**INTERNATIONAL HELLENIC UNIVERSITY**
**School of Economics & Business Administration**
**MSc in Strategic Product Design**

# *"A Feasibility Study on the Generation of an Authentic Copy of a Greek Paleontological Find Utilising Reverse Engineering and Rapid Prototyping Techniques"*

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*“Afroditi, watching you working, on the archeological site of Sissi-Crete, has been an inspiration and a stimulant for my involvement with the concept of digital heritage. Thank you for your patience and your understanding during my studies.*

*This thesis is dedicated to you.*
*January 2014*

**Abstract**

This dissertation demonstrates a feasibility study on the generation of an authentic copy of a Greek paleontological find utilising Reverse Engineering and Rapid Prototyping techniques. A part of the jaw bone of a cave bear (Ursus spelaeus) that lived during the Pleistocene and became extinct about 10,000 years ago, is digitized using a three-dimensional scanner. The resulting point-cloud of the scans is treated with appropriate software for the creation of surfaces and ultimately for a digital model. The digital model is further processed to CAD models and to STL files, which are used for the generation of a physical model by rapid prototyping with the aid of a Fused Deposition Modeling (FDM) apparatus. An analytical methodology is presented revealing the step by step approach from the scanning to the prototyping. Finally the results derived from the research are discussed and recommendations are presented.

**Acknowledgements**

I would like to express my deepest appreciation to International Hellenic University and all those who provided me the possibility to work on this dissertation. A special gratitude I give to Dr Dimitris Tzetzis, for his contribution in making the necessary arrangements and meetings with Ephorate of Palaeoanthropology and Speleology of Northern Greece and for the significant guidance and consultation he provided me during the research and the writing of this thesis.

I also have to refer with much appreciation to the crucial role of the staff of Ephorate of Palaeoanthropology and Speleology of Northern Greece, who gave the permission to use the specific find and especially the conservators Vivi Bilali and Chrysa Fotiadou for their cooperation.

Furthermore I would like to thank my colleague Nikos Papas, MSc Mechanical Eng. for his help and support in the lab and mainly for his friendship.

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# 1. Introduction

## 1.1. General Review

As part of starting and promoting cooperation between the International Hellenic University (IHU) and the Ephorate ofPaleoanthropology and Speleology of Northern Greece (E.P.S.N.G.), the implementation of a pilot research project is suggested for the dimensional surveying (3D scanning) of a paleontological find and dimensional reproduction of its copies (rapid prototyping), which then will be used entirely by E.P.S.N.G. for educational and scientific purposes.

The paleontological find (28cm x 15.4cm x 3 cm) is a part of the jaw bone (Figure 1.1) of a cave bear (Ursus spelaeus)which was found in 2007 in Kastoria area.

**Figure 1.1.**The part of the jaw – bone of the cave bear, found in Kastoria.(In courtesy of the Ephorate of Palaeoanthropology & Speleology of Northern Greece)

The specific species of bear lived in Europe during the Pleistocene (2.588.000 to 11.700 years before present) and became extinct before approximately 10.000 years ago. Its name derives from the fact that fossils (Figure 1.2 – 1.3) of this species were mainly found in caves, indicating that the cave-bear spent more time in caves than the brown bear, which only uses caves for hibernation. (http://en.wikipedia.org/wiki/Pleistocene" \o "Pleistocene")

**Figure 1.2.**Skeleton fossils of a cave bear that was located and exhibited in the Bear Cave in Romania.

(http://en.wikipedia.org/wiki/File:Ursus_spelaeus_Sergiodlarosa.jpg)

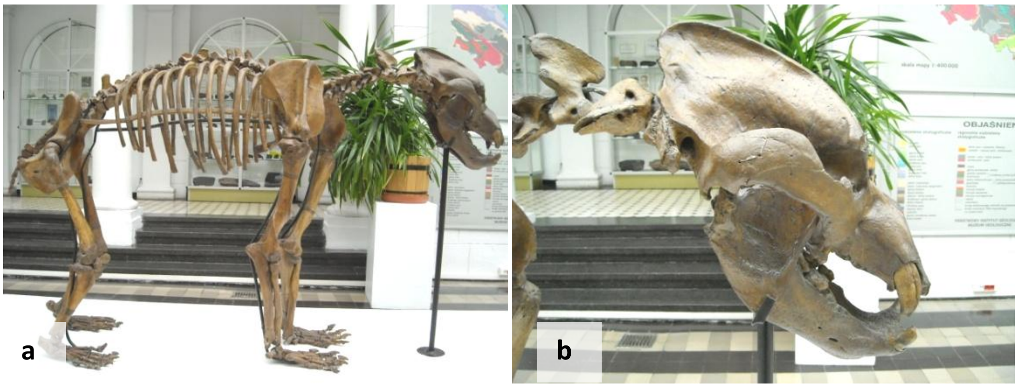



**Figure 1.3. a.**Skeleton of a cave bear and **b.**detail of its skull exposed in the Geological Museum of the Polish Geological Institute in Warsaw.

(http://commons.wikimedia.org/wiki/File:Ursus_spelaeus_skeleton.jpg
http://commons.wikimedia.org/wiki/File:Ursus_spelaeus_skull_lateral.jpg)

It was vegetarian and occasionally carnivorous. The weight of the male bears reached the 500 k. while the females' the 250k. Its length, from head to tail, could be up to 3,50m. while their height could be up to 1,70m. (http://www.spilaiodrakoukast.gr/index.php/el/to-spilaio/perografi-spilia)

The paleontological find examined in this study, had been discovered in the 'Cave of Dragon' (Figure 1.4) next to Kastoria Lake, during recovery activities.

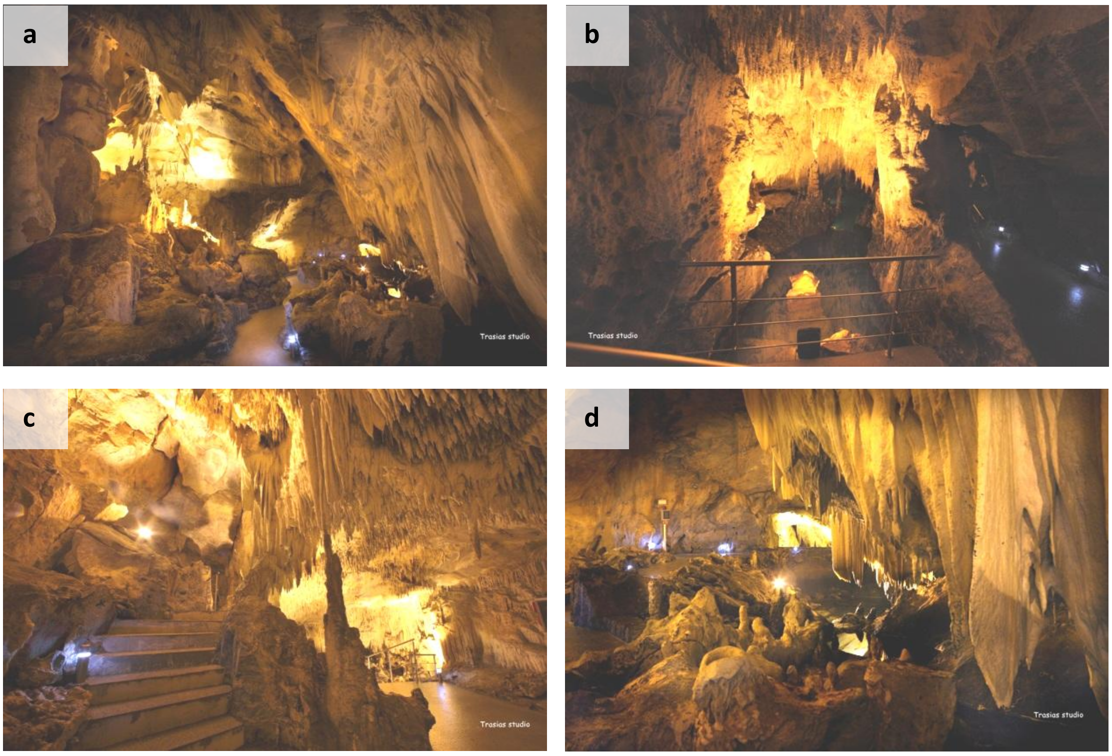



**Figure 1.4. (a,b,c,d) .** Interior pictures of the 'Cave of Dragon' next to Kastoria Lake.

(http://www.spilaiodrakoukast.gr/index.php/el/to-spilaio/photogallery)

A Juxtaposition of the examined find and the scull of a cave bear found in Siberia is displayed in Figures 1.5 and 1.6.

**Figure 1.5.**The jaw of the cave bear (Ursus spelaeus). (In courtesy of the Ephorate of Palaeoanthropology & Speleology of Northern Greece)

**Figure 1.6.**The skull of an Ursus spelaeus, found in Siberia, in Russia.
(http://en.wikipedia.org/wiki/File:Ours_des_carvernes_-_Cr%C3%A2ne.jpg)

## 1.2. Purpose

A purpose of this study is to examine the feasibility of Reverse Engineering of the aforementioned paleontological find and use Rapid Prototyping techniques in order to produce its authentic copy. The resulting copy (upon request from the Public Benefit Corporation of the Municipality of Kastoria "Oresteia" - the management authority of the Cave) will be exhibited in the location, exactly where the finding was found inside the Cave of Dragon after reconstruction and painting of its surface from the staff of the E.P.S.N.G. The exposure of the 10.000-old fossil for exhibition to the conditions of light, harsh temperatures and humidity, which exist in the Cave of Dragon, is prohibited so alternative solutions were sought. Parallel to the generation of an authentic copy, this study examines the data derived from the research taken so to potentially use them in the future in other applications and the further edit and manipulation of them.

## 1.3. Objectives

The main objective of the current work is to use a laser scanner in order to scan the fossil and to generate digital data (point cloud) which describe the highly complex geometry of the scanned object. Additionally, the research aims in the advanced processing of these digital data and converting them to the corresponding format for modeling and prototyping by materialization of the physical model. The low-cost but highly accurate “NextEngine” 3-dimensional laser scanner is used for the scanning procedure while for the rapid prototyping the 3D Systems “Bits from Bites-3d touch” and the Stratasys Mojo FDM equipment were used both capable of building up layers of Acrylonitrile - Butadiene – Styrene (ABS) plastic with dimensional accuracy up to 0.1mm. The model is formed from the molten plastic using the data from a Computer Aided Design (CAD) model. Finally, the “ScanStudioHD” the “Solidworks” and the “Axon2” software are utilised for the processing of the point cloud, the CAD modeling and the conversion to STL respectively, so to be able to transfer the digital data to the FDM apparatus and thereby to build the prototype.

## 1.4. Structure

In chapter 2 the literature review is presented. The generalized process of Reverse engineering and the two methods of Rapid prototyping are introduced along with the related topics of occlusion, fused deposit modeling and color jet printing respectively. Subsequently, the apparatus used for this research is described and a topic concerning the relationship between reverse engineering and digital heritage is highlighted.

In chapter 3, the methodology of the current research work is described analytically. The step by step approach from scanning to the generation of physical models is analyzed along with a number of pictures describing the action taken.

In chapter 4, the data are presented while a generalized discussion of the results takes place by explaining the actions taken and the choices made.

In chapter 5, the conclusion summarizes the important outcomes of this work and followed by chapter 6 where recommendations and future work are proposed, which can use the data retrieved and analyzed and continue the examination of related themes.

## 2. Literature Review

### 2.1. Preliminary Review

Three-dimensional digitization is taking an important role in the documentation of archeological findings. The recent proliferation of commercial three-dimensional digital scanning devices has made 3D scanning, and virtual and physical replication, a practical reality in the field of heritage preservation. 3D scanning produces a high-precision digital reference document that records condition, provides a virtual model for replication, and makes possible easy mass distribution of digital data. In addition to research, documentation, and replication, 3D data of artifacts are increasingly being used for museum collections storage and packing designs.

(http://www.si.edu/MCIImagingStudio/3DScanning)

An extensive project at the Technische Universität Berlin used laser scanners to digitize complete mounted skeletons and skin mounts as described by Gunga et al. 1995; Gunga et al. 1999, Bellmannet al. 2005; Suthau et al. 2005; Gunga et al. 2007; Gunga et al. 2008. Bates et al. 2009 has also employed such laser scans, albeit apparently at a lower accuracy (Hohloch, 2009).

(http://palaeo-electronica.org)

The quality of 3D scanned data is influenced by many factors, such as scanned surface color, glossiness, geometry, ambient light, scanner resolution, and proper selection of scanned segments. The laser 3D scanners are also influenced by ambient light. Preparatory phase of digitizing process includes selecting proper combination of scanner's sensor aperture and shutter time, depending on the characteristics of scanned surface (Lemeš, 2009).

(http://www.am.unze.ba)

Another application used is rapid prototyping. Scale models of bones can be produced at almost any scale, as well as molds for casting, or negatives of the bones that can serve as storage casts or as mounting racks for museum exhibition. Research Casting International used full scale 3D prints of the exhibition skeleton of the MFN Kentrosaurus to construct the armature that was used for the new mounting of the skeleton in 2007. (http://palaeo-electronica.org)

## 2.2. Reverse Engineering

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

Raja (2010, pp.2) defines engineering as the *'process of designing, manufacturing, assembling, and maintaining products and systems'.* He distinguishes the two types of engineering, the forward engineering and the reverse engineering (RE). In traditional engineering process the engineers generate physical objects and systems using engineering principles and documentation expressed as mechanical drawings, CAD models, measuring devices. In product development for example an engineer would follow a path from understanding the engineering principles related to communicating and describing the ideas or the product by sketches and mechanical drawings and then by using computerized numerical control machines the idea of the product would be manufactured and materialized.

Reverse engineering started as a product copy function introduced by the Japanese either to improve the products of their competitors or to avoid the normal design and development process. Due to their success in product development, using this method, the rest of the world accepted it and used it for achieving excellent design result. Reverse engineering is the reverse process of forward engineering. It creates a CAD model from an existing physical model. More specifically the reverse engineering delivers a CAD model from 3D points which have been obtained by the use of scanning machines.

According to Raja (2010, pp. 2), the process of digitally capturing the physical entities of a component, referred to as reverse engineering (RE), is often defined by researchers with respect to their specific task *(Motavalli & Shamsaasef 1996).* Abella et al. (1994) described RE as the basic concept of producing a part based on an original or physical model without the use of an engineering drawing. Yau et al. (1993) also defined RE, as the "process of retrieving new geometry from a manufactured part by digitizing and modifying an existing CAD model."

For a better understanding of the RE definition, the anaphora of its modern applications and the reasons it is used, is believed it is appropriate to be reported.

i) In the aircraft industry, when there is requirement for spare parts and the original manufacturer is incapable of manufacturing them.

ii) The original manufacturer might be out of work or no longer produces the specific products.

iii) It is very common in industries, especially when paper drawings were in use, this documentation to get lost or not updated parallel with the product redesigns or improvements. This had emerged the need for product development without mechanical drawings. RE provided the solution for this obstacle.

iv) One other of RE applications lies on the field of inspection and quality control where the manufactured object can be described by the RE techniques and then compared to its CAD model used for the production of the part.

v) In animation in games and movies very often the data used are generated from a sculpture or model in scale by the RE applications.

vi) The reproduction of artworks and objects of cultural heritage by scanning and collecting 3D data of the authentic ones.

vii) Many high competitive industries use the referred methodology to analyze and compare their rivals' product.

viii) Applications in architecture and construction documentation.

ix) Finally, dental and surgical prosthetics, body parts, footwear and clothing are only a few of the nowadays applications of RE(Bilalis, 2013 & Raja, 2010).

