, when the NURBS are created, the last thing to do is select all patches from the tree on left side and make it Fit.

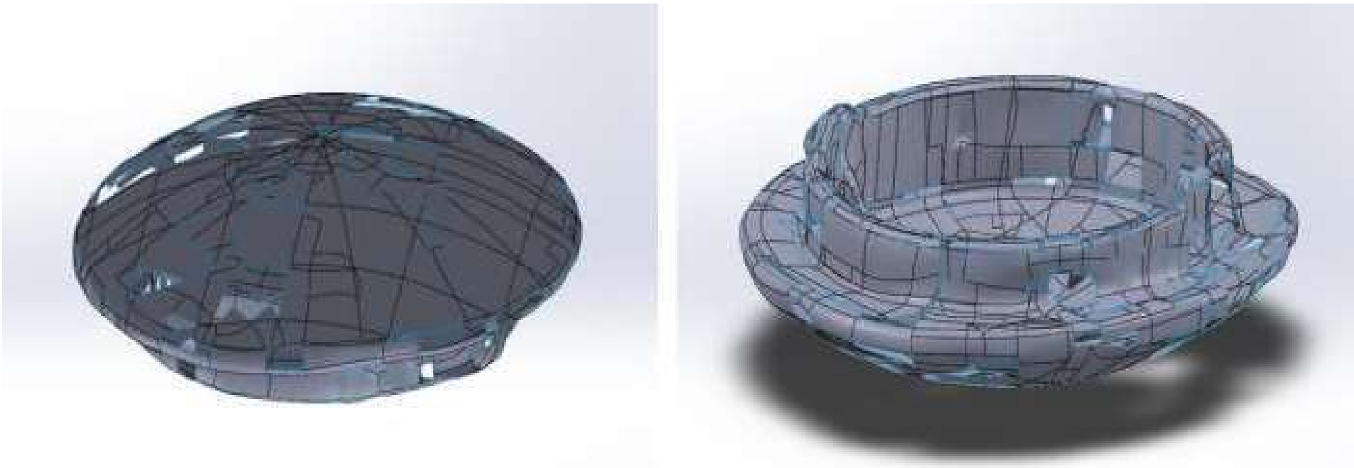


Fig 18: Surfaces directly exported to CAD software

The patch was exported directly to Solidworks in .STEP format, the results are shown in the images above the CAD had missing sections in it, these are the regions where the Polyworks software was not able to generate the NURBS patch, the reason for this is that the file didn't have enough data to begin with. Since the result obtained were not manufacturable it was decided to conclude this method

.

4.2 Exporting Planes & Sketches: The method of extracting features was used for this test where a simple block was taken which had slot, a step and a through hole.

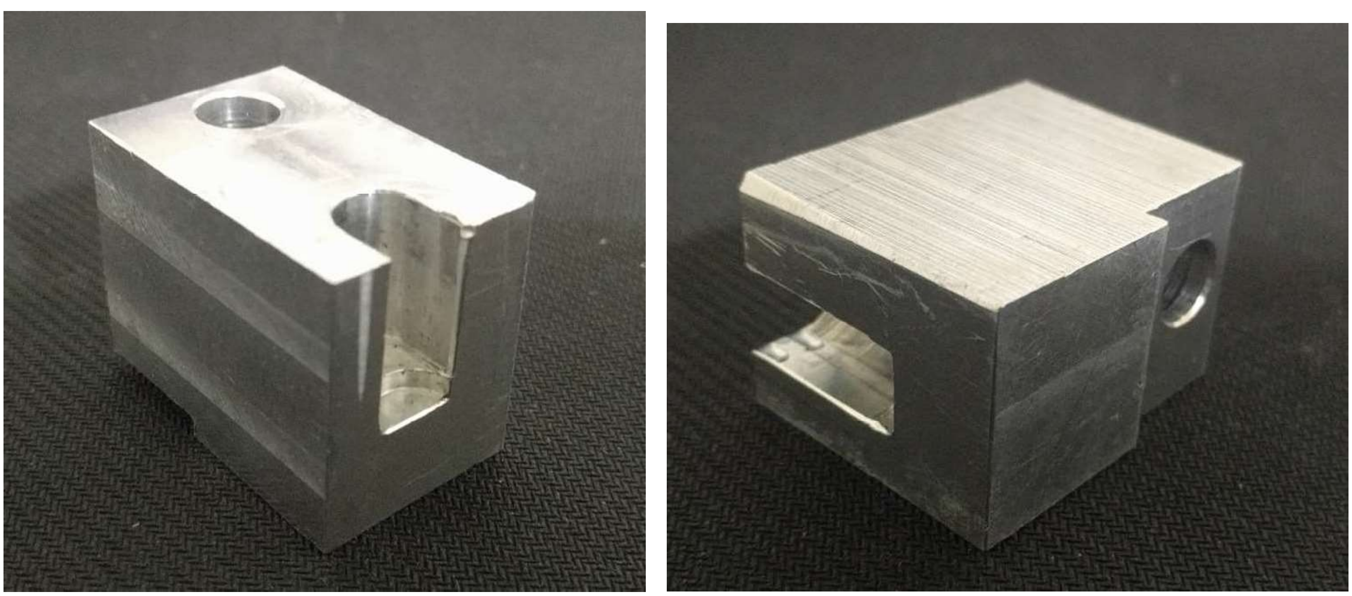
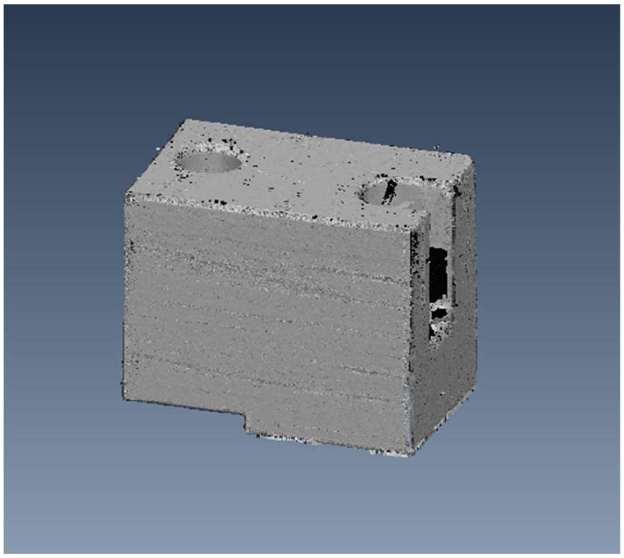


Fig 19: Block to be RE using method 2

4.2.1 Data Acquisition: Since we had difficulty with the alignment of scans, it was decided that the best approach would be to get a single good scan by having the part oriented properly.



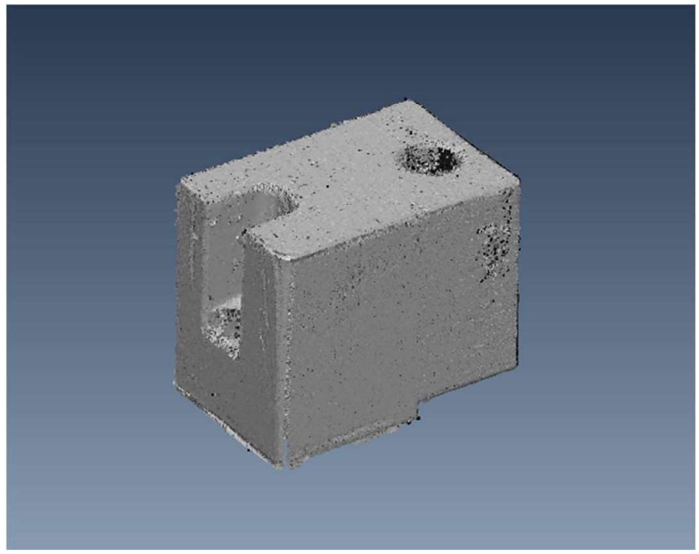
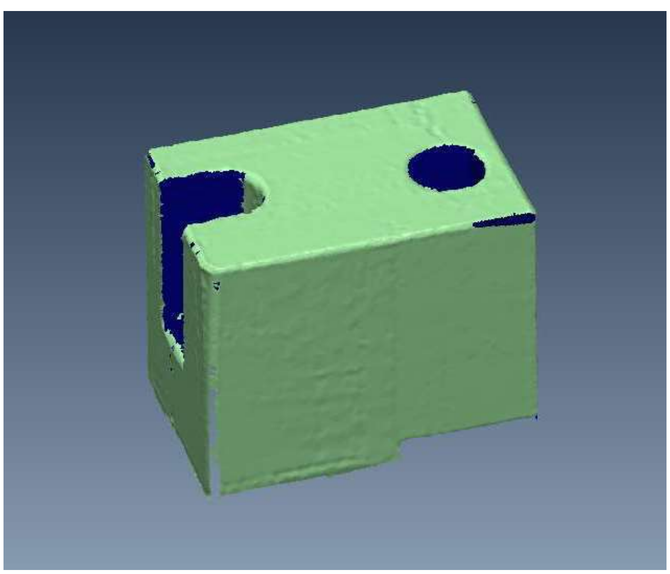


Fig 20: Point clouds of the Block

For this test the scan quality was kept at fine mesh which ended up generating 4.5 million points for a small part which is 2”x2”x4” roughly.

4.2.2 Segmentation & Surface fitting: The results observed was like night and day, cause when the end cap was scanned, the Polyworks software which gives a real time assessment of whether the region scanned is good to work with, often had missing data when converted to polygonal models. Hence one good scan was enough to work with. The part was then converted to polygonal model so that editing can be done.