In Computer Aided Design (CAD), Computer Aided Manufacturing (CAM) and Computer Aided Engineering (CAE) the data are communicated most often by CAD models in order to direct to the physical model, product. In CAE through CAD – CAM technologies the work flow can be assumed from the CAD model to the physical one. In Computer Aided Reverse Engineering (CARE) it is the other way round; from a physical model the CAD model is derived, as illustrated in Figure 2.1.

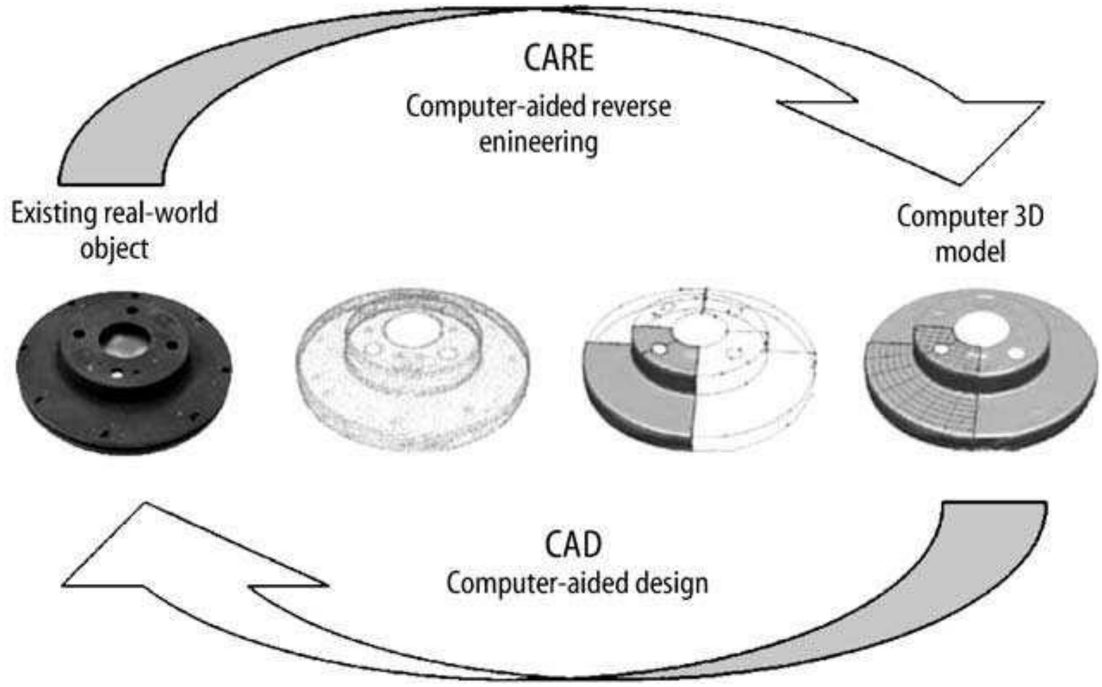



**Figure 2.1.**Computer-aided reverse engineering (CARE) process. (Raja, 2010. pp.13)

2.2.2. Generalized RE process

The generic process of reverse engineering consists of three phases as shown in Figure 2.2.The first phase is scanning. The object is scanned by 3D scanners which produce the set of points that comprise the surface of the object. There are two types of 3D scanners: the contact and the noncontact ones.

Point Processing is the second phase of RE process and refers to the elaboration of the set of points taken by the 3D scanning. Some of the actions involved with this phase are the alignment, the noise reduction, sampling and polygon meshing, resulting to a finer scanned data format.

The third phase is consisted of the Applications of geometric product development. The scanned data delivered from the second phase are converted to other formats of geometric modeling such as IGES, VDA, STL, DXF, OBJ, VRML, ISO G Code, etc. (Raja, 2010).

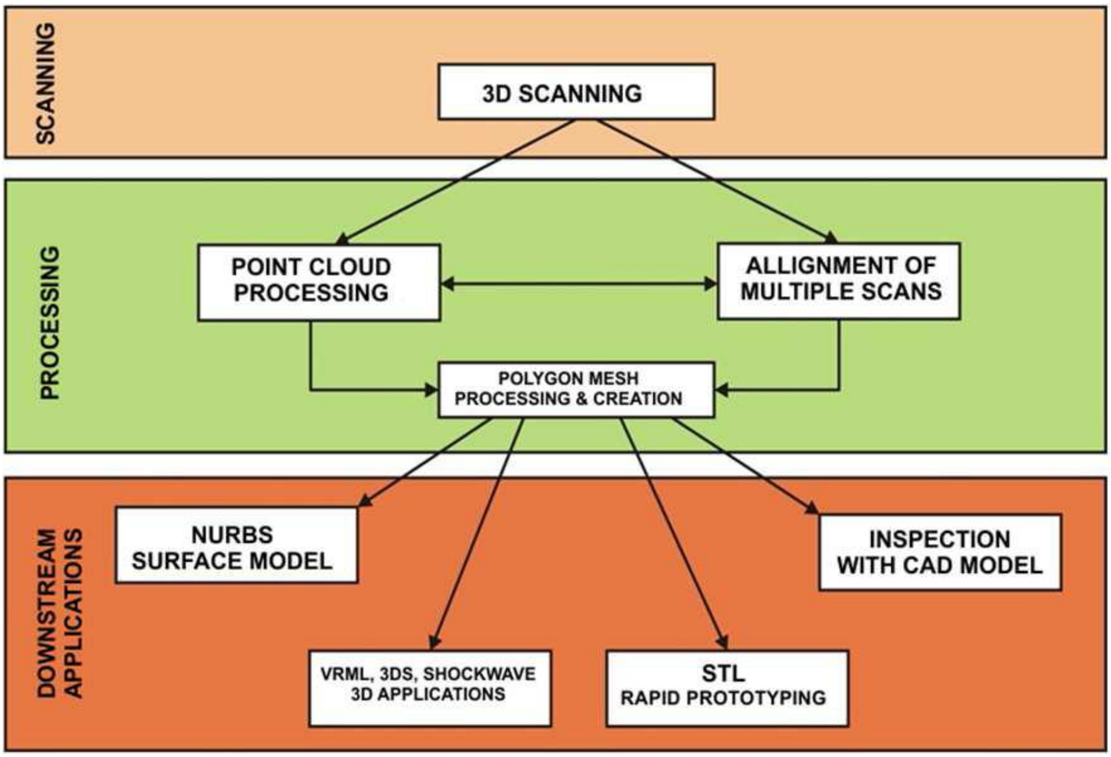



**Figure 2.2.**The generalized RE process. (Bilalis, 2013. pp.17)

2.2.3. 3D scanners – noncontact scanners – laser scanners

As previously mentioned, there are two methods for collecting the 3D – scanned data; the contact method and the noncontact method. The contact method uses contact probes which follow exactly the contours of the surface (Bilalis, 2013). These scanning machines, based in CMM technologies, (CMM-Coordinate Measuring Machines) have tolerance range between 0.01 to 0.02 mm.

The estimated time of the scanning procedure is depending on its size and the probe must deviate in order to register a point. This method can be slow while the contact pressure is maintained during the whole process. The above comment reveals the principle reason for not using the contact method for this project since it might have damaged the paleontological find and jeopardized its entity.

Noncontact methods use 3D scanners of laser, optics or sound waves sources, in order to –accurately– define the distances that specify the geometry of the scanned object. Laser scanners in particular can collect a large number of points; they have good accuracy, high speed, ability to detect colors but sensitivity to transparent or reflective surfaces.

Other big advantages of laser scanners are that they are portable equipment, easy to use by people who don't need to be as experienced as the operators of contact scanners are (Bilalis, 2013).

**Figure 2.3.** Contact scanners. (Bilalis, 2013. pp. 23)

### 2.2.4. Laser scanning Triangulation

Most laser scanners are based on the principle of triangulation method shown in Figure 2.4 and Figure 2.5. A high energy light source focuses and projects at a specified angle θon to the surface of an object. The reflection from the lighted point on the surface is sensed by a photosensitive device. Since the fixed base line length (L) between the light source and the camera is known, along with the values of angle θ, the focal length of the camera F, the position of the illuminated point P by using geometric triangulation, the position of the illuminated point Pi can be calculated with respect to the camera coordinate system (Park and DeSouza, 2005):

$$Z = \frac{FL}{P + F\tan\theta}$$

$$X = L - Z\tan\theta$$

The measurement errors in *P* and θcan be determined from the following equation:

$$\Delta Z = \frac{Z^2}{FL}\Delta P + \frac{Z^2 sec^2\,\theta}{L}\Delta\theta$$

The error in the *Z* measurement is directly proportional to *Z*2 but inversely proportional to the focal length and the baseline length.

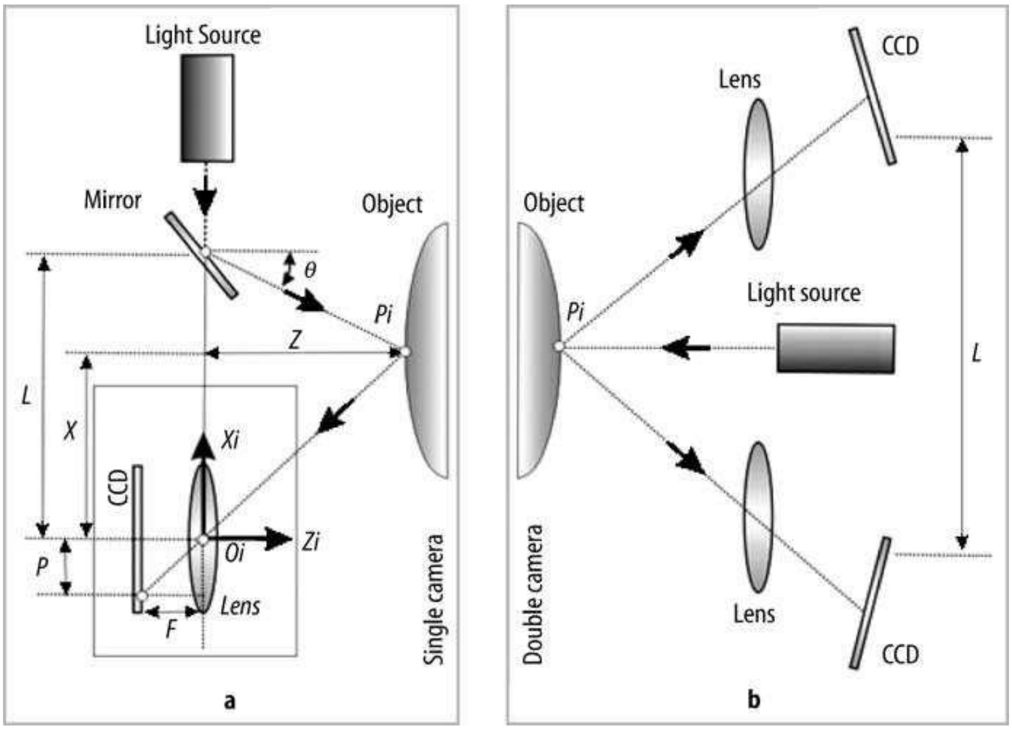



**Figure 2.4.** Triangulation methods: (a) Single and (b) double camera arrangement. (Raja, 2010. pp.38)

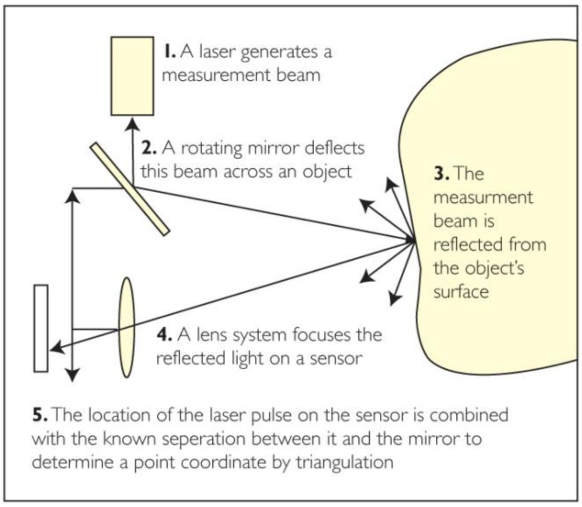



**Figure 2.5.** Single camera triangulation method. (English Heritage, 2007. pp.8)

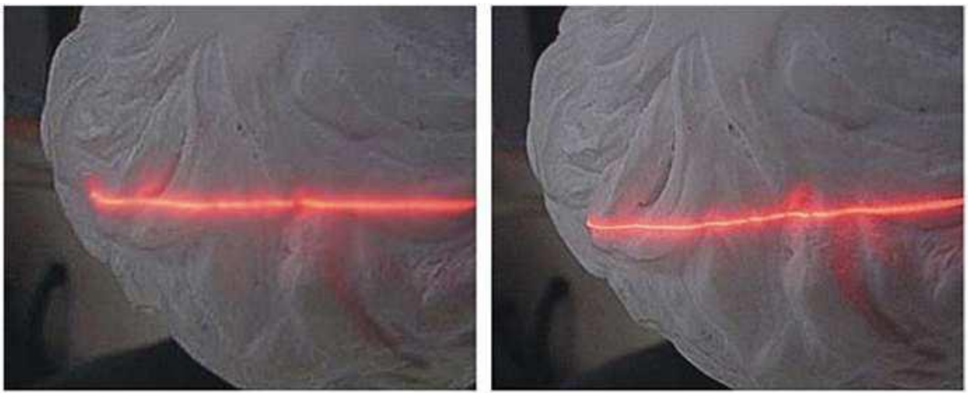


**Figure 2.6.** Laser beams of different intensity. (Bilalis, 2013. pp.44)

## 2.2.5. Occlusion

A common problem with computer vision systems that must be considered is that of occlusion. Occlusion or more specifically *self-occlusion* is referring to the problem of an object being hidden by the object itself. In most of the cases even for the simplest forms the camera can see a part of the object but not the whole of it (e.g. even a sphere hides its reverse side by its front)(Raja, 2010). Complicated morphology provokes even more complicated occlusions.

The camera and the laser cannot view simultaneously the same surfaces of the scanned object; thus self-occlusion may not allow the laser to illuminate a surface that the camera images and vice versa (Raja, 2010). The occlusion in scanning could be minimized by using several procedures but it can hardly be eliminated. In order to deal with the self-occlusion problem, the selection of multiple views is considered to be the necessary and safest solution.

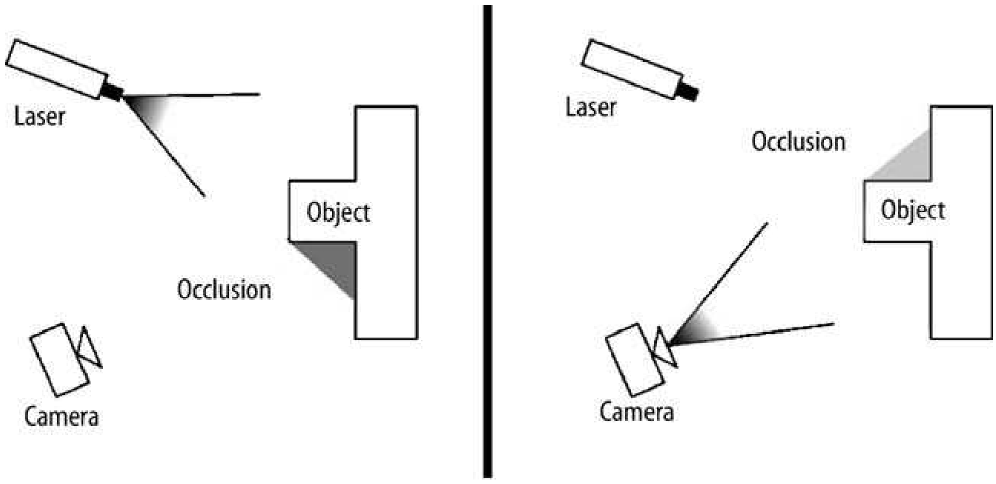



**Figure 2.7.** Occlusion in laser scanning process. (Raja, 2010. pp. 26)

## 2.2.6. Surface representation - Point cloud

The set of points in a common three dimensional coordinate system is defined as a *point cloud*. A point cloud could include a variety of number of points, which are defined by the three coordinates (x, y, z). The number of points in point clouds could range from a few up to millions.

The external surface of an object is represented by the sum of all these points. Additionally the inner part of objects could be scanned as well by some scanners using X rays.

The point cloud itself can be used for creating 3D CAD models and a series of rendering, animation, visualization and mass customization applications (Bilalis, 2013). However the point cloud has limited use in comparison with the Polygon Mesh of Surface Modelin which it needs to be transformed in order to proceed with the elaboration of the scanned data.

**Figure 2.8.** Point cloud of a relief surface. (Bilalis, 2013. pp.31)

One of the procedures of transforming a point cloud to a 3D surface is to build a network of triangles over the vertices of the point cloud (Delaunay triangulation).

### 2.2.7. Polygon Triangular Mesh

A vertex is a point in 3D space. An edge is a line segment that joins two vertices. A face is a closed set of edges and a polygon is a closed set of faces. Polygons and faces are equivalent in systems that support multi-sided faces.

Vertices edges and flat faces create a polygon mesh which can define the polyhedral shape of an object. Most of the time, the flat face is a triangle, defined by three vertices, defined by their x, y, z coordinates. The texture of a scanned object can be displayed on the created polygon mesh when required.

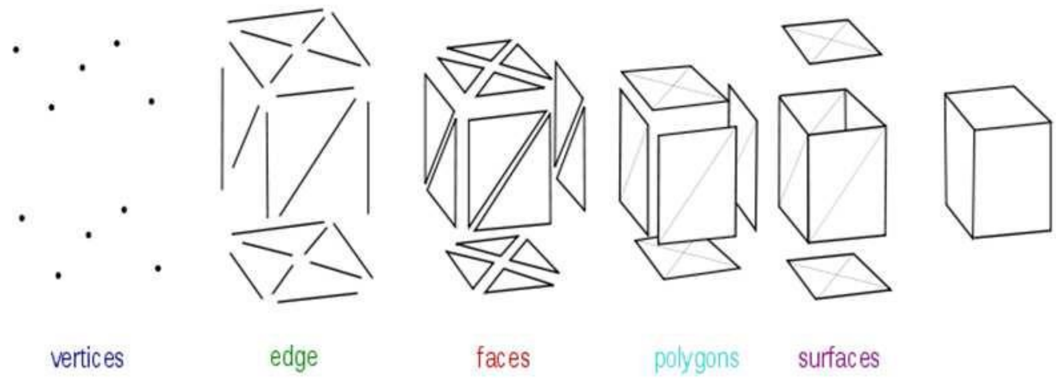



**Figure 2.9.** Vertices, edges, faces, polygons and surfaces. (Bilalis, 2013. pp.35)

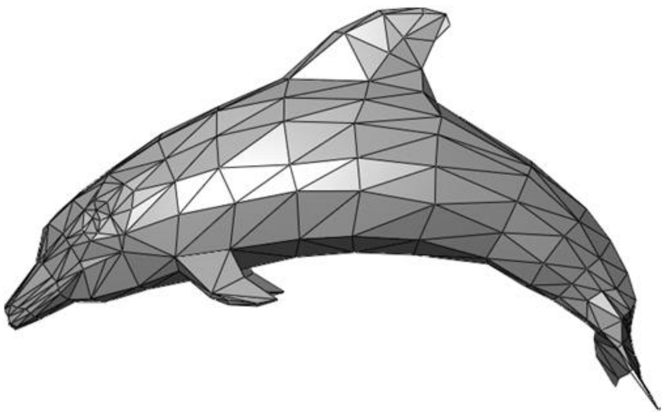


**Figure 2.10.** The extracted polygon mesh from a point cloud represents the polyhedral shape of the dolphin. (Bilalis, 2013. pp.34)

### 2.2.8. 3D Data Processing

A series of RE operations are required in order to complete the RE processing of an object (Raja 2010) as shown in Figure 2.11 which describes the four phase RE data processing with its fundamental RE operations (Figure 2.11). The four phases of the whole RE processing chain are: the points and images phase, the polygon phase, the curve phase and the NURBS surface phase. Every one of them consists of each owns operations. These RE operations, that are required, can be found in the most available RE softwares[1].

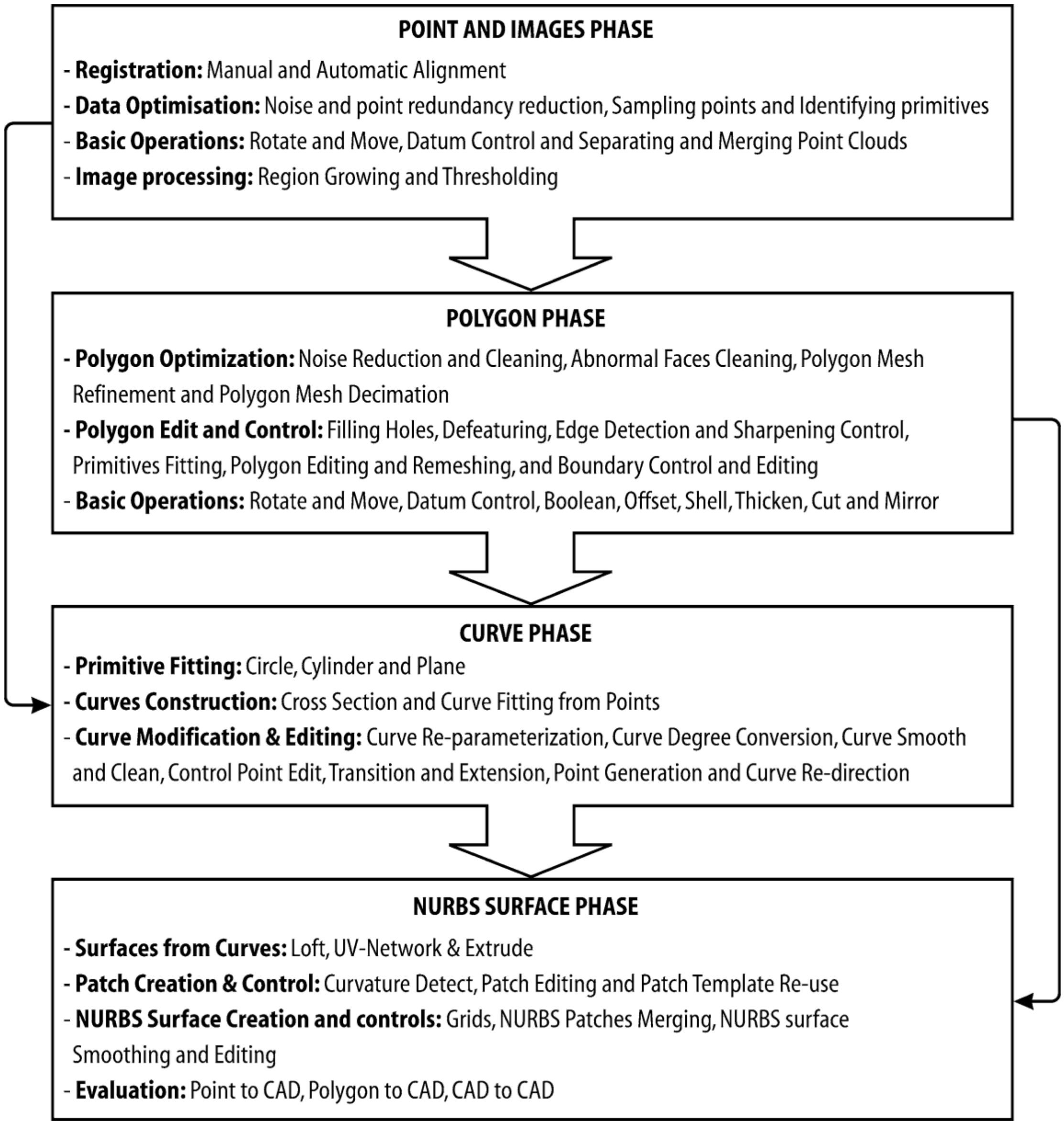



**Figure 2.11.** The four phases of the RE data processing. (Raja, 2010. pp.54)

[1] GSI Studio, Geomagics, CopyCAD, Rapidform, Polyworks, Paraform, ICEM surf, and Magics RP. Raja 2010. pp. 55

### 2.2.8.1. *Points and images phase*

*a) Data Registration/Alignment*

In order to deal with problems such as occlusion during scanning, multiple scans of the object are indicated. Usually, the point clouds taken by the multiple scans are not aligned to each other but there are cases (Scan Studio Software) that there is a possibility of automatic alignment. In any other case, common curvature areas must be recognized and orientated in a common coordinate system. This alignment procedure is based on pairing two point clouds of different scannings so they both share the same space in an x, y, z, system.

There can be either manual or automatic alignment. In automatic alignment x, y, z coordinates are used. When aligned manually, three or more pins (points) specify the collimation of the two point clouds (Figure 2.12).

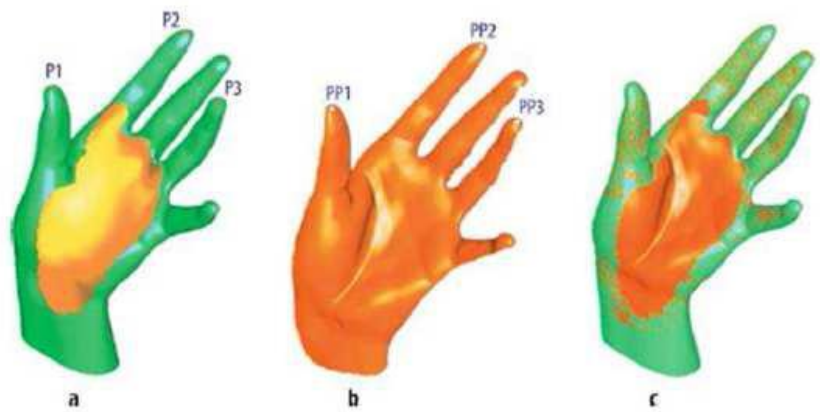



**Figure 2.12.** (a) The first point cloud with three landmark points (P1, P2, and P3). (b) The second point cloud with three landmark points (PP1, PP2, and PP3) that correspond to those of the first point cloud. (c) The resulting point cloud after registration (Bilalis, 2013 and Raja 2010).

*b) Trimming*

When scanned data are collected after a scanning operation, if not always, there is a number of points, which can be either overlapping or points with no interest. The trimming or noise reduction procedure is then needed to remove the undesired data. This noise reduction can be implemented manually or automatically.

If an automatic operation is chosen, the corresponded software allocates the point position based on statistical information data and reduces the number of points when points are too close to one another.

In some cases there is interest only for a particular area in the point cloud and then the rest of the points are deleted manually. This manual trimming is being held with the aid of tools provided from the operational software.

*c) Sampling points*

Due to multiple scans taken during the scanning operation a large number of point cloud data is collected. Sampling is the procedure which minimizes the number of points and consequently creates smaller sized files which can be manipulated easier.

There are three sampling methods according to the selection method the points are chosen and to the resulting effect:

i) *By curvature*: Points which lie on a given curvature can be chosen. Following this approach, there is a larger sampling of points which stand on regions of lower curvature and smaller sampling of points on regions of high curvature.

ii) *Randomly by total percentage of points*: The points are selected randomly or within a specified region or over the entire model and are reduced to a given percentage.

iii) *Uniformly*: The model space is equally subdivided into cells and points from each cell are getting sampled (Raja, 2010).

The sampling function is important because the point cloud becomes well-structured and easier to handle (Figure 2.13).

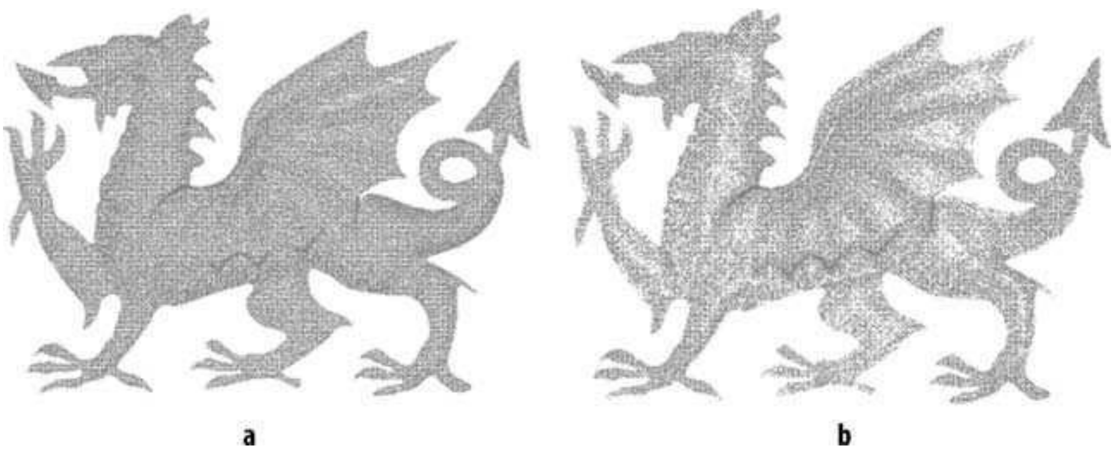



**Figure 2.13.** Point cloud before and after sampling.(Raja, 2010. pp.62)

2.2.8.2. Polygon phase

*a) Noise Reduction*

Noise reduction (Figure 2.14) in this phase is based on the same principles as mentioned at 'Trimming' in the point phase. When the polygon model is produced from a point cloud usually noise can be detected. The noise reduction occurring is based on the surface curvature and improves features such as edges and sharp corners. The result is a very good mesh and a finer polygon model.

In the polygon phase other operations executed are abnormal face cleaning, polygon mesh refinement and decimation (Figure 2.15), filling holes, defeaturing, edge detection, primitives fitting, polygon editing and boundary control. Faces which are abnormal because they share three or more edges (nonmanifold faces) or faces which share the same vertex with edges or intersect with another are treated and are getting smooth and relaxed.

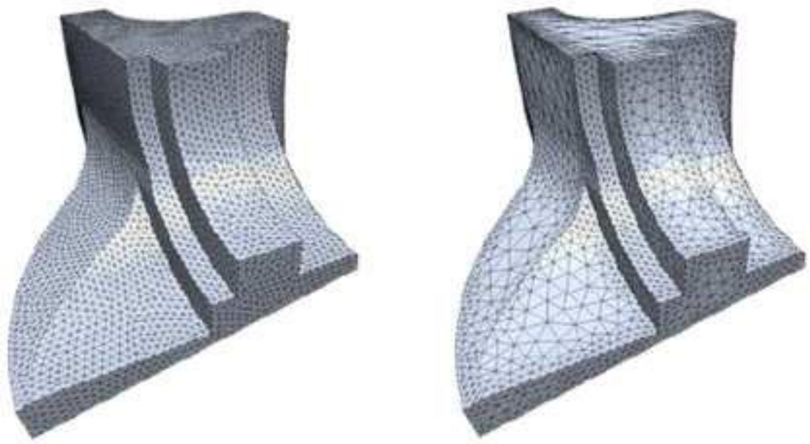


**Figure 2.14.** Polygon phase refinement. (Bilalis, 2013. pp.73)

*b) Polygon Mesh Refinement and decimation*

The polygon mesh refinement and decimation can be considered in analogy with a point mesh refinement and decimation of the point phase. New vertices can be added resulting a larger number of triangles of the polygon model. This improves the quality of the represented surface on the polygon model smothering the surface of a chosen section. The polygons can further be manipulated by being further divided in three or four triangles for every original triangle. If chosen this polygon mesh procedure can decrease the number of triangles of the polygon model without diverting from the required surface quality.