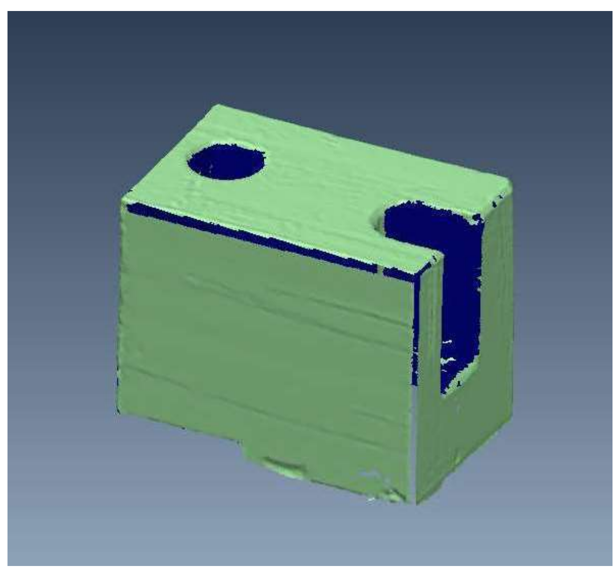


Fig 21: Polygonal model of test 2

4.2.3 CAD model Generation: The second method to reverse engineer is extracting features from the scanned part. Polyworks provides tools with which the user can generate planes, cylinders, & spheres. This can be done by selecting the data points in a specific region and selecting the type of feature to be created. These features can then be locked, aligned either parallel or perpendicular to reference (in our case a local co-ordinate system) or to other features.

The second thing in addition to the features which Polyworks provide is creating sketch in reference to the data points gathered this allows the user to extract lines, circles and arcs which can be used as a reference when exported.

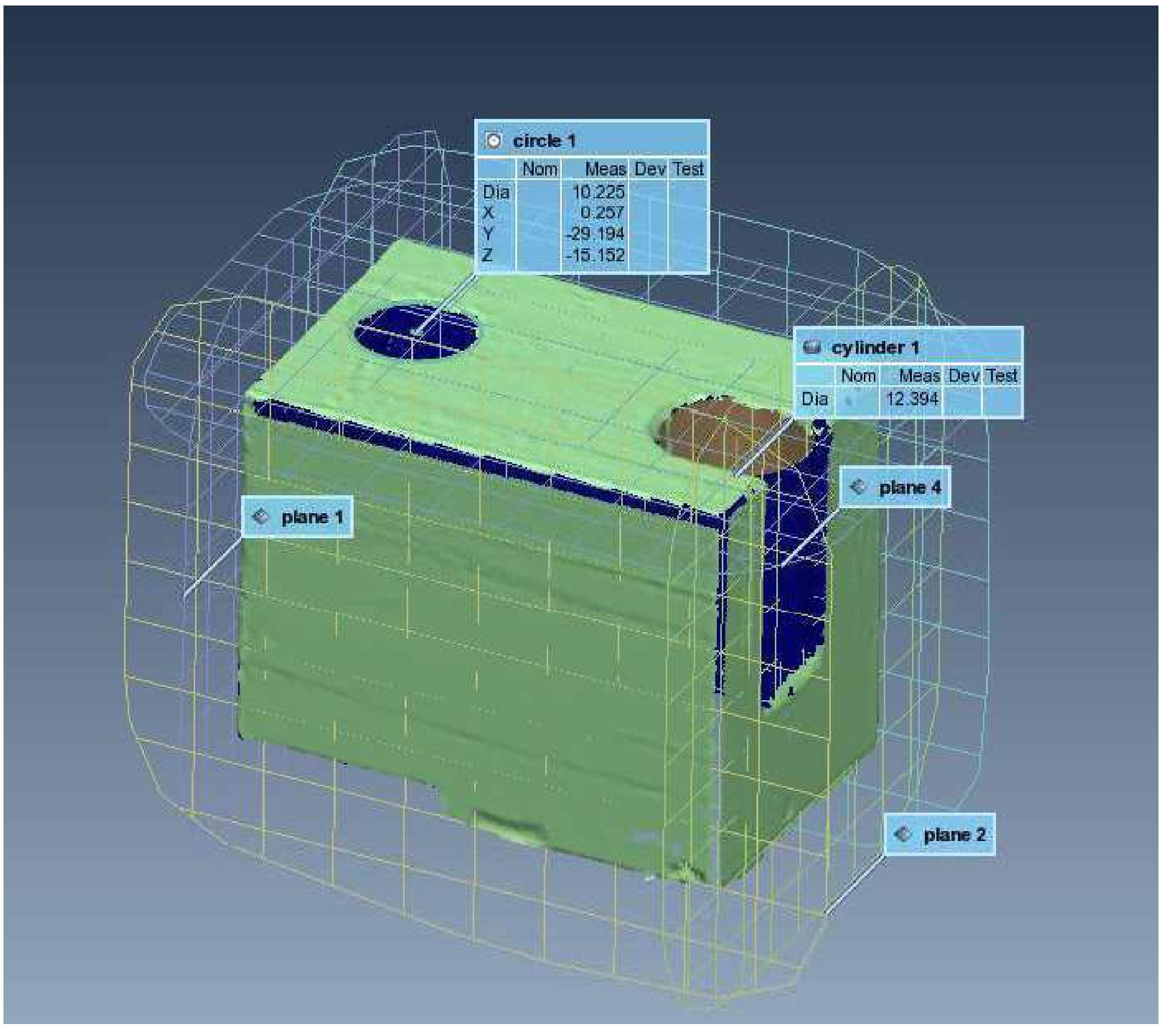


Fig 22: Features created onto the Polygonal model

Once the features are created the model can be exported to the CAD software of choice, in our case it was exported again to Solidworks in the form of an .IGES files.

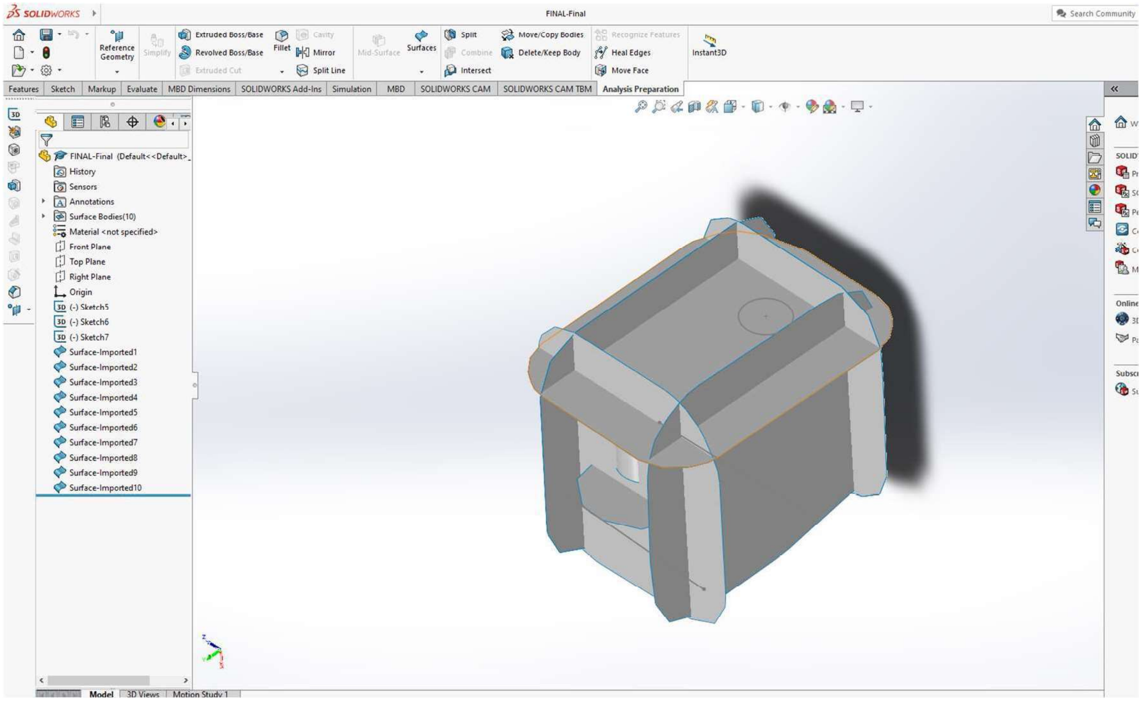


Fig 23: Planes and Sketches exported to Solidworks.

As seen in the image above the features and sketches were imported as surfaces into the software and was trimmed to obtain our final CAD model as seen in the images below

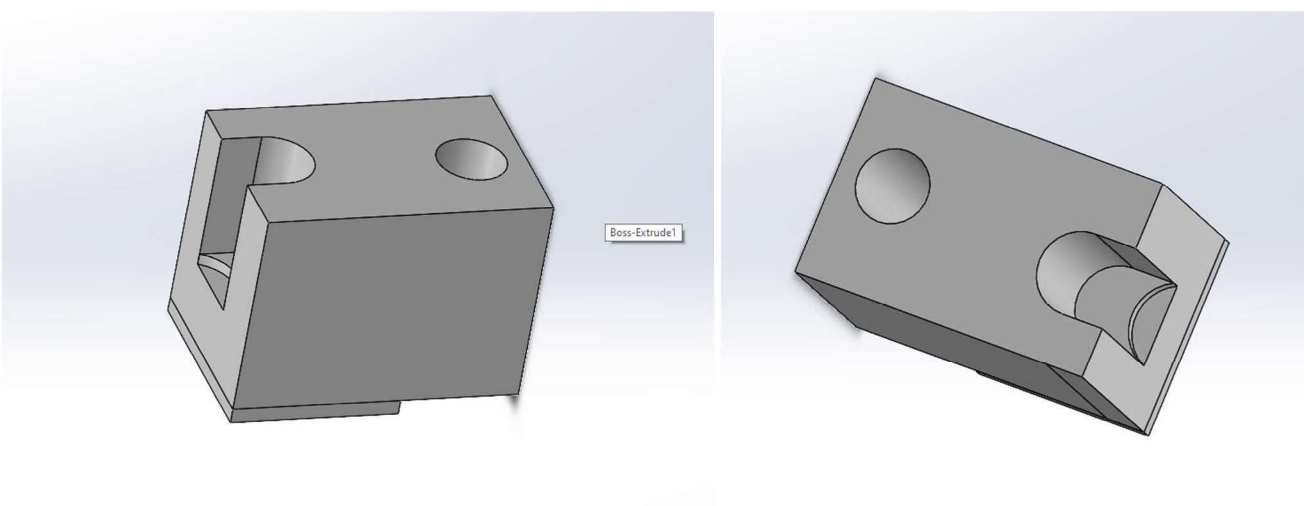
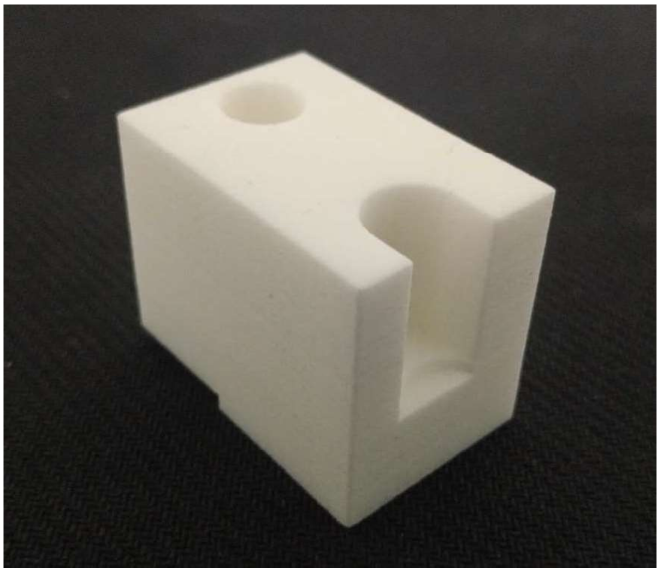


Fig 24: STEP file created after trimming/editing

Once the CAD files are generated the next step is to have them fabricated using additive manufacturing.