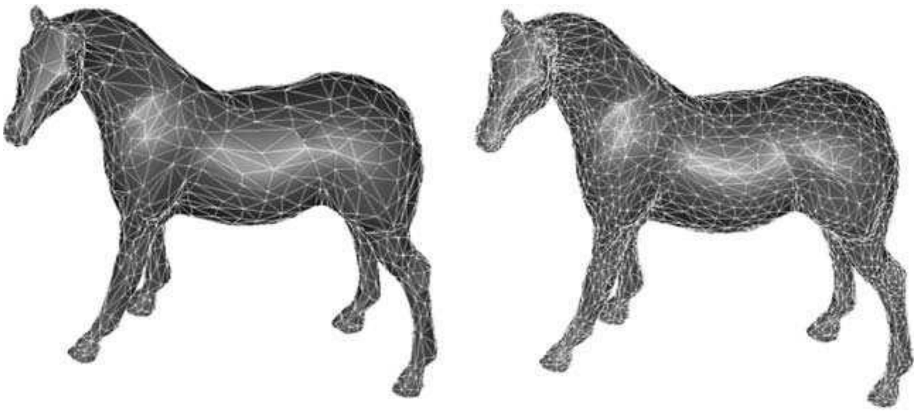



**Figure 2.15.** (a) A horse model with 2500 triangles created by applying polygon decimation to (b) the same model with 6000 triangles. (Raja, 2010. pp.63)

*c) Filling Holes*

Because of self – occlusion or other reasons there might be regions where data are not enough to create polygons; these regions are displayed as holes (Figure 2.16). A filling hole treatment generates polygon triangles to fill the hole and the polygon mesh is reconstructed so the polygon layout to be seen continuous and filled.

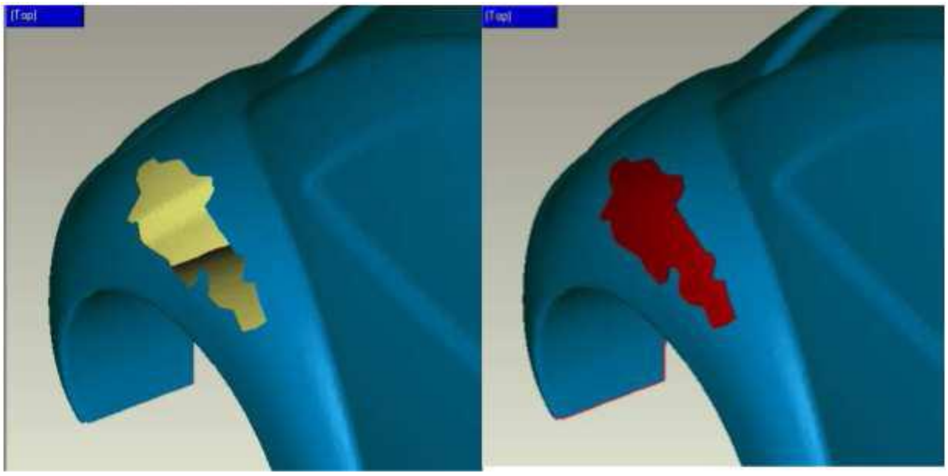


**Figure 2.16.** Filling holes in polygon mesh. (Bilalis, 2013. pp.77)

*d) Defeaturing*

This procedure refines and smoothes a selected region. The selected area showing Figure 2.17 is refitted with a new polygon surface resulting to the removal of the undesired feature.

**Figure 2.17.** The feature in selected region is deleted**.** (Bilalis, 2013. pp.78)

*e) Edge Detection*

After a polygon mesh is produced from a point cloud, the undetected edges of the scanned object are recognized and usually filleted or rounded.

*f) Primitives Fitting*

When mechanical parts are scanned in polygon phase features such as planes, cylinders and spheres can be easily recognized.

*g) Polygon editing and Remeshing*

The polygon mesh can be controlled by editing the triangles which consist the mesh and tools are available such as splitting edge and flipping edge of triangles.

h) Boundary Control

As it is indicated by the name, the boundary edges can be repaired and manipulated.

*2.2.8.3. Curve phase*

The polygon model provides the CAD entities which are used as references for the geometric modeling in CAD software. In this phase the data is editing fitting and sectioning and the more point data is available the better the curves are constructed. These CAD entities generated in this phase will be imported into the CAD packages resulting to the generation of CAD models.

*2.2.8.4. NURBS phase*

Nurbs (Non Uniform Rational B-Splines) are one geometry type used to create 3D curves and surfaces in all CAD systems (Bilalis, 2013. pp91). Most of the RE software create automatically nurbs surfaces from polygon models. The nurbs surfaces can be generated from the CAD entities delivered from the Curve phase or by surface fitting operations of polygon meshes.

2.2.9. File types

In the current research a number of different file types and formats have been used transferring the data collected from the scanning operation. This data communication was able by importing and exporting or converting in different formats into a range of software programs. A short description of some of the related file types is considered necessary at this point (Bilalis, 2013. pp.98):

'***ASCII (or ASC)*** *– an X, Y, Z point cloud file in ascii text format*

***DWG*** *- this is a native AutoCad drawing file*

***DXF*** *– "Drawing Interchange File" - a neutral version of a DWG file*

***IGES*** *– "Initial Graphics Exchange Specification" – a neutral format for exchanging CAD data between many different software programs*

***OBJ*** *– an open data format that represents the vertices of polygons*

***PLY****– it supports relatively simple description of a single object as a list of nominally flat polygons storing properties such as color and transparency, texture coordinates and surface normals*

***PRT*** *– a native CAD format for Pro/ENGINEER and NX (Unigraphics)*

***SLDPRT*** *– a native CAD format for SolidWorks*

***STEP*** *– "Standard for the Exchange of Product model data," (ISO 10303) an advanced neutral format for exchanging CAD data between many different software programs.*

***STL*** *– "Standard Tessellation Language" - a polygonal model format similar to OBJ and several others*

***WRL (VRML)*** *– "Virtual Reality Modeling Language," a polygonal file similar to OBJ, STL and several others and can include color*

***X_T*** *- a semi-neutral CAD format Converting Raw Point Clouds into CAD Formats. Two main categories*'

## 2.3. Rapid Prototyping

### 2.3.1. The method

The techniques and technologies which produce physical objects from CAD data constitute what is known as Rapid Prototyping (RP). The physical objects are made layer by layer and in some cases they do not serve on the dimensional communication of the design but they can also be patterns or mold inserts.

The term 'rapid' implies that the step from CAD data to generation of the prototype is automated and not fast as someone might think. Although sometimes the prototyping can take a long time it is relatively much shorter of the time required by the traditional manufacturing. Especially when the intended product has organic form it is easier to be produced by RP.

The generic process of RP consists of six phases (Raja, 2010. pp.100-102):

i. The generation of CAD model either by CAD techniques or by scanning an existing object.

ii. Converting the CAD data to STL format (Standard Triangulation Language). The STL format had been affiliated with the RP industry since all CAD software is capable of importing and exporting this format. The STL file is a solid visualization of the product geometry consisted of triangles.These triangles define the geometry and more triangles define in a better way a given geometry. Nevertheless high number of triangles makes larger STL files. The optimum balance between the accuracy and the number of triangles is always required.

iii. The STL file is sliced in layers with a given thickness.

iv. Creating support structures. Due to the fact that the prototype is generated layer by layer in some cases there is need of creating supports to hold the object while it is building up. The supports can easily be removed after the end of the procedure.

v. Producing the model layer by layer. This is an automatic procedure during which the PRP machine is constructing the object layer by layer of predefined thickness.

vi. Postprocessing. In some cases, when supports have been made, the product must be cleaned and separated from them. It might need extra cleaning and finishing. (Figure 2.18)

The most common RP techniques used are:

• Stereolithography

• Selective laser sintering

• Fused deposition modeling

• Three-dimensional printing

• Laminated object manufacturing

• Multijet modeling

• Laser-engineered net shaping

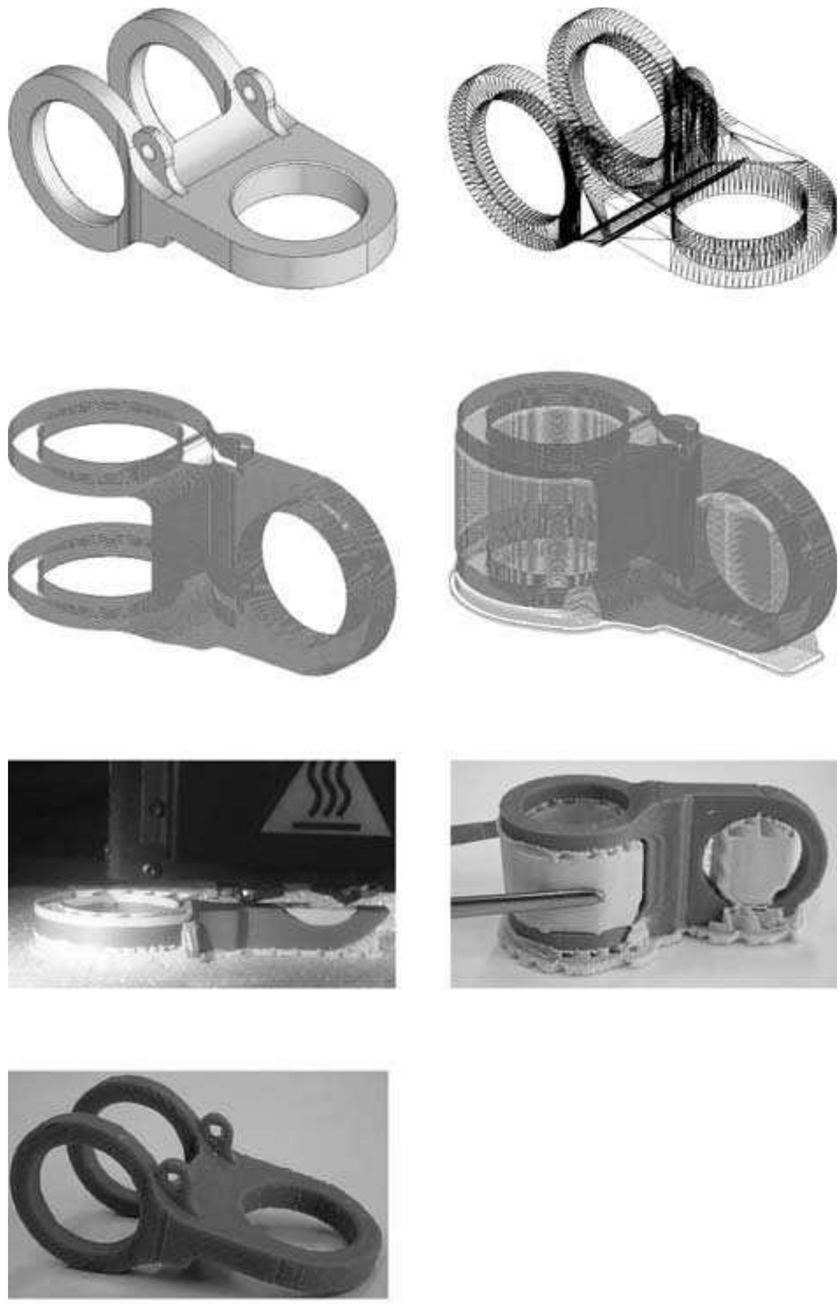


**Figure 2.18.** The basic RP process (FDM).(Raja, 2010. pp.101)

## 2.3.2. Fused Deposition Modeling

The second most widely used process of Rapid Prototyping is the Fused Deposition Modeling (FDM). A filament thread of plastic is unrolled from a coil and lead into an extrusion head. The plastic material is heated and sequentially ejected through a small snout. The molten plastic becomes solid instantly after being deposited on the plateau on which the object is built. As the extrusion head is attached to a mechanical stage, it produces one layer at a time of the requested geometry.

The whole system is incorporated into a heated oven chamber at a moderate temperature above the glass transition temperature of the polymer. As the object is built layer by layer usually the hanging parts of some layers must be supported by supports. This support material has to be removed after the generation of the model. This is the reason some of the FDM machines are able to use both ABS and PLA in order to distinguish the material of the body and the one of the support.

Some of the FDM advantages are that they are easy to operate, quiet and fast when producing small parts, providing a wide range of materials and colors and the FDM products have relatively good mechanical properties.

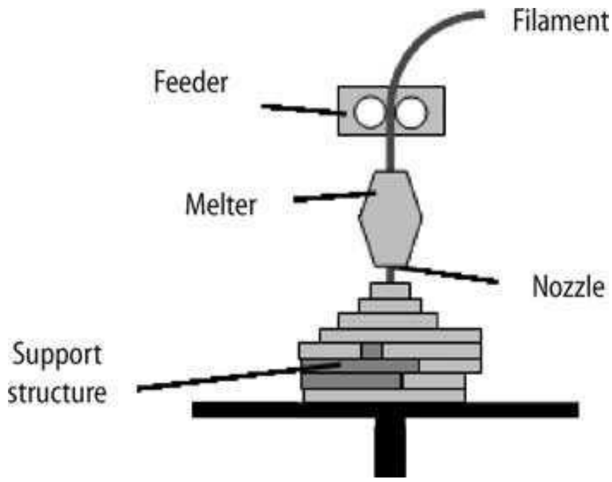



**Figure 2.19.** Schematic of FDM process. (Raja, 2010)

## 2.3.3. 3D Printing – Colored Jet Printing

"Three-Dimensional Printing was developed at Massachusetts Institute of Technology. Three-dimensional printing (3DP) builds the part in the usual layer-by-layer fashion using an ink-jet printer to eject an adhesive bonding material onto successive layers of powders. The binder is deposited in areas corresponding to the cross sections of the solid part, as determined by slicing the CAD geometric model into layers. The binder holds the powders together to form the solid part, while the unbounded powders remain loose to be removed later. While the loose powders are in place during the build process, they provide support for overhanging and fragile features of the part. When the build process is completed, the part is heat treated to strengthen the bonding, followed by removal of the loose powders. To further strengthen the part, a sintering step can be applied to bond the individual powders." (Groover, 2013. pp. 759)

The powders are made of ceramic, metal or cermet and the binders are made of polymeric or colloidal silica or silicon carbide.

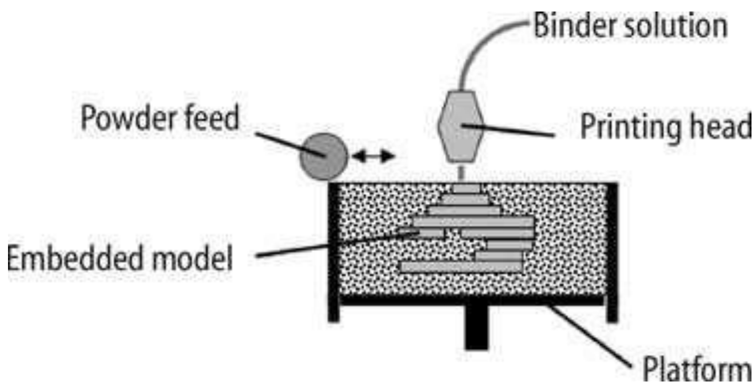



**Figure 2.20.** Schematic of the 3-D printing process. (Raja, 2010)

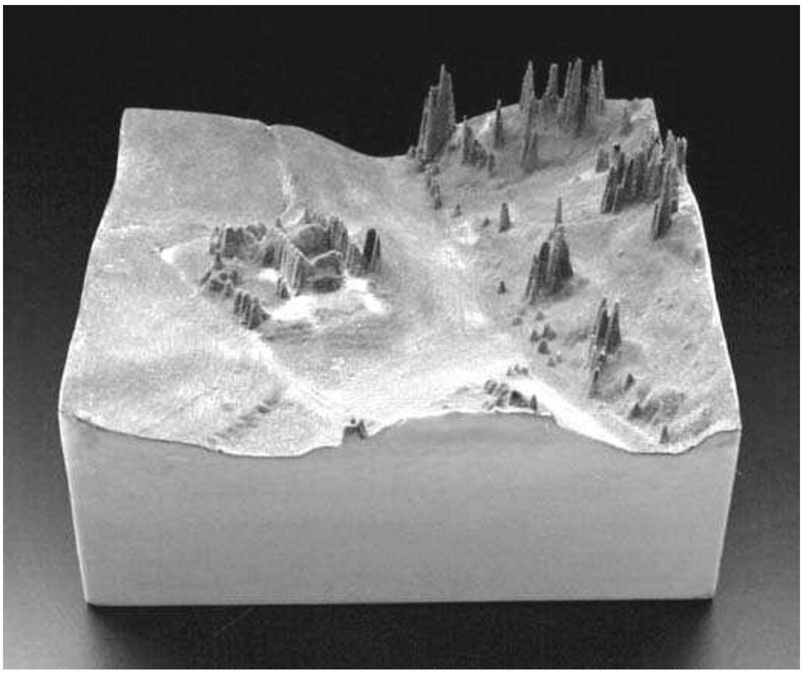


**Figure 2.21.** 3-D printed landscape. (Raja, 2010)

## 2.4. Apparatus description

### 2.4.1. Nextengine scanner – Scanstudio description

Since the turn of the millennium, scanning technology has gone from an exotic application to a realistic option for recording archaeological sites and objects. Though the hardware and software remain relatively expensive, use of the technology through rental or use agreements has put it within the reach of many archaeological projects. As scanning technology has matured, archaeology has become a viable area of competition for technology manufacturers. This was evident in the vendor display area of the Computer Applications in Archaeology (CAA) 2007 conference in Berlin. The displays were dominated by scanning companies offering hardware, software and services.

The NextEngine Desktop 3D Scanner scanner contains two arrays of four solid state lasers, two 3.0 megapixel cameras, and two lights for image capture. The arrayed lasers and sensors use NextEngine MultiStripe Laser Technology and synchronous RGB color texture capture to produce digital models with textured surfaces. The scanner is complemented by a rotary servo positioner, which is auto-incremented under software control. Separate power is required for the scanner, which is connected to the computer and turntable with USB 2.0 cables.

Objects are held in front of the scanner by the positioning plate which can accommodate objects weighing up to twenty pounds and measuring up to 8 inches in diameter and 11 inches in height. Larger objects can be scanned in part, composite captured, and assembled in the scan alignment software.

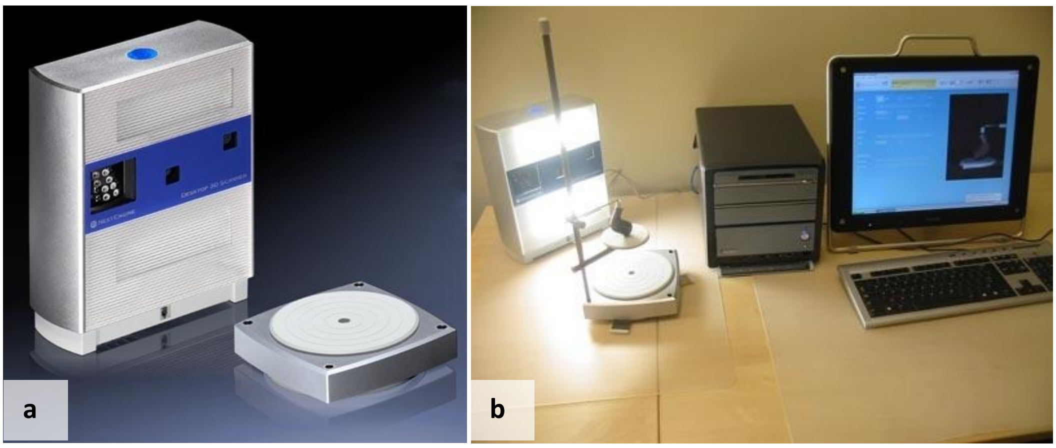



**Figure 2.22. (a-b).**Pictures of Nextengine laser scanner. (nextengine.com)

The ScanStudio software provided has three purposes: to focus and define the scan parameters, to align multiple scans, and to post-process aligned scan data. The software interface has been designed to support the typical scan project workflow from left to right across controls located at the top of the screen. Individual scans appear as thumbnails across the bottom. The first controls available invoke the camera, scan density and intensity controls.

Optimal scanning of an object requires some experimentation. The software and hardware support experimentation with short scan times, readily available scan results and scan controls that are easy to read and manipulate. Multiple views of the object also provide feedback on scan density and color. The scanned object can be seen with textured surface, surface, mesh and scan points.

Performance Specifications:

- Object Size: No preset limit. Objects larger than field can be composite captured with supplied software.
- Field Size: 5.1" x 3.8" (Macro) and 13.5" x 10.1" (Wide)
- Resolution: 200 DPI in Macro Mode and 75 DPI in Wide Mode
- Texture Density: 400 DPI in Macro Mode and 150 DPI in Wide Mode
- Dimensional Accuracy: + or - 0.005" in Macro Mode and + or - 0.015" in Wide Mode
- Acquisition Speed: 50,000 points/sec throughput, two minute per scan of each facet
- Typical Datasets: Typical small models are 250,000 points after processing

### 2.4.2. 3D touch BFB FDM printer

BFB 3D Printer has evolved from the Reprap Project at Bath University. It builds up layer of either PLA or ABS plastic based on FDM technology. The Axon2 software is also provided for converting the 3D design into BFB files. It prints objects of approximate directions 8 x 10,8 inches. It can print with minimum layer thickness of 0,1 mm.

**Figure 2.23.** A picture of 3D touch BFB Printer. (www.bitsfrombytes.com)

2.4.3. Mojo FDM machine

Mojo is based on FDM technology building models in ABS thermoplastic. It prints in minimum layer thickness of 0,007 inches = 0,178 mm.

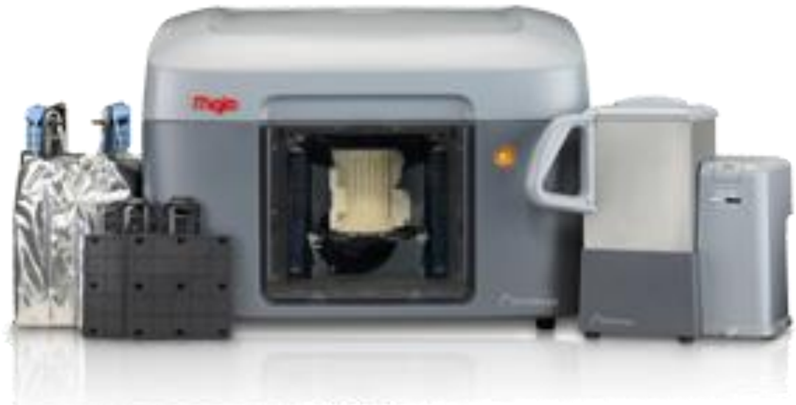


**Figure 2.24.** Picture of Mojo FDM Printer. (http://www.stratasys.com/3D-Printers/idea-series/mojo#sthash.WpFqbe68.dpuf)

2.4.4. Project 860 Pro CJP Printer

Although the Pro CJP Printer is not included in the apparatus used in this study it is mentioned because it is one of the best representatives of CJP Technology. As it can be seen next in discussion and conclusion, this printer would be undoubtedly the ideal choice for importing the PLY files generated to deliver a high quality exact copy of the scanned object.

Project 860 Pro CJP Printer can create parts from a full 24-bit palette of colors, resulting in multiple color prototypes.

### 2.4.5. Software used

#### *2.4.5.1.* Solidworks

SolidWorks is a 3D mechanical CAD program that runs on Microsoft Windows and is being developed by Dassault Systèmes SolidWorks Corp. It is a -based solid modeler, and utilizes a parametric feature based approach to create models and assemblies.(http://en.wikipedia.org/wiki/SolidWorks)

Features refer to the building blocks of the part. They are the shapes and operations that construct the part. Shape-based features typically begin with a 2D or 3D sketch of shapes such as bosses, holes, slots, etc. This shape is then extruded or cut to add or remove material from the part. Operation-based features are not sketch-based, and include features such as fillets, chamfers, shells, applying draft to the faces of a part, etc.

The features are used for editing and manipulation IGES and CAD files generated from the data process phase.

#### *2.4.5.2.* Axon2

Axon2 converts all STL files into print files for all BFB printers. The BFB files produced are imported to the FDM machine for the materialization of physical models. Axon2 is also used to set up the operational parameters of the 3D Touch Printer such as the material, the temperature and the layer thickness of the filaments.

## 2.5. RE and Digital Heritage

Reverse engineering more than any other method of producing digital documentation and exacting authentic copies is applied these days gradually on the field of cultural heritage. There can be mentioned plenty of cases of cultural heritage objects being reversed engineered or at least 3d digitized by 3d scanners. The generated scanned data have been used for digital archiving, virtual restoration and visualization, physical restoration, implementation of authentic copies. A few examples, that can be mentioned, are the synthetic modeling and reverse engineering of the four horses of the basilica of San Marco in Venice (Figure 2.25), the 3d documentation of the upper Paleolithic cave of Parpallo Cave, the virtual 3D reconstruction of the east pediment of the temple of Zeus at Olympia (Figures 2.26 – 2.27), pottery analysis with the aid of laser scanning (Figure 2.30) etc.

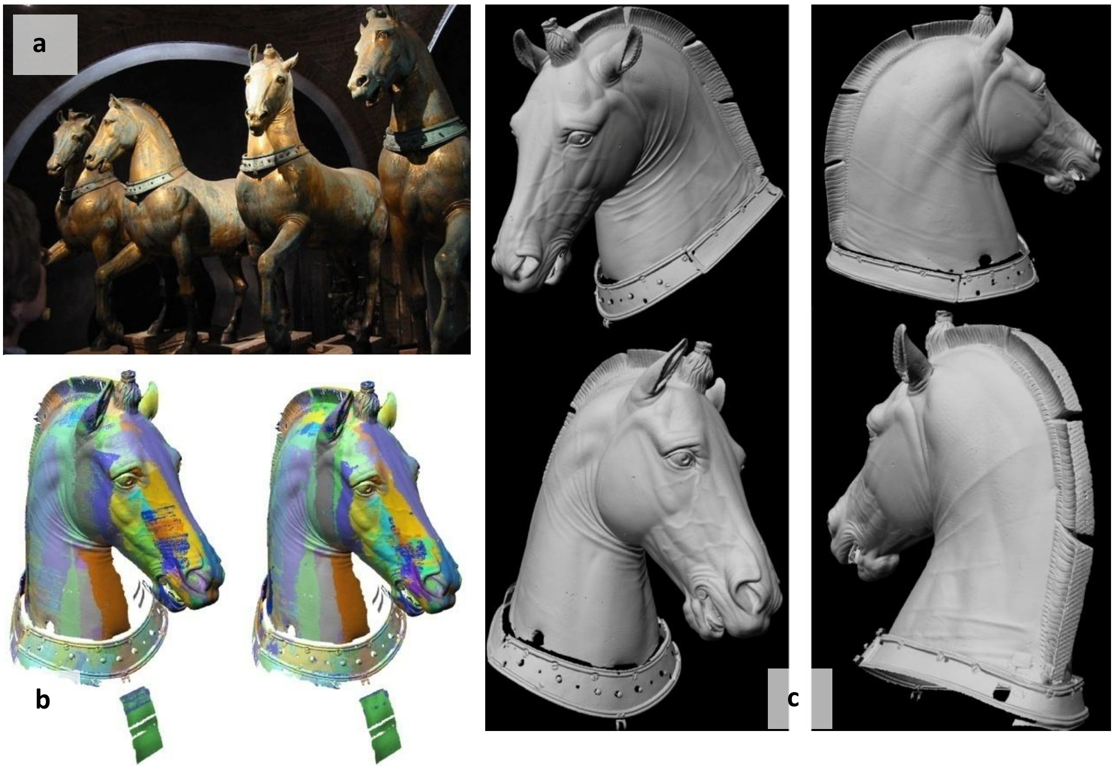
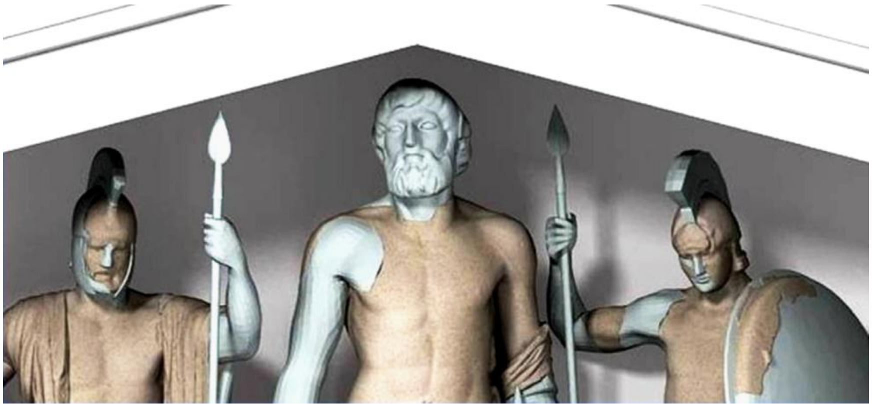



**Figure 2.25. (a)** The four Venice horses of the basilica of San Marco, **(b)** the aligned model and the same model after overlap reduction of the number of the points, **(c)** views of the processed model (Fassia et al. 2007)

**Figure 2.26.** Scanning the fragments of the east pediment of the temple of Zeus at Olympia. (Patay-Horváth. 2013).

a



b

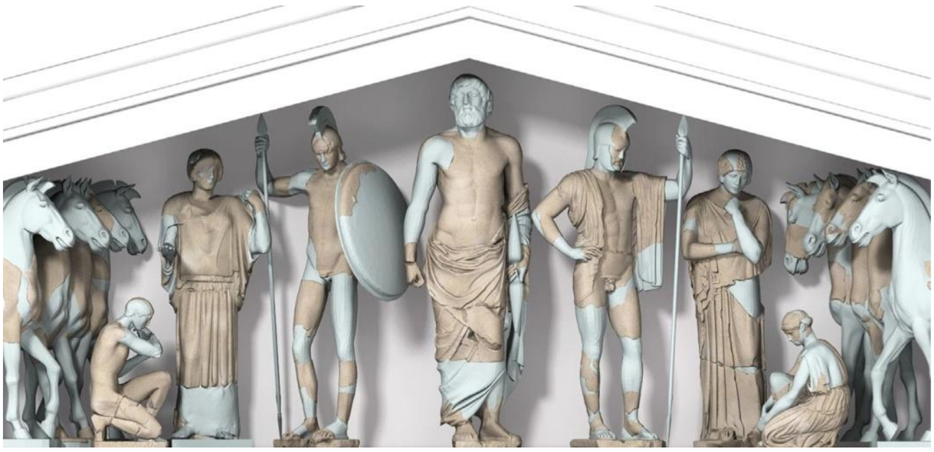


**Figure 2.27. (a,b)** Twoof the final virtual 3D processed modelsof the east pediment of the temple of Zeus at Olympia(Patay-Horváth. 2013).