4.2.4 Fabrication: Our test pieces created using method 2 of reverse engineering were manufactured using PA-12 also known as nylon 12 in white colour using an SLS 3D printer, the choice was made based on the availability.



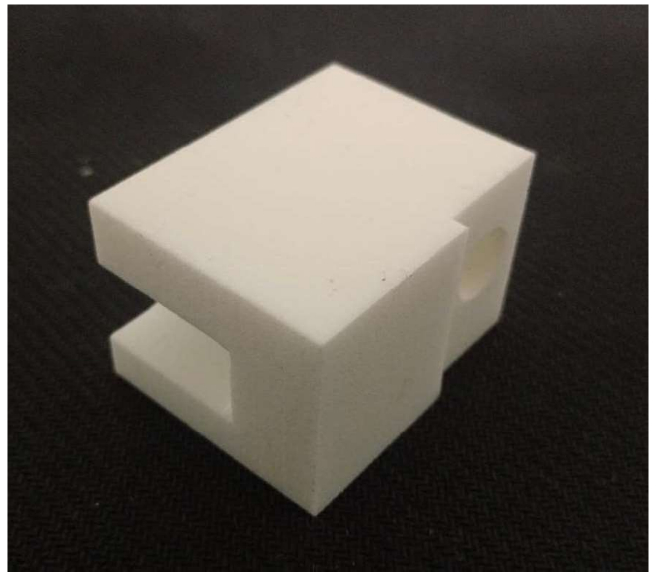


Fig 25: RE part printed using SLS

There is a wide ever-growing catalog of materials available for selective laser sintering, the most known polymer is nylon specifically PA-11 & PA-12 which are compared in the table down below, in addition with PEEK. Once the CAD is generated after RE one can consider exploring different materials for it to be manufactured with and used right away for the application it is intended for.

Materials	PA-11	PA-12	PEEK
Density (lb./ft^3)	**64.30 – 65.55**	**63.05 – 63.68**	**81.16 – 84.40**
Young's Modulus (ksi)	**179.85 – 190**	**174.05 – 203.05**	**545.34 – 572.90**
Yield Strength (ksi)	**8.3 – 8.7**	**3 – 6.1**	**12.6 – 13.8**
Tensile Strength (ksi)	**8 – 9.5**	**5.1 – 10**	**10.2 – 15**
Fracture Toughness (psi.in^1/2)	**3.33e3 – 7.31e3**	**1.84e3 – 5.53e3**	**2.48e3 – 3.91e3**
Melting Point (ºF)	**356 – 374**	**320 – 408.2**	**611.6 – 654.8**
Glass Transient Temperature (ºF)	**96.8 – 118.4**	**104 – 109.4**	**289.4 – 314.6**

Mold Shrinkage (%)	**1.09 – 1.32**	**0.3 – 1.5**	**1 – 1.21**

Most of the additive manufacturing procedures are developed for polymeric materials [18]. The characterization of powders used in the aerospace industry involves documenting the average particle size, surface area, flowability, apparent density, moisture content, and the porosity in a powder. These attributes mentioned are mostly considered the minimum required information by the end-user. The powder flow is the most crucial characteristic that is critical to all AM methods. The flow measurement is essential for the powder's bulk flow as it is transported to the working area, but the powder is distributed by a feeder, which places the individual particles in place before welding. As important as the measurement of flow is to the AM process, the measurement of apparent density indicates how the particles will pack in the powder bed. If the powders are irregular in shape, the packing will be poor, and the apparent density will be low. On the other hand, if the particles are spherical and free of satellites, the apparent density will be high. This is the preferred condition for powders used in AM.

4.2.5 Evaluation: Now to test the accuracy of our method to reverse engineer a part the printed part was scanned again and compared with the CAD file as a reference, but before we could scan the part it had to be painted a different colour as the scanner has difficulty picking up white. Hence the final part was painted with a very thin coat of enamel blue as seen in the images below.

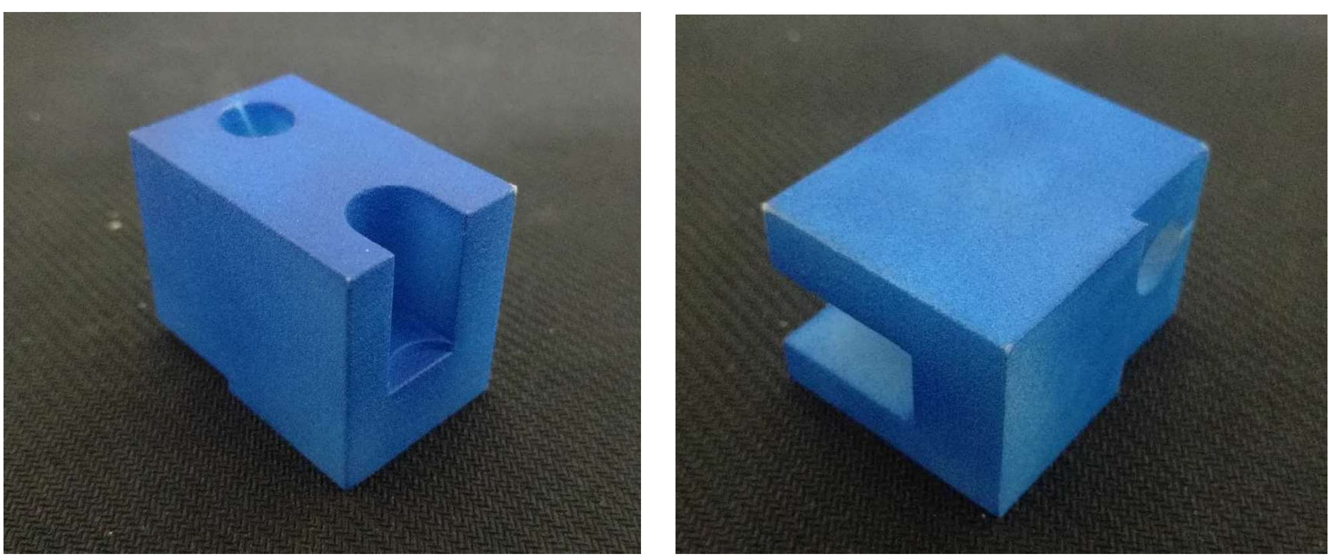


Fig 26: Part painted blue for detection

Once the point cloud was collected from the printed part, the CAD was imported in .IGES file and mated together using the command best-fit to reference, in the alignment menu.

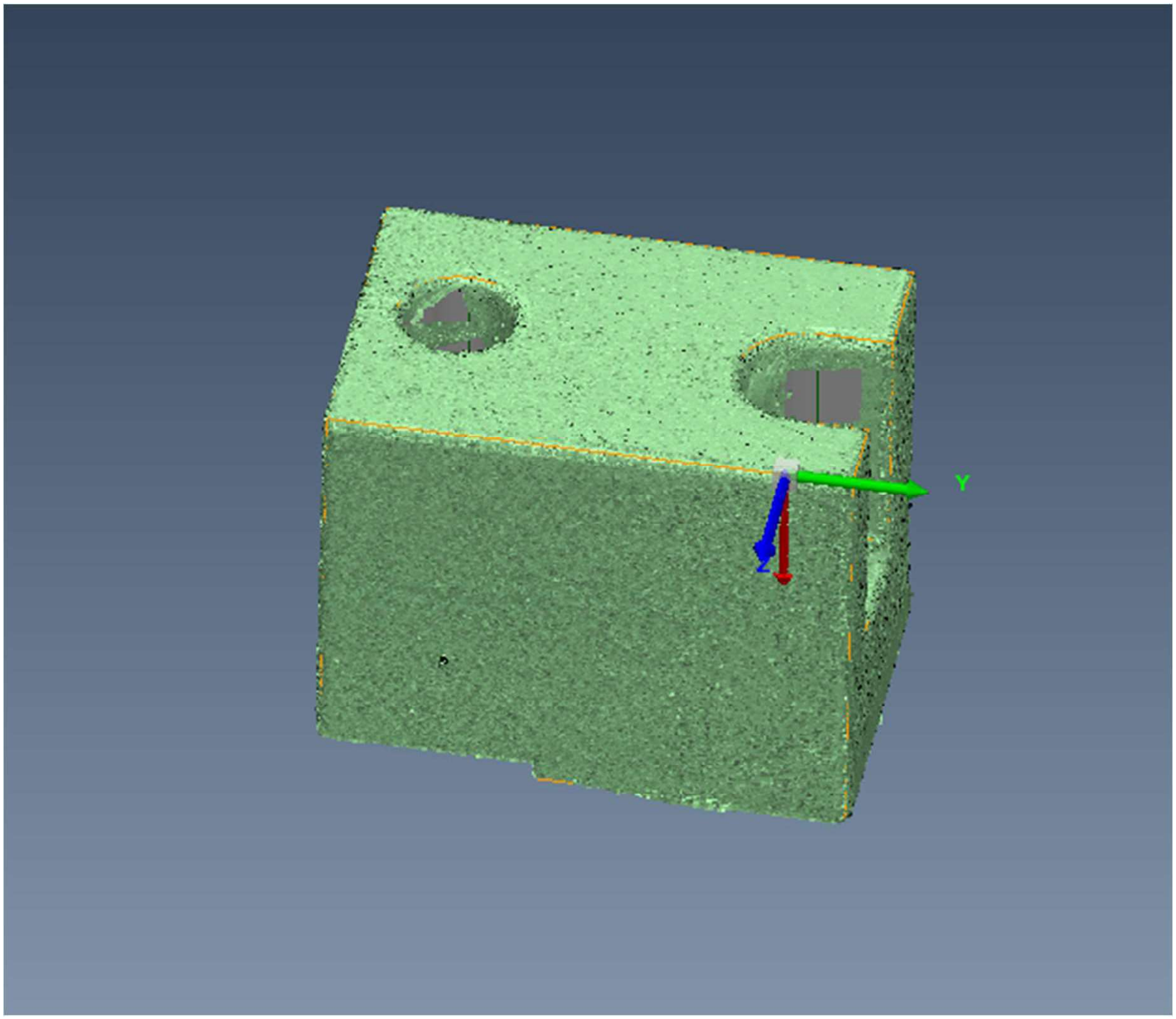
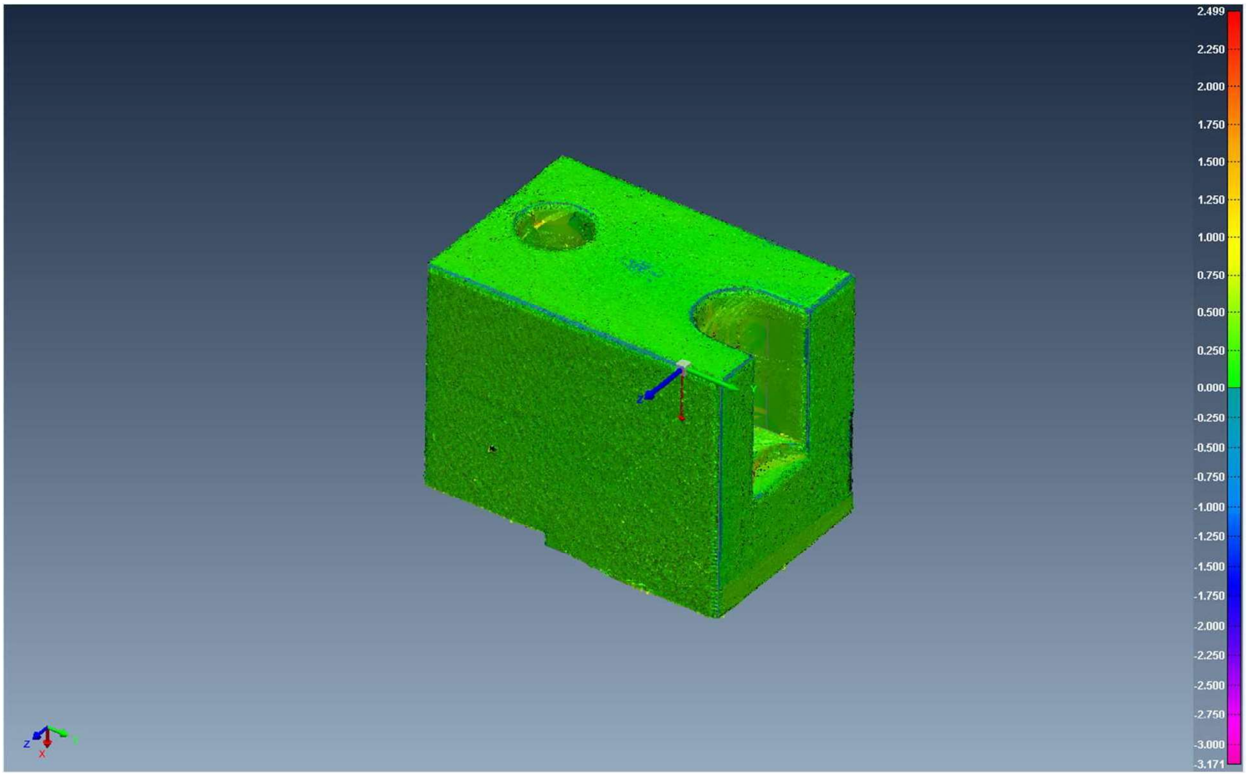
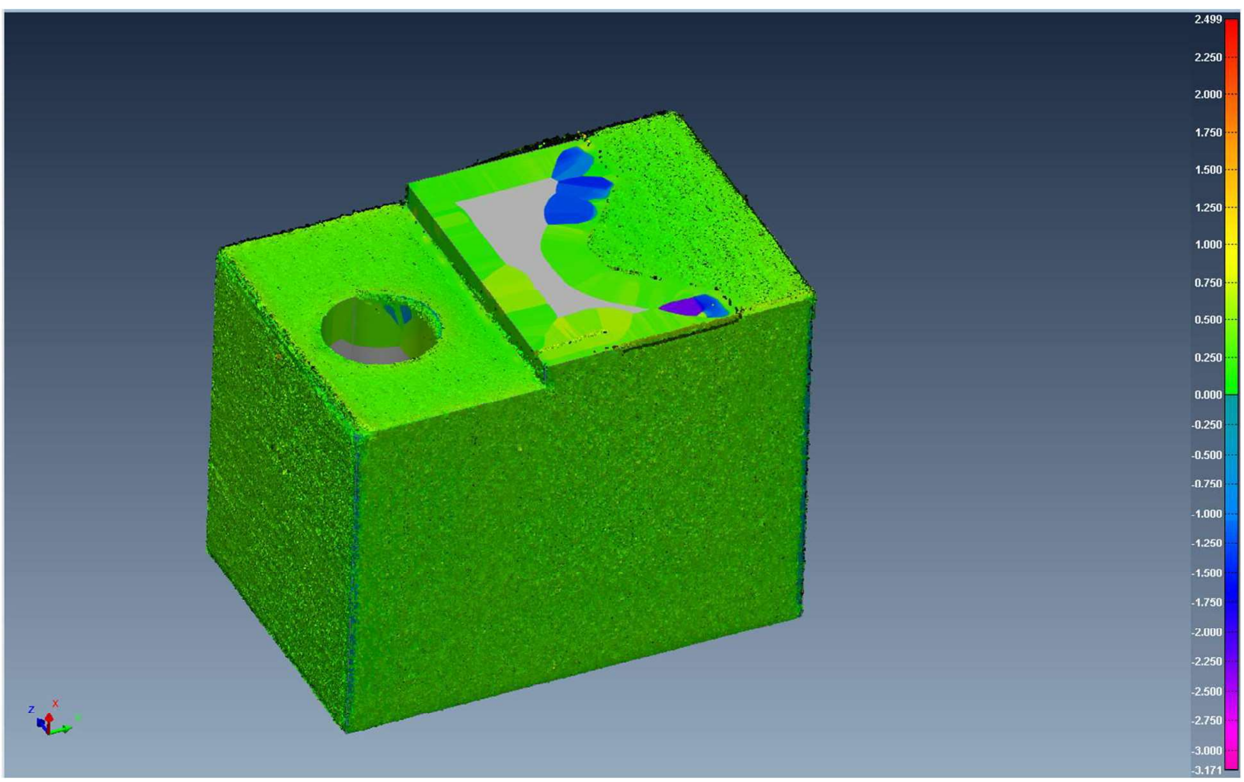


Fig 27: Point cloud mated to reference (CAD geometry)

Next step was to plot the surface deviation using the tool colour map present in the toolbar section, the units were selected to be millimeter (mm), and the tolerance was set 1.5mm for upper limit and -1.5mm for lower limit for the part to be considered a success. Multiple points were anchored on each side of the part to check for deviation as seen in the following images.


2.499
2.250
2.000
1.750
1.500
1.250
1.000
0.750
0.500
0.250
0.000
-0.250
-0.500
-0.750
-1.000
-1.250
-1.500
-1.750
-2.000
-2.250
-2.500
-2.750
-3.000
-3.171

(a)


2.499
2.250
2.000
1.750
1.500
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1.000
0.750
0.500
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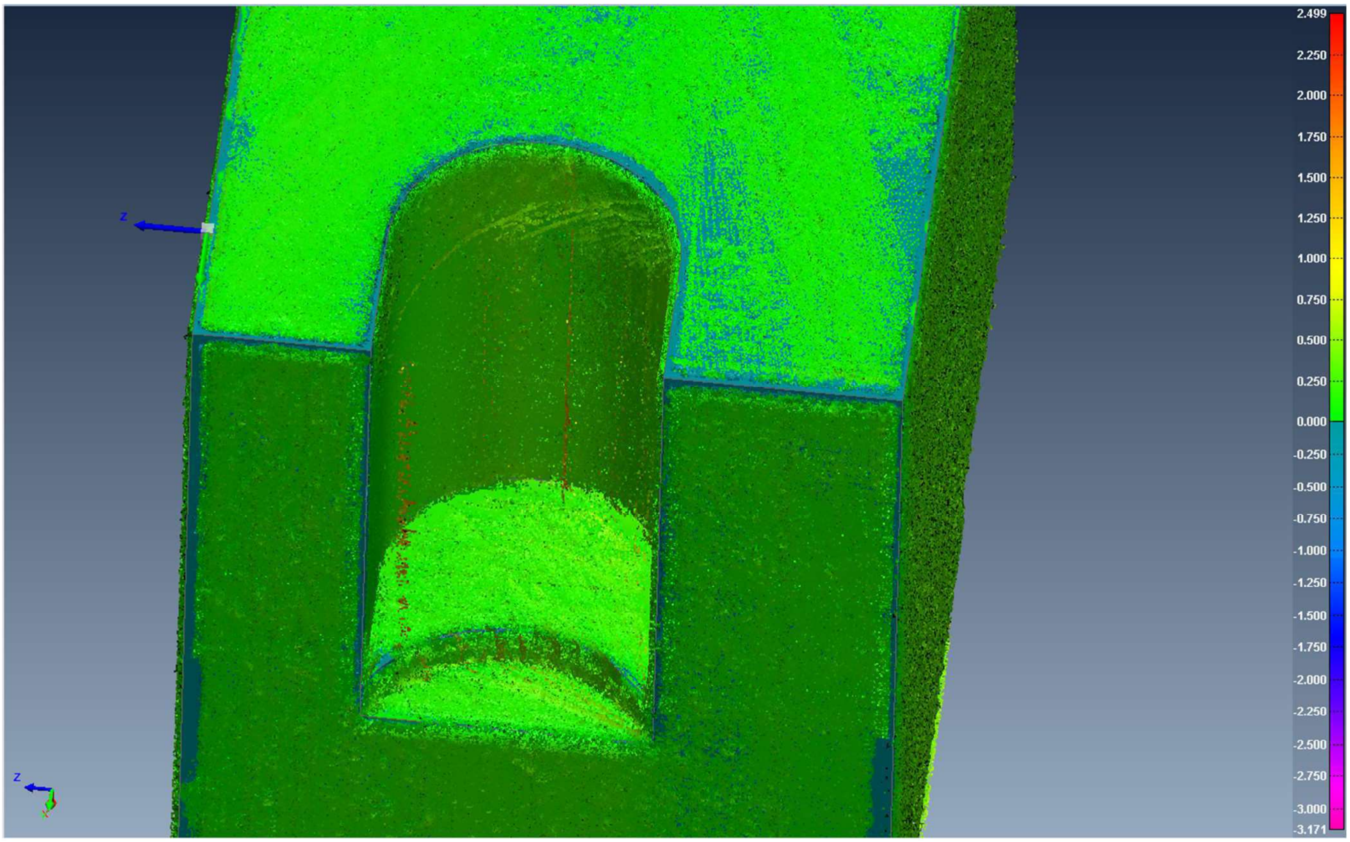
0.000
-0.250
-0.500
-0.750
-1.000
-1.250
-1.500
-1.750
-2.000
-2.250
-2.500
-2.750
-3.000
-3.171