**Figure 2.28.** 3D Scanning. (a, b) 3D scanning in situ of the artifact (c - d) Data scanned under processing. (Li et al. 2010)

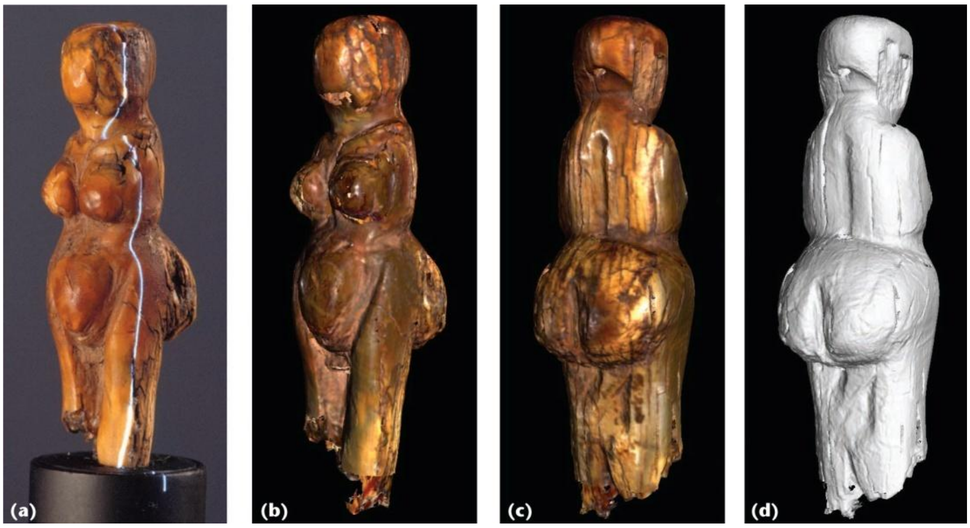



**Figure 2.29.** Palaeolithicfigurines.(a) The ArmlessLady scannedwith color laser, (b) (c)Renderings ofthe shape andcolor model, (d) A shadedview of thegeometryenhances surfacedetails. (Godin et al. 2002)

Laser scanning in particular is very popular documentation method since it delivers high numbers of data without contacting the sensitive from the age, archaeological or paleontological findings.

Modern museology is more than ever interested in 3d digitization and reverse engineering not only for restoration purposes but for enriching the exhibitions and exhibits in order to extend to the public through new technologies. Additionally the museums are expected to be self-financed and for that reason along, improvements are required concerning their promotion and advertisement through social media and internet.

Reverse engineering plays already a very decisive part in reference to the popularity of visiting cultural heritage museums adding value to the product and to the experience of guests.

a

b

c

**Figure 2.30. (a,c)** 3D models derived from triangulated point clouds of shreds of pottery from various sites and periods of a large pilot project, where 3d scanning technology was used (Avshalom Karasik , Uzy Smilansky. 2008).

Finally, focusing on Modern Paleontology, plenty of case studies and literature had been found relating 3d laser scanning applications to recent revelations regarding both paleontological trace and body fossils. According to Belvedere et al (2010) a laser scanner had been used to generate a 3d digital model of a slab found from the Middle Jurassic of Msemrir (Morocco). That new approach allowed detailed description of the specimen and identification of new footprints on the surface.

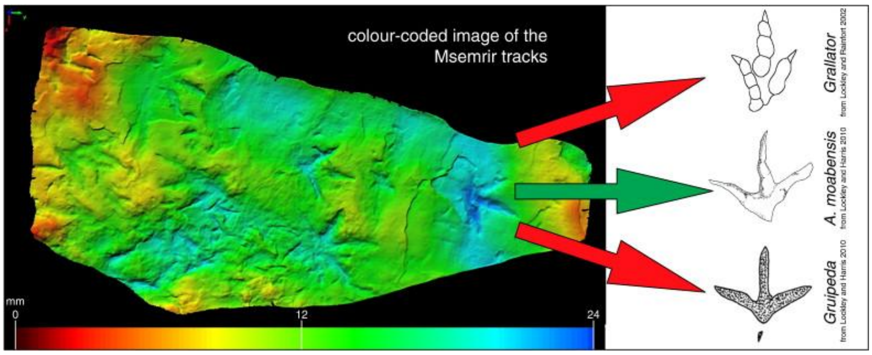



**Figure 2.31.** 3D models derived colored-coded image of Msemrir tracks.

# 3. Methodology

## 3.1. Introduction

In this chapter the methodology of work for the current research is presented. This step by step approach was derived from the literature review described previously and from the logic sequence exported from the software interface.

## 3.2. Scanning

The research started with the scanning of the specimen by the use of NextEngine Laser scanner. The set up of the scanner was set in '*Wide mode*' meaning that the scanned object was placed approximately 17 inches from the scanner achieving accuracy of 0.015" and field of view 10x13''. The scanned object was placed on different positions in order to overcome the phenomenon of self-occlusion (Figures 3.1 – 3.2).

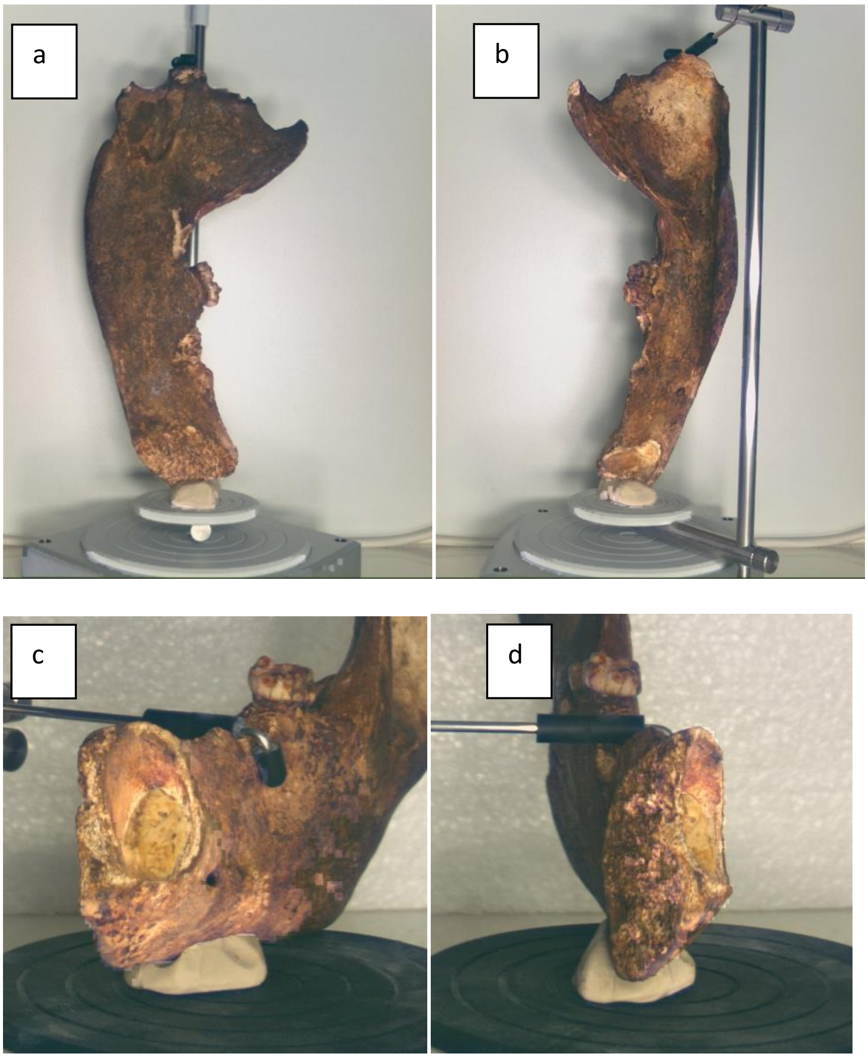



**Figure 3.1. (a,b,c,d)** Different positioning of jaw-bone during scanning.

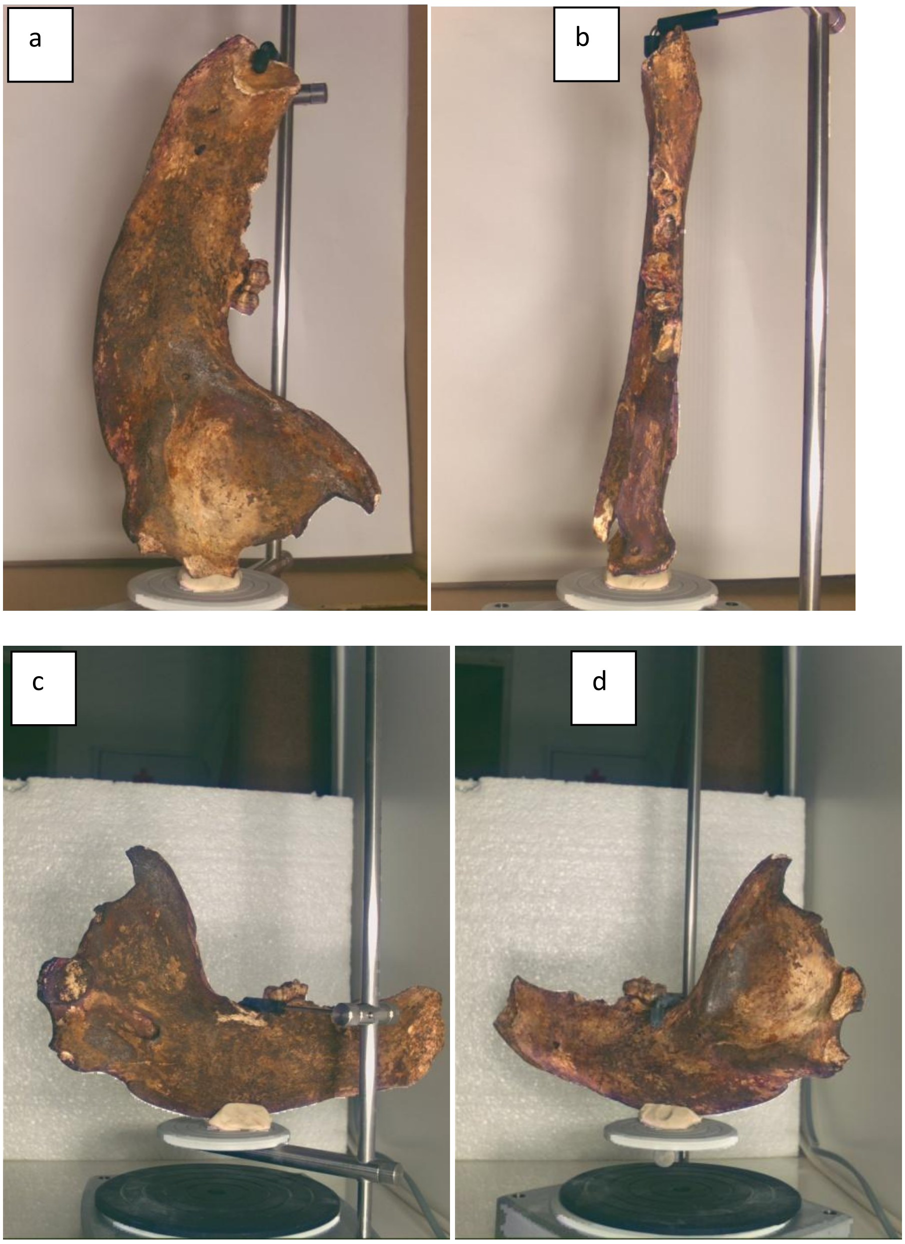



**Figure 3.2. (a,b,c,d)** Different positioning of jaw-bone during scanning.

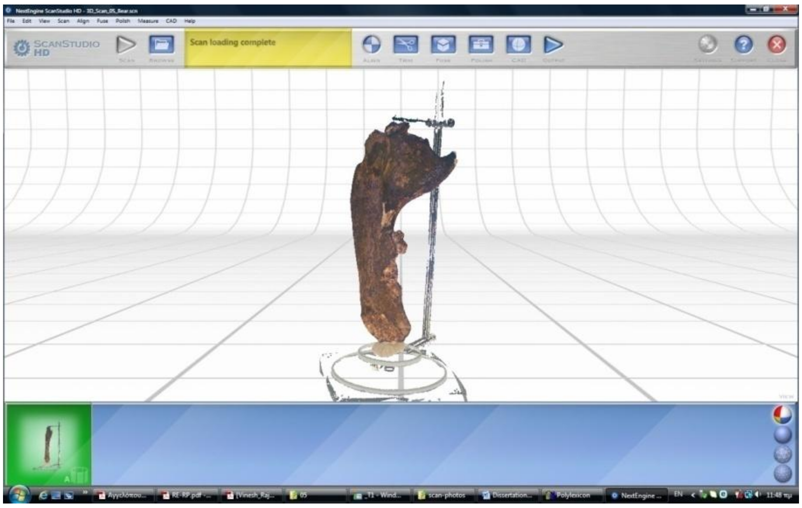


**Figure 3.3.**Point cloud display after scanning.

## 3.3. Generation of point clouds

The result of scanning was the generation of point clouds. The produced point clouds were displayed each time on a window of the scan studio software as shown in Figure 3.3. The point registration revealed the level of effectiveness of each scan and helped to the selection of the most successful scans. Four scan families were chosen to be used for the continuing of the study.

A short description of the scan families and of the treatment they had undertaken is necessary at this point, for the better understanding of the data process phase followed:

a) The scan family named SCF1 was consisted of 10 scans of the scanned object in the 360 mode, meaning that the turn base had been turning for 36 degrees 10 times making a 360 degree scan. The point clouds generated after each of the scans were automatically aligned. The resulting point cloud was displayed as shown in Figure 3.4.

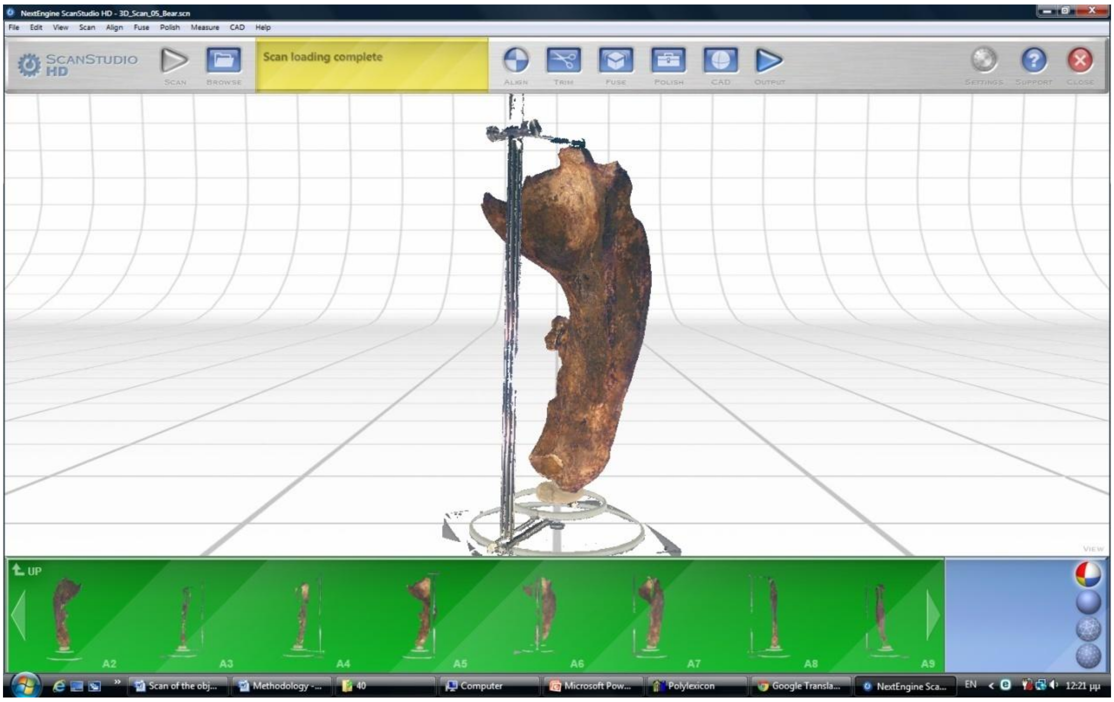



**Figure 3.4.**Scan Family SCF1.

b) The scanned family named SCF2 (Figure 3.5) was set up as a bracket mode of three scans, focusing at the one end of the jaw-bone that could not be ''seen'' from the laser or the CCD camera during the previous placement of the object on the turn base.