(b)



(c)

Fig 28: (a & b) Top and bottom sections (c) Focusing on slot

From the deviation plot it can be deduced that the part manufactured is very accurate to the CAD model generated using reverse engineering method 2 which is exporting features and sketches. A detailed report is added at the end of the paper which shows the tolerance of 96 points anchored around the surface and edges of the part. It is to be considered that the colour mapping has some accuracy error which can be seen in the **Fig 28 (c),** the edges on the corners have blue deviations because after rescanning the part the point cloud had missing data hence the colour mapping plot shows the region as fail surface deviation. Another example of this would be **Fig 28 (b),** where there is a grey patch. The grey patch is the original CAD file on top of which the point cloud resides, this is because while scanning that region served as the base when orienting the printed part. The slot is also where we see some deviation as the original part was metal and scanning the slot region was difficult as metal begin reflective when the laser is shined onto it.

Chapter 5

Conclusion and Future work

This paper has presented two different methods of reverse engineering, out of which the second method of exporting features and sketches was able to recreate the original geometry with much better accuracy. The deviation analysis shows that all the point, 96 in total anchored onto the surface of the reverse engineered part cleared the set upper and lower limit for tolerances of 1.5mm.

The method of exporting NURBS didn't yield great results as the extracted surfaces had missing patches. The other issue was alignment of multiple halves, as it required multiple iterations and setting to have the halves mated, and the result for each iteration won't be same, it had noise caused by the overlap of points which was difficult to get rid of, and only half of those points were treatable in Polyworks Modeler. Another alignment process of having the point clouds aligned using IMAlign feature gave slightly better results. But even this method had a hit and miss kind of results throughout the research. Further research would be required to get a proper process developed to yield a constant result.

The other issue which was faced during the research was the system paired with the Faro-arm laser scanner provided best results when the mesh quality was set to fine or extra fine, but if a larger part was supposed to be scanned the system would lag and sometimes even crashed. Standard mesh setting did not experience any lag, but the data gathered from it doesn't yield great results and the point clouds often have missing data when converted to polygonal models. Maybe, once the alignment process is well developed multiple small scans can be taken with fine mesh without putting too much stress onto the system on which the software is installed and yield better results when converted to polygonal model/mesh.

When we talk about future work for this project, the first thing to consider would be topology optimization as reverse engineered parts can be further improved on, and when considering a part being manufactured using traditional methods but now with the availability of additive manufacturing opens new doors in design consideration and making the original part lighter and more efficient. This could benefit a lot in aerospace and automotive Industries.

Different additive manufacturing processes and materials can also be considered as discussed in Table 1 & 2 depending on the application which can range from prototyping to end use parts. This also opens the door to evaluate the parts for structural integrity by checking the load begin applied doesn't fail the part.