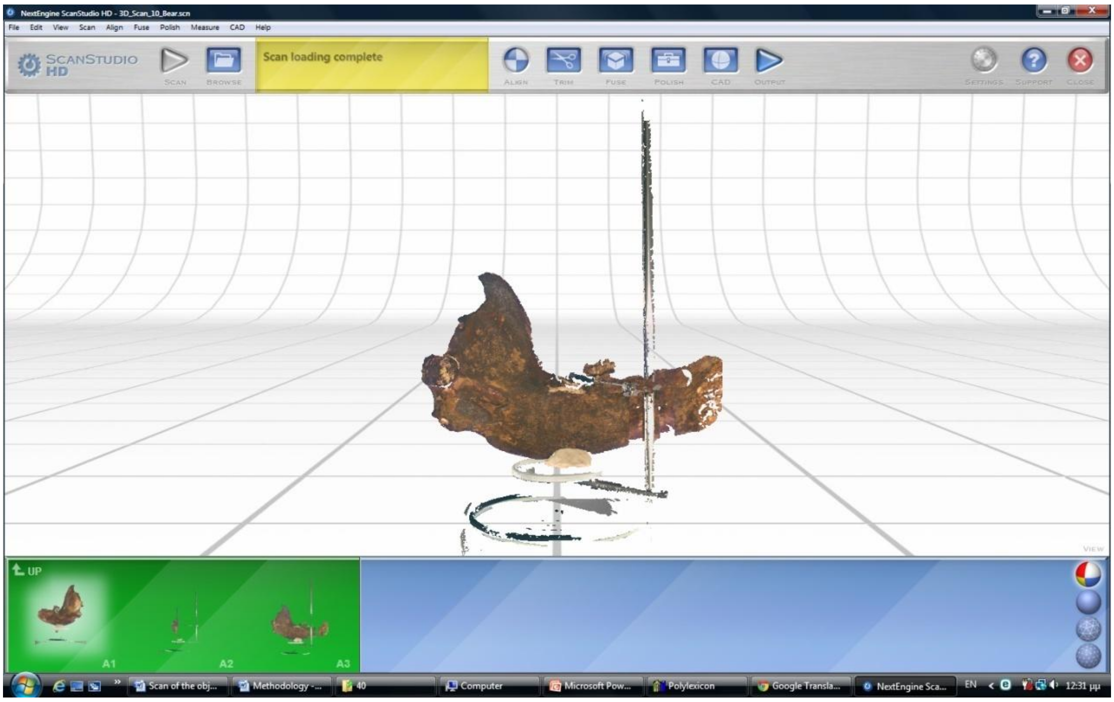



**Figure 3.5.**Scan Family SCF2.

c) Similarly the scanned family named SCF3 (Figure 3.6) had as target of scanning the other end of the jaw. A that time the method of taking manually single scans after turning the turn base was selected. That was done for a better control of the procedure and of the scanned data collected due to the complexity of the geometry of hat part.

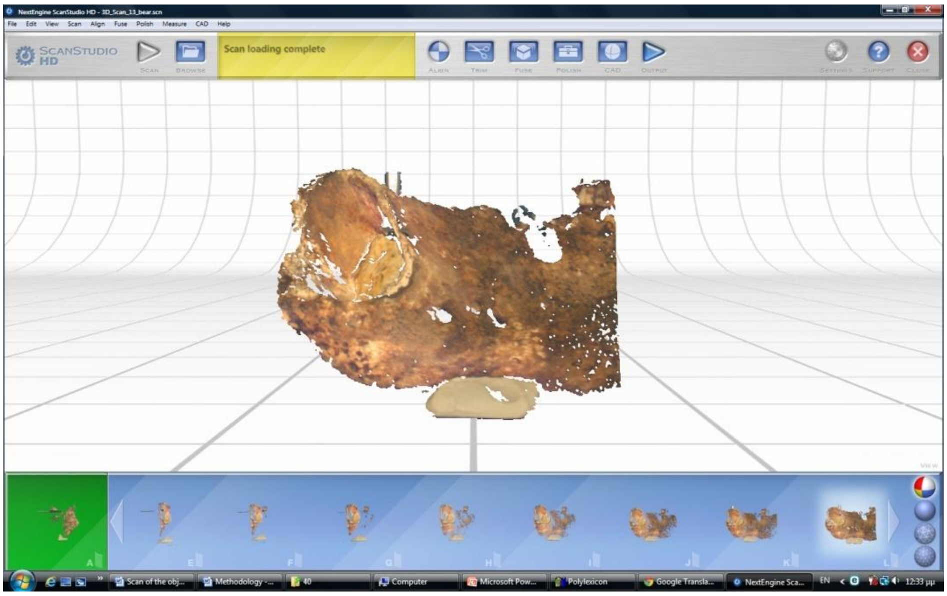



**Figure 3.6.**Scan Family SCF3.

d) Finally for the scan family named SCF4 the object was placed 180 degrees upside down than the SCF1. Twelve scan had been taken in 360 degree mode, one scan every 30 degrees turn of the turn table.  The generated point clouds where automatically aligned as shown in (Figure 3.7).

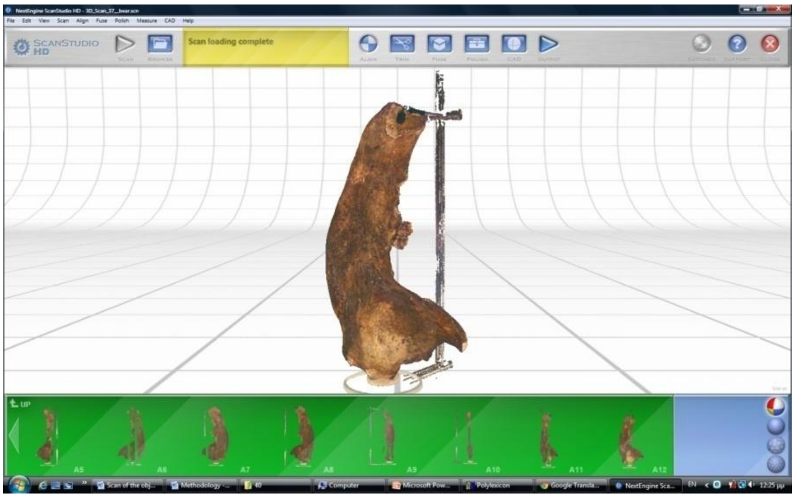


**Figure 3.7.**Scan Family SCF4

### 3.4. Scan data process

The scan data were processed initially with the aid of Scan studio software.  More specifically, the actions taken were trimming, aligning, volume merging, remeshing, holes filling and data simplifying. Trimming or noise reduction was executed initially for each of the point clouds of the referred scan families. The manually alignment had followed producing one point cloud.

The volume merging, remeshing, hole filling and data simplifying was achieved by the use of tool FUSE of the related software (Figures 3.8 – 3.10).

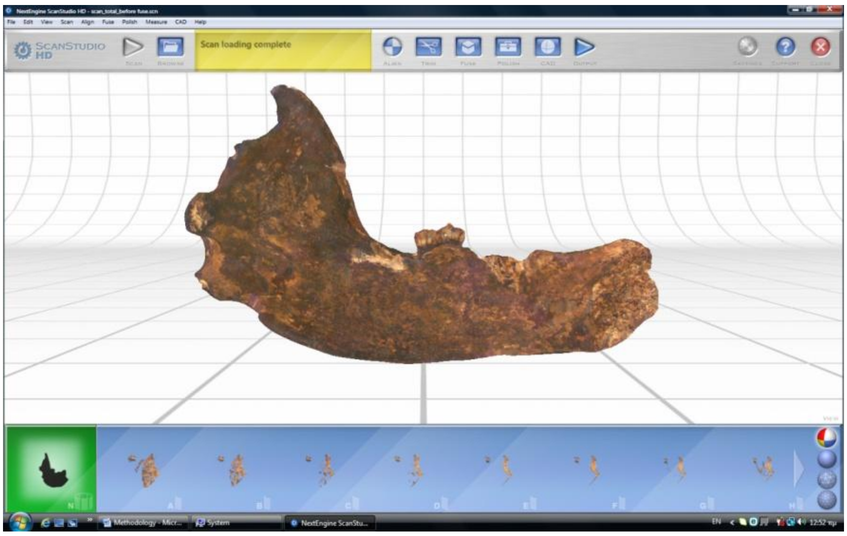


**Figure 3.8.** Colored vie of polygon mesh after fusing in ScanStudio.

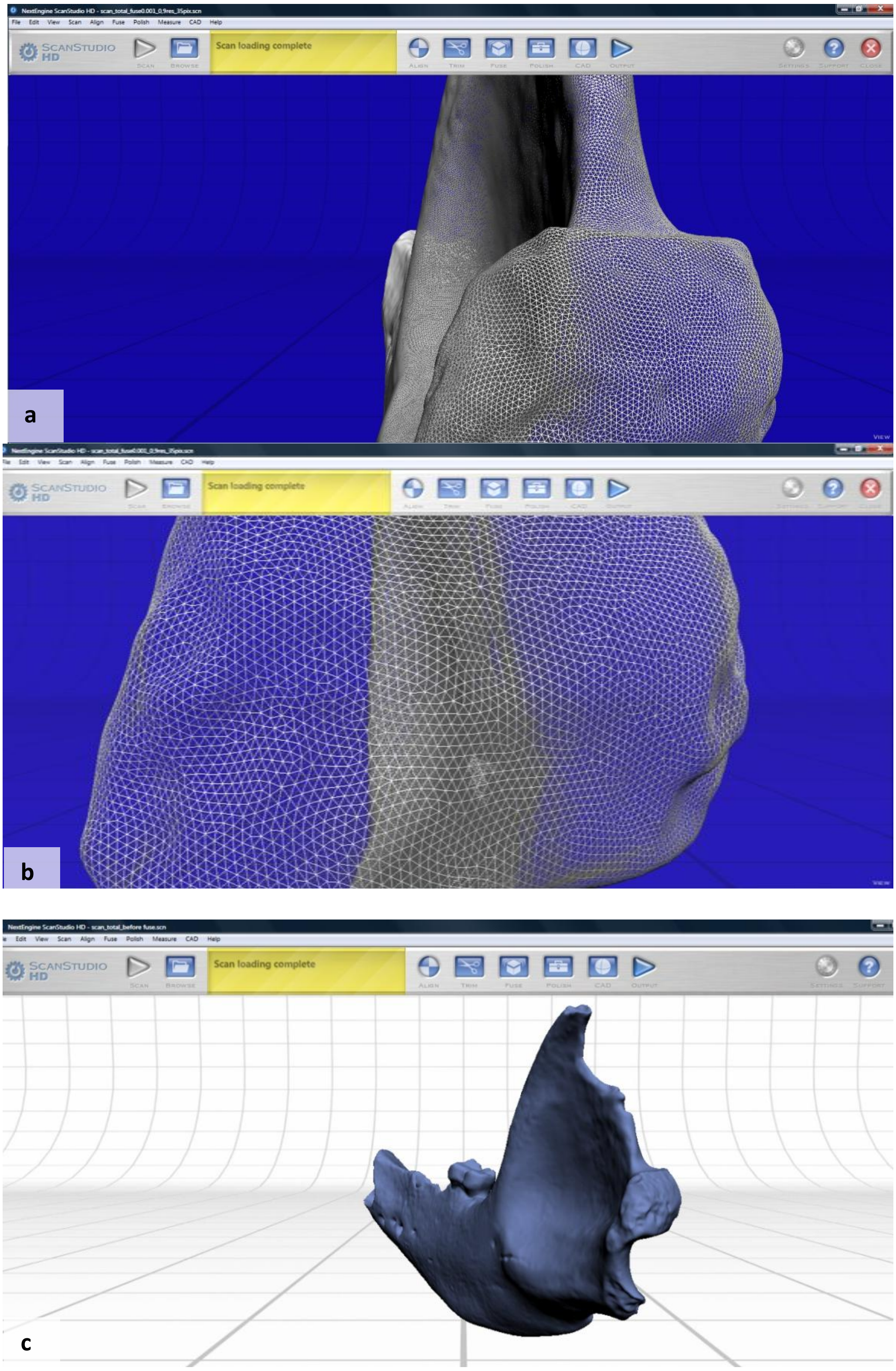



**Figure 3.9. (a)** Magnification of mesh display after fusing (back view). **(b)** Further magnification of mesh (back view). **(c)**Shaded view of polygon mesh after fusingin ScanStudio (back view).

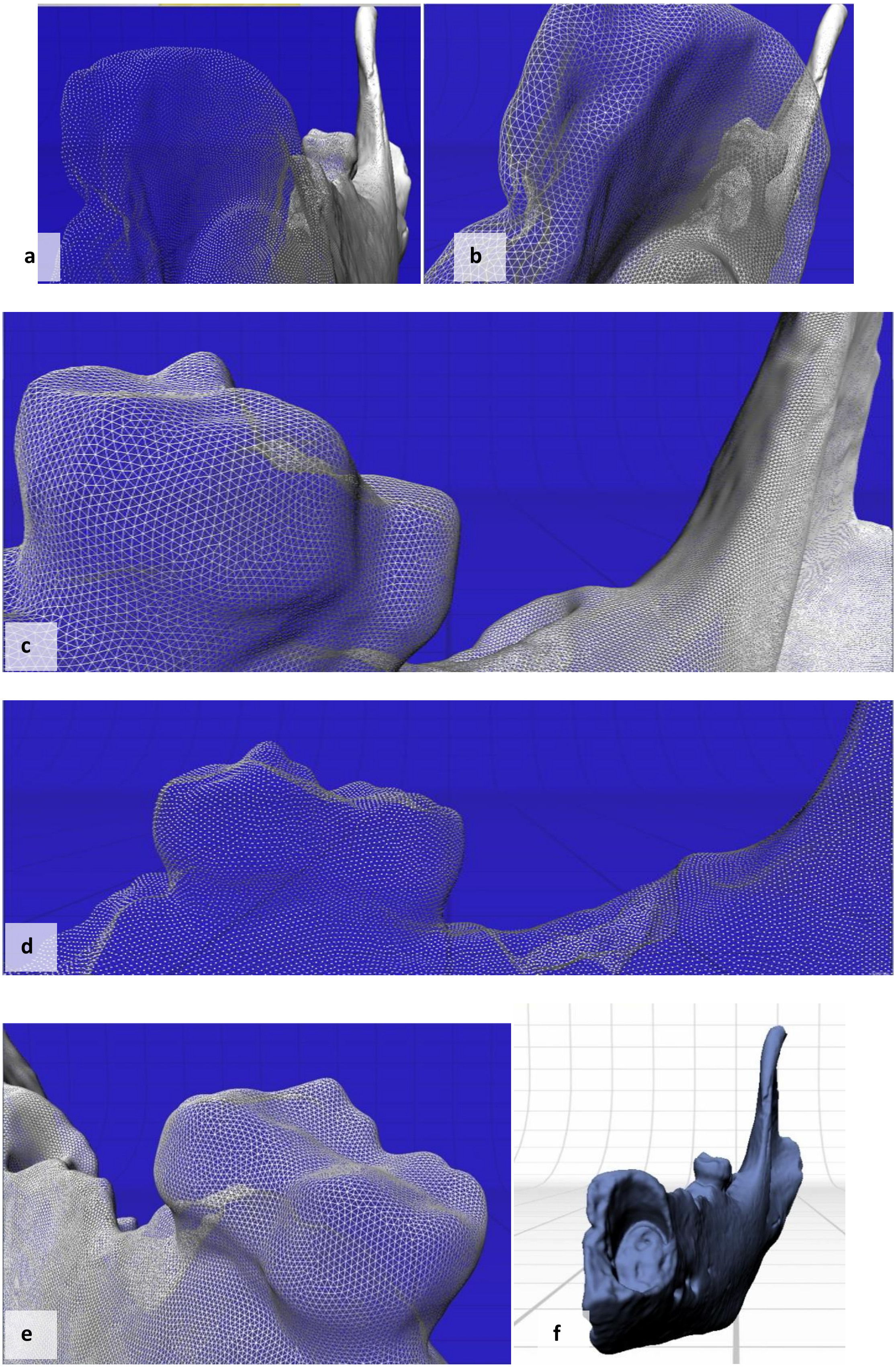



**Figure 3.10. (a)** Display of mesh after fusing (front view) **(b)**Magnification of mesh (front view) **(c)**Mesh display of tooth after fusing **(d)**Detailed view of point cloud after fusing (tooth)**(e)** Mesh display of tooth after fusing (turned view) **(f)**Shaded view of polygon mesh (front view).