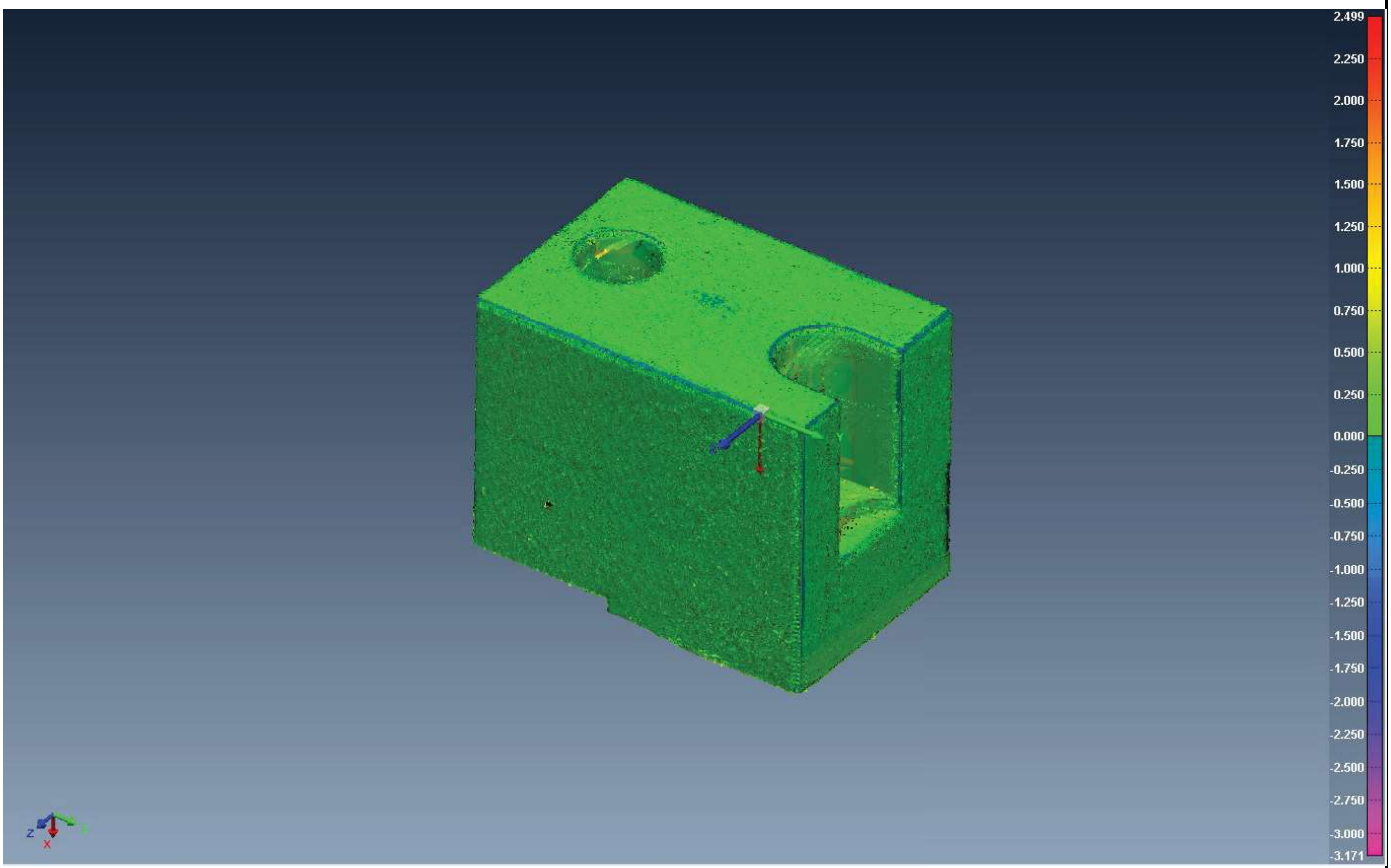
Appendix A

Surface Deviation Report

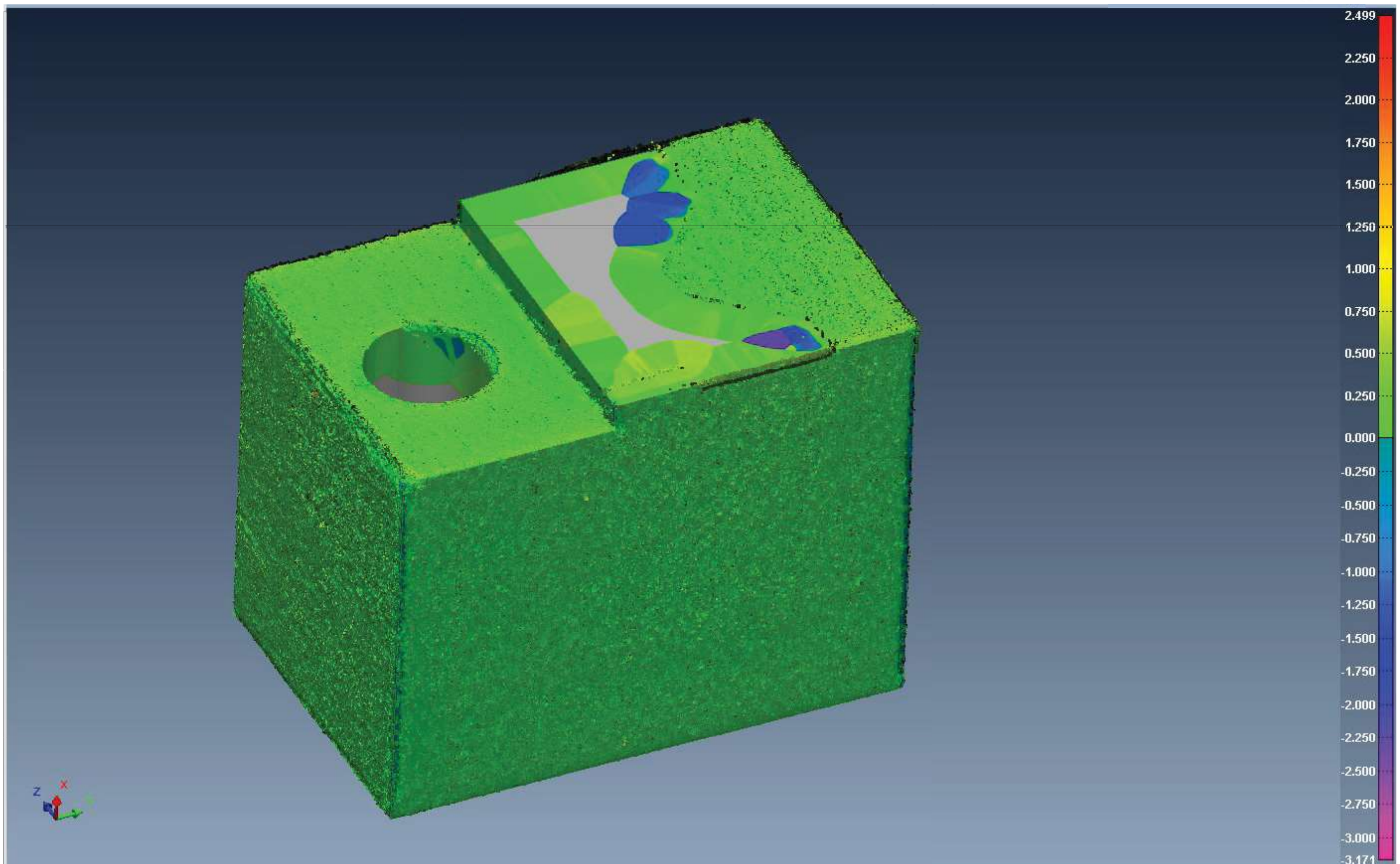
PolyWorks by innovmetric

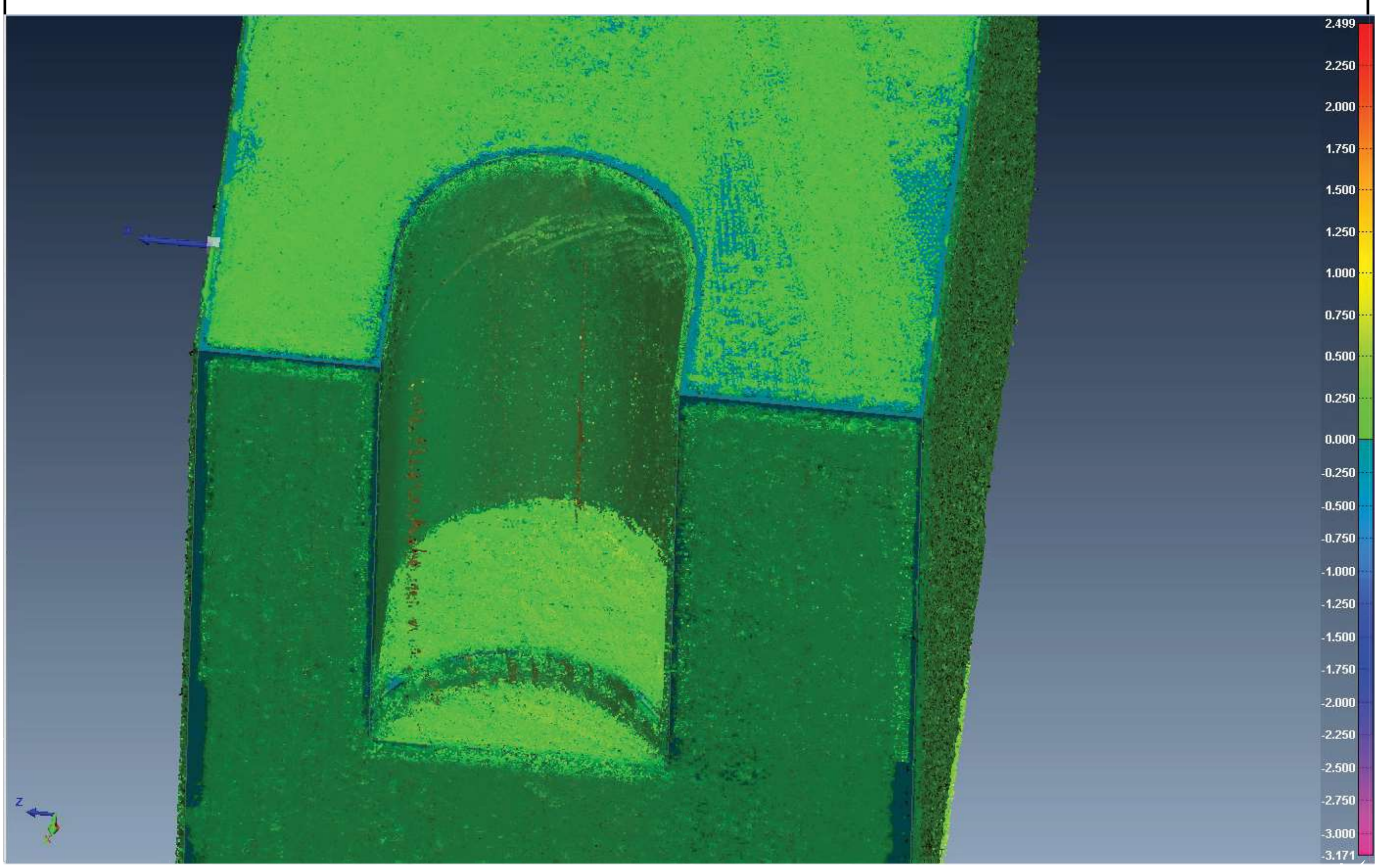
innovmetric

Report Author: Gurtej Singh
Date: 12/26/2021



Organization:	UTA	**Part name:**	SLS_final
Operator:	Gurtej Singh	**Part number:**	1
E-mail:		**Drawing #:**	1
Workspace:	Thesis	**Serial #:**	
Project:	Thesis-SLS	**Device: Faro Arm**	


2.499
2.250
2.000
1.750
1.500
1.250
1.000
0.750
0.500
0.250
0.000
-0.250
-0.500
-0.750
-1.000
-1.250
-1.500
-1.750
-2.000
-2.250
-2.500
-2.750
-3.000
-3.171


2.499
2.250
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1.250
1.000
0.750
0.500
0.250
0.000
-0.250
-0.500
-0.750
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-2.500
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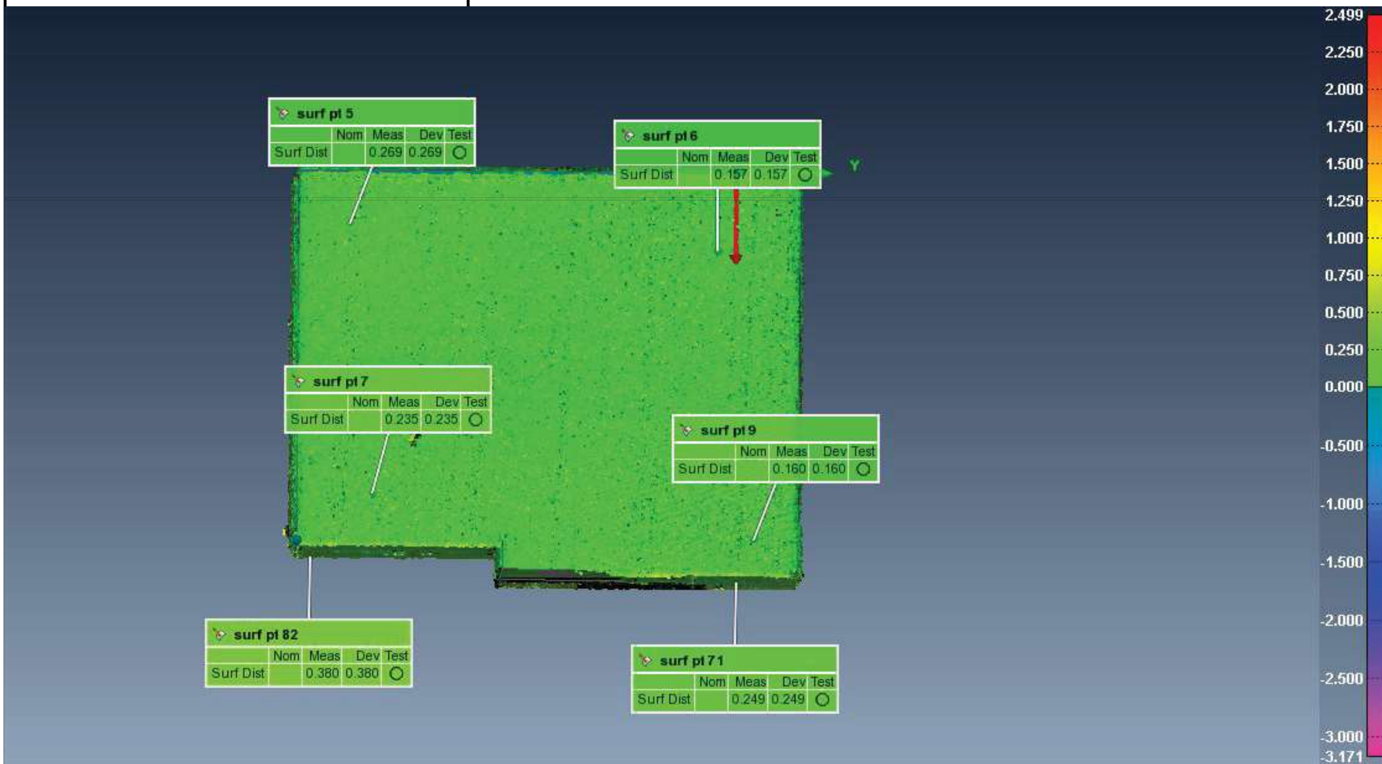
-3.171


surf pt 5
Nom Meas Dev Test
Surf Dist 0.269 0.269
surf pt 6
Nom Meas Dev Test
Surf Dist 0.157 0.157
surf pt 7
Nom Meas Dev Test
Surf Dist 0.235 0.235
surf pt 9
Nom Meas Dev Test
Surf Dist 0.160 0.160
surf pt 82
Nom Meas Dev Test
Surf Dist 0.380 0.380
surf pt 71
Nom Meas Dev Test
Surf Dist 0.249 0.249
2.499
2.250
2.000
1.750
1.500
1.250
1.000
0.750
0.500
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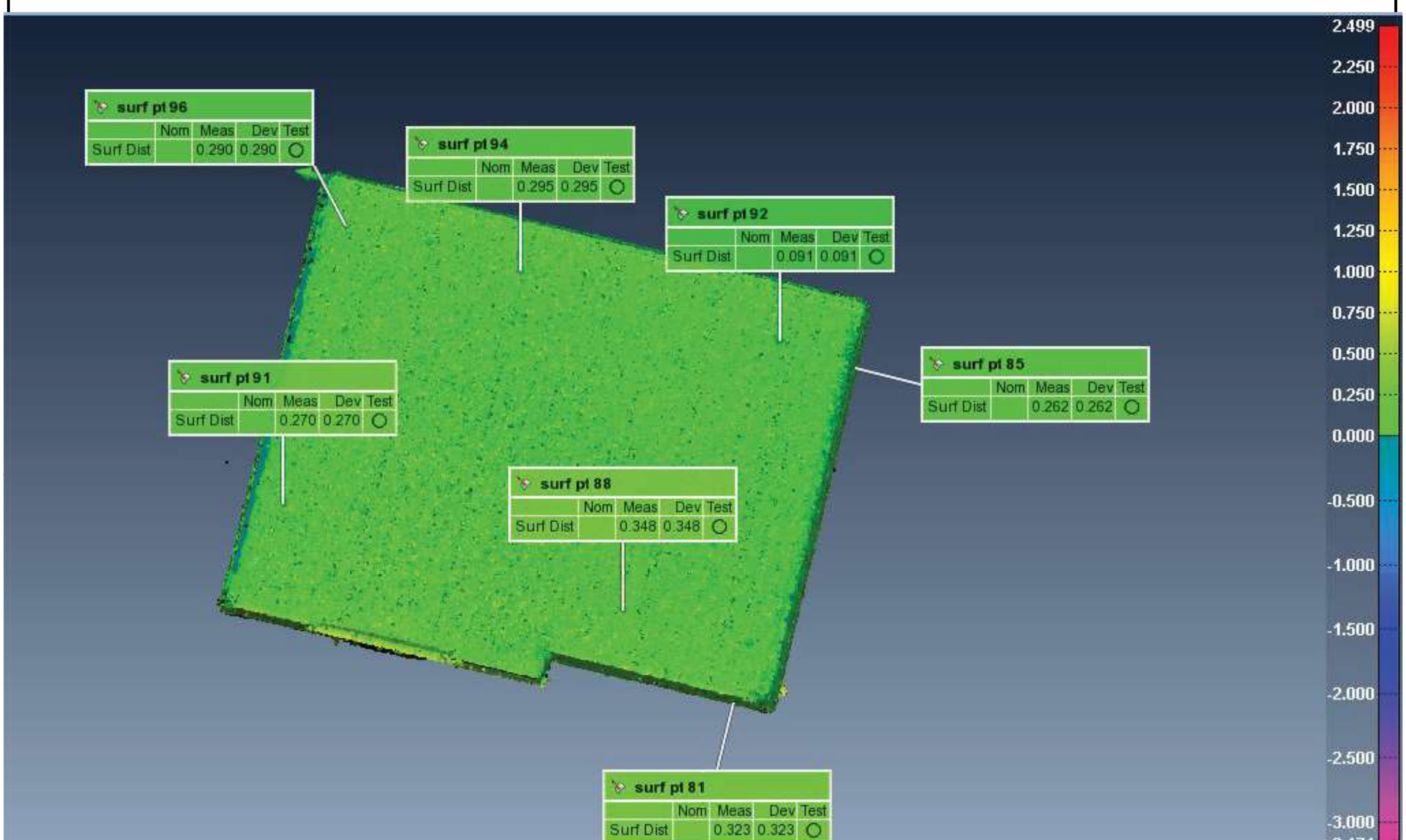
0.000
-0.500
-1.000
-1.500
-2.000
-2.500
-3.000
-3.171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Nom Meas Dev Test
Surf Dist 0.290 0.290
surf pt 94
Nom Meas Dev Test
Surf Dist 0.295 0.295
surf pt 92
Nom Meas Dev Test
Surf Dist 0.091 0.091
surf pt 85
Nom Meas Dev Test
Surf Dist 0.262 0.262
surf pt 91
Nom Meas Dev Test
Surf Dist 0.270 0.270
surf pt 88
Nom Meas Dev Test
Surf Dist 0.348 0.348
surf pt 81
Nom Meas Dev Test
Surf Dist 0.323 0.323
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2.250
2.000
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1.500
1.250
1.000
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-0.500
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-2.000
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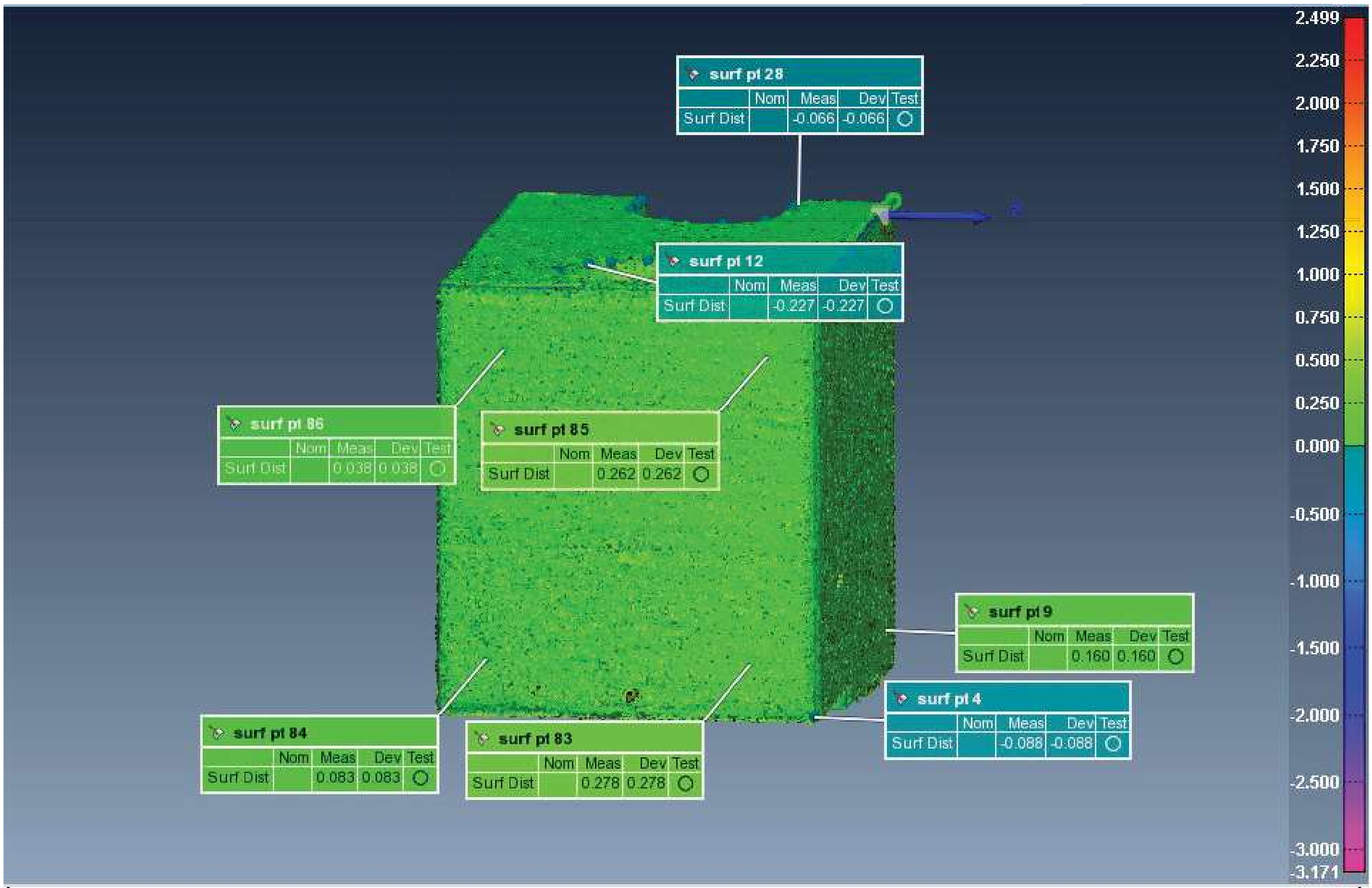
-3.000
-3.171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Surf Dist -0.066 -0.066
surf pt 12
Nom Meas Dev Test
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surf pt 86
Nom Meas Dev Test
Surf Dist 0.038 0.038
surf pt 85
Nom Meas Dev Test
Surf Dist 0.262 0.262
surf pt 9
Nom Meas Dev Test
Surf Dist 0.160 0.160
surf pt 4
Nom Meas Dev Test
Surf Dist -0.088 -0.088
surf pt 84
Nom Meas Dev Test
Surf Dist 0.083 0.083
surf pt 83
Nom Meas Dev Test
Surf Dist 0.278 0.278
2.499
2.250
2.000
1.750
1.500
1.250
1.000
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-2.000
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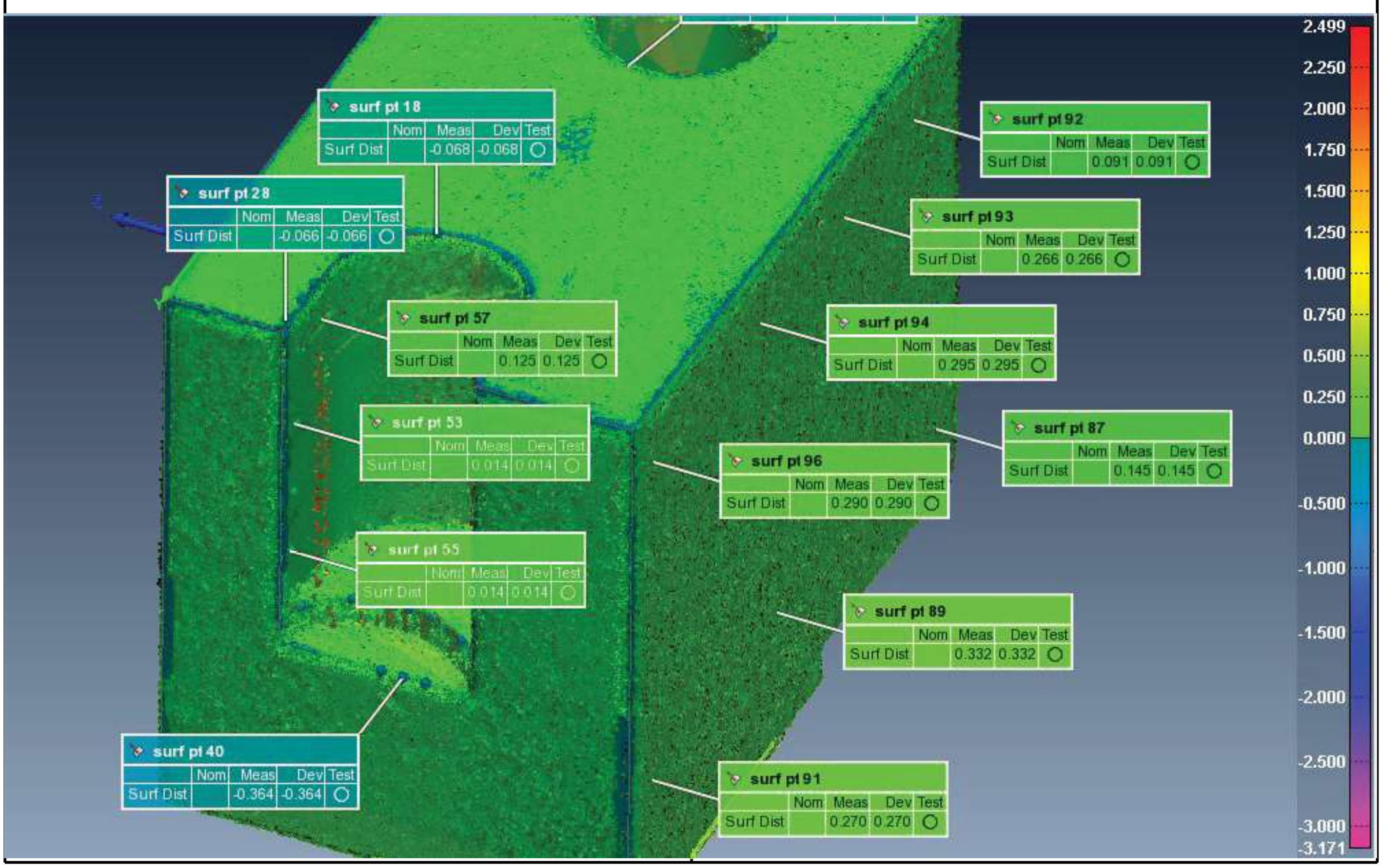
-3.000
-3.171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Nom Meas Dev Test
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surf pt 28
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Surf Dist -0.066 -0.066
surf pt 92
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Surf Dist 0.091 0.091
surf pt 93
Nom Meas Dev Test
Surf Dist 0.266 0.266
surf pt 57
Nom Meas Dev Test
Surf Dist 0.125 0.125
surf pt 94
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surf pt 96
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Surf Dist 0.290 0.290
surf pt 55
Nom Meas Dev Test
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surf pt 89
Nom Meas Dev Test
Surf Dist 0.332 0.332
surf pt 40
Nom Meas Dev Test
Surf Dist -0.364 -0.364
surf pt 91
Nom Meas Dev Test
Surf Dist 0.270 0.270
2.499
2.250
2.000
1.750
1.500
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1.000
0.750
0.500
0.250
0.000
-0.500
-1.000
-1.500
-2.000
-2.500
-3.000
-3.171

Comparison Point Table

Units	Millimeters
Coordinate Systems	world
Data Alignments	best-fit to ref 1
Linked Objects	FINAL-Final.IGS

Name	Control	Nom	Meas	Tol	Dev	Test	Out Tol
surf pt 4	Surface Distance		-0.088	±1.500	-0.088	Pass	
surf pt 5	Surface Distance		0.269	±1.500	0.269	Pass	
surf pt 6	Surface Distance		0.157	±1.500	0.157	Pass	
surf pt 7	Surface Distance		0.235	±1.500	0.235	Pass	
surf pt 8	Surface Distance		0.211	±1.500	0.211	Pass	
surf pt 9	Surface Distance		0.160	±1.500	0.160	Pass	
surf pt 10	Surface Distance		-0.228	±1.500	-0.228	Pass	
surf pt 12	Surface Distance		-0.227	±1.500	-0.227	Pass	
surf pt 13	Surface Distance		-0.118	±1.500	-0.118	Pass	
surf pt 14	Surface Distance		-0.279	±1.500	-0.279	Pass	
surf pt 15	Surface Distance		0.035	±1.500	0.035	Pass	
surf pt 16	Surface Distance		0.233	±1.500	0.233	Pass	
surf pt 17	Surface Distance		0.342	±1.500	0.342	Pass	
surf pt 18	Surface Distance		-0.068	±1.500	-0.068	Pass	
surf pt 19	Surface Distance		-0.204	±1.500	-0.204	Pass	
surf pt 20	Surface Distance		-0.185	±1.500	-0.185	Pass	
surf pt 21	Surface Distance		-0.192	±1.500	-0.192	Pass	
surf pt 22	Surface Distance		-0.235	±1.500	-0.235	Pass	
surf pt 23	Surface Distance		-0.341	±1.500	-0.341	Pass	
surf pt 24	Surface Distance		-0.123	±1.500	-0.123	Pass	
surf pt 25	Surface Distance		0.006	±1.500	0.006	Pass	
surf pt 26	Surface Distance		-0.050	±1.500	-0.050	Pass	
surf pt 27	Surface Distance		-0.130	±1.500	-0.130	Pass	
surf pt 28	Surface Distance		-0.066	±1.500	-0.066	Pass	
surf pt 29	Surface Distance		-0.177	±1.500	-0.177	Pass	
surf pt 31	Surface Distance		-0.325	±1.500	-0.325	Pass	
surf pt 32	Surface Distance		-0.328	±1.500	-0.328	Pass	
surf pt 33	Surface Distance		-0.422	±1.500	-0.422	Pass	
surf pt 34	Surface Distance		-0.403	±1.500	-0.403	Pass	
surf pt 39	Surface Distance		-0.157	±1.500	-0.157	Pass	
surf pt 40	Surface Distance		-0.364	±1.500	-0.364	Pass	
surf pt 41	Surface Distance		-0.104	±1.500	-0.104	Pass	
surf pt 43	Surface Distance		0.238	±1.500	0.238	Pass	
surf pt 44	Surface Distance		0.223	±1.500	0.223	Pass	
surf pt 45	Surface Distance		0.282	±1.500	0.282	Pass	
surf pt 46	Surface Distance		0.262	±1.500	0.262	Pass	

Organization:	Part name:
Operator:	Part number:
E-mail:	Piece: piece 1

surf pt 49	Surface Distance	0.267	±1.500	0.267	Pass
surf pt 50	Surface Distance	0.057	±1.500	0.057	Pass
surf pt 51	Surface Distance	0.279	±1.500	0.279	Pass
surf pt 52	Surface Distance	0.030	±1.500	0.030	Pass
surf pt 53	Surface Distance	0.014	±1.500	0.014	Pass
surf pt 54	Surface Distance	0.010	±1.500	0.010	Pass
surf pt 55	Surface Distance	0.014	±1.500	0.014	Pass
surf pt 56	Surface Distance	0.238	±1.500	0.238	Pass
surf pt 57	Surface Distance	0.125	±1.500	0.125	Pass
surf pt 58	Surface Distance	0.046	±1.500	0.046	Pass
surf pt 60	Surface Distance	-0.054	±1.500	-0.054	Pass
surf pt 61	Surface Distance	0.395	±1.500	0.395	Pass
surf pt 62	Surface Distance	0.303	±1.500	0.303	Pass
surf pt 63	Surface Distance	0.272	±1.500	0.272	Pass
surf pt 64	Surface Distance	0.209	±1.500	0.209	Pass
surf pt 65	Surface Distance	0.300	±1.500	0.300	Pass
surf pt 66	Surface Distance	0.394	±1.500	0.394	Pass
surf pt 67	Surface Distance	0.388	±1.500	0.388	Pass
surf pt 68	Surface Distance	0.020	±1.500	0.020	Pass
surf pt 69	Surface Distance	0.231	±1.500	0.231	Pass
surf pt 70	Surface Distance	0.174	±1.500	0.174	Pass
surf pt 71	Surface Distance	0.249	±1.500	0.249	Pass
surf pt 78	Surface Distance	0.179	±1.500	0.179	Pass
surf pt 80	Surface Distance	0.306	±1.500	0.306	Pass
surf pt 81	Surface Distance	0.323	±1.500	0.323	Pass
surf pt 82	Surface Distance	0.380	±1.500	0.380	Pass
surf pt 83	Surface Distance	0.278	±1.500	0.278	Pass
surf pt 84	Surface Distance	0.083	±1.500	0.083	Pass
surf pt 85	Surface Distance	0.262	±1.500	0.262	Pass
surf pt 86	Surface Distance	0.038	±1.500	0.038	Pass
surf pt 87	Surface Distance	0.145	±1.500	0.145	Pass
surf pt 88	Surface Distance	0.348	±1.500	0.348	Pass
surf pt 89	Surface Distance	0.332	±1.500	0.332	Pass
surf pt 90	Surface Distance	0.276	±1.500	0.276	Pass
surf pt 91	Surface Distance	0.270	±1.500	0.270	Pass
surf pt 92	Surface Distance	0.091	±1.500	0.091	Pass
surf pt 93	Surface Distance	0.266	±1.500	0.266	Pass
surf pt 94	Surface Distance	0.295	±1.500	0.295	Pass
surf pt 95	Surface Distance	0.243	±1.500	0.243	Pass
surf pt 96	Surface Distance	0.290	±1.500	0.290	Pass

Organization:	**Part name:**
Operator:	**Part number:**
E-mail:	**Piece:** piece 1

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