### 3.5. Exporting Scan data

The collected data (Polygon mesh) were exported as STL files for further processing.

### 3.6. Importing to corresponding software for optimization

The STL files composed in the previous phase were imported to corresponding software for optimization, which could provide ulterior development.

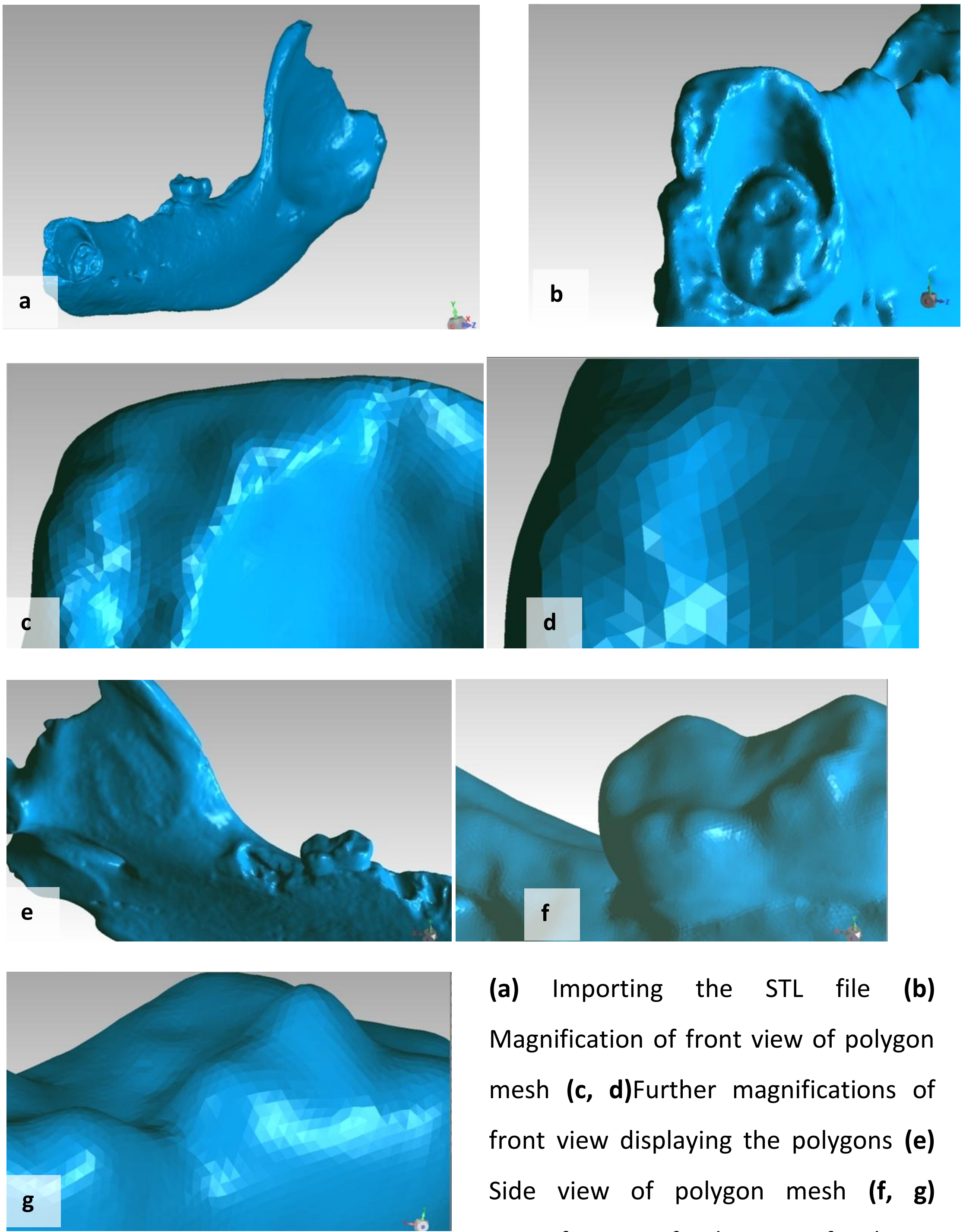



**Figure 3.11.** **(a)** Importing the STL file **(b)** Magnification of front view of polygon mesh **(c, d)**Further magnifications of front view displaying the polygons **(e)** Side view of polygon mesh **(f, g)** Magnification of side view of polygon mesh.

## 3.7. Data optimization

The imported polygon mesh was examined for non-manifold edges, self intersections, spikes or small holes. The polygon mesh was retriangulated to produce a more uniform tessellation. Multiple versions of meshes were created, with different number of triangles, and with thin shells.  The Figure 3.12.a demonstrates the selection of polygons of given curvature, that were was increased, and on the other hand in Figure 3.12.b the selected polygons in red color have been decreased.

Additionally, polygon models with thin shell were made (Figures 3.13 – 3.14) to enrich the potential 3d printed model options. Finer polygon models have been produced and better STL files of the entire object were exported.

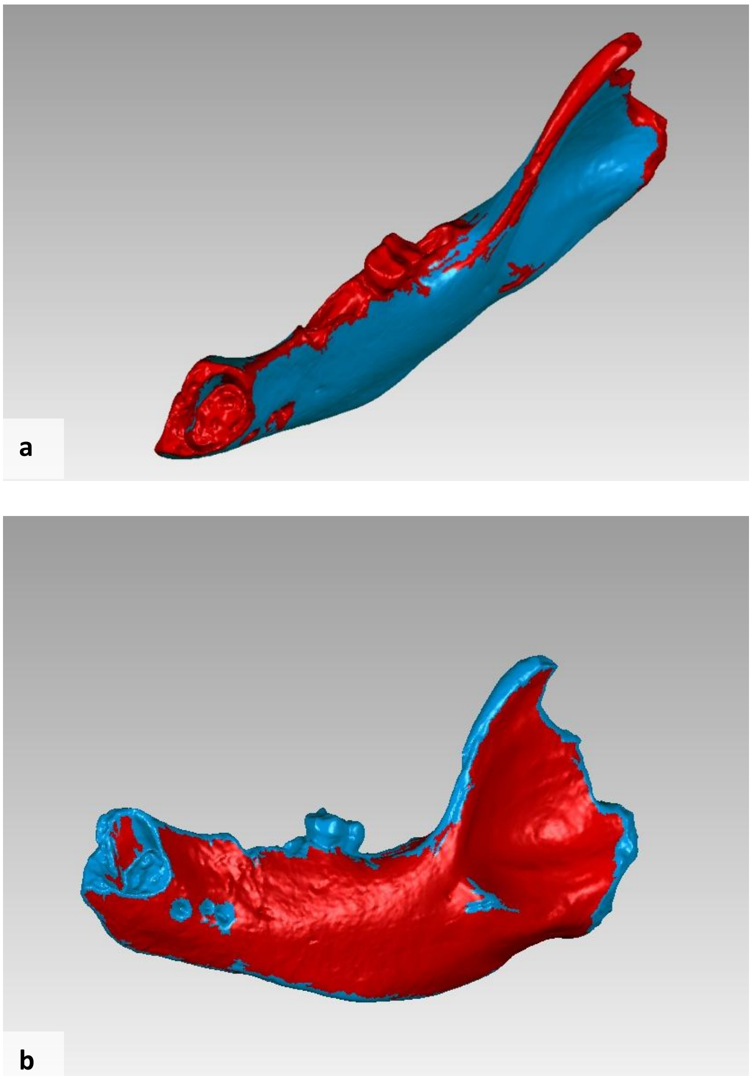



**Figure 3.12. (a)** Areas with high curvature are selected **(b)**Areas with low curvature are selected.

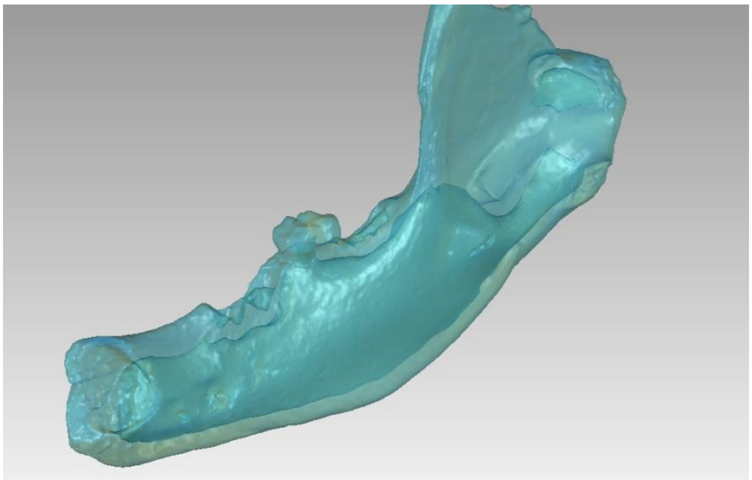


**Figure 3.13.** Transparent view of thin shell model.

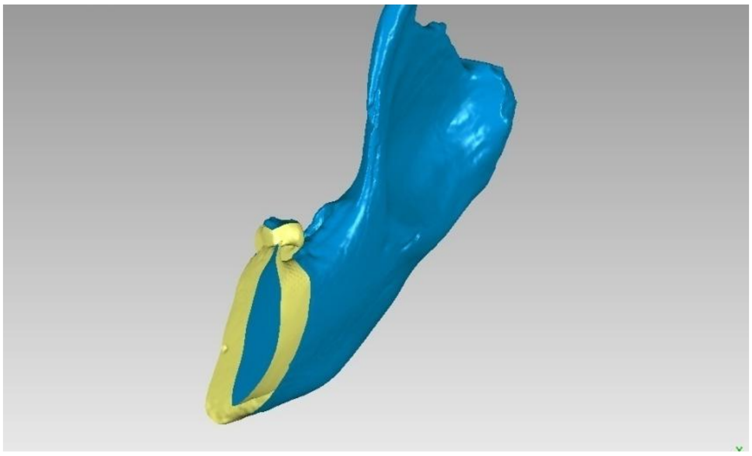


**Figure 3.14.**CAD view of thin shell model.

### 3.8. Generation of STL and PLY files for CJP

Before moving to the generation of surfaces and to CAD models, the process of data optimization described in last paragraph was repeated for polygon models imported in PLY format.

A variety of properties can be stored in PLY files including: color and transparency, surface normals, texture coordinates and data confidence values.

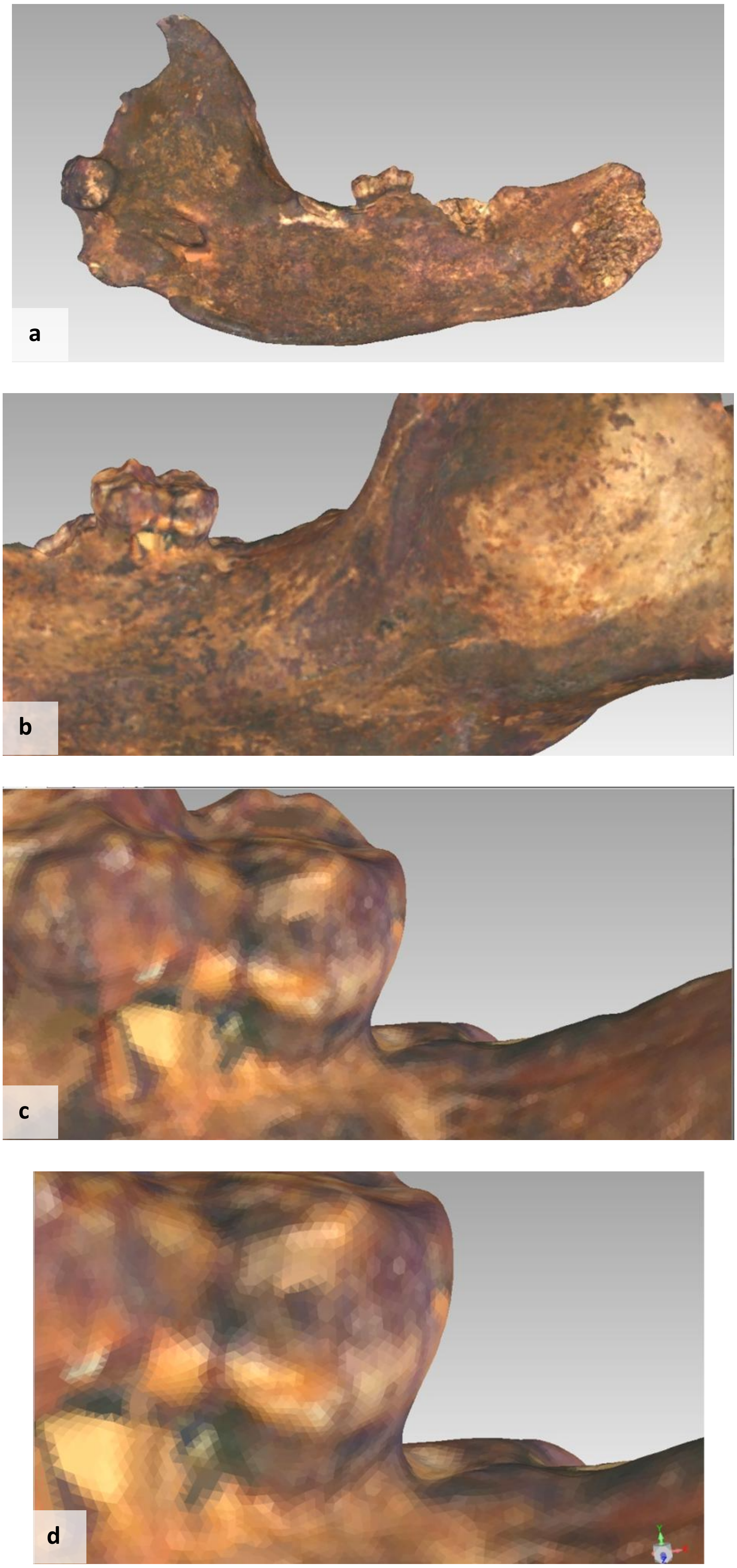



**Figure 3.15. (a)**View of model in PLY format displaying texture **(b)** Turned side view **(c)** Magnification of tooth (side view) **(d)** Further magnification of polygon mesh, focusing on the colored polygons which describe the texture.

The generation and exporting of optimal PLY and STL files of the entire body of the jaw-bone was implemented to ensure that this kind of format was able to be achieved as result of this study.

PLY files can be used in Colored Jet Printing technology printers and multi-colored object can be produced having almost the same "texture" in respect of color with the original scanned object.

This statement is discussed more extensively in the chapter of "Conclusion".

### 3.9. Generation of surfaces, CAD, IGES models for further processing

Up to this phase optimal STL files for FDM processing were produced but the data analysis has been continued. This was necessary in order to examine the capability, of producing data which could be used for printing the jaw-bone in pieces and not only as an entire object. This procedure can overcome any prototype size limitations of the FDM apparatus in the case there are bigger in size objects in the future. In this phase the polygon models were converted to NURBS surface models and consequently to IGES and CAD models (Figure 3.16).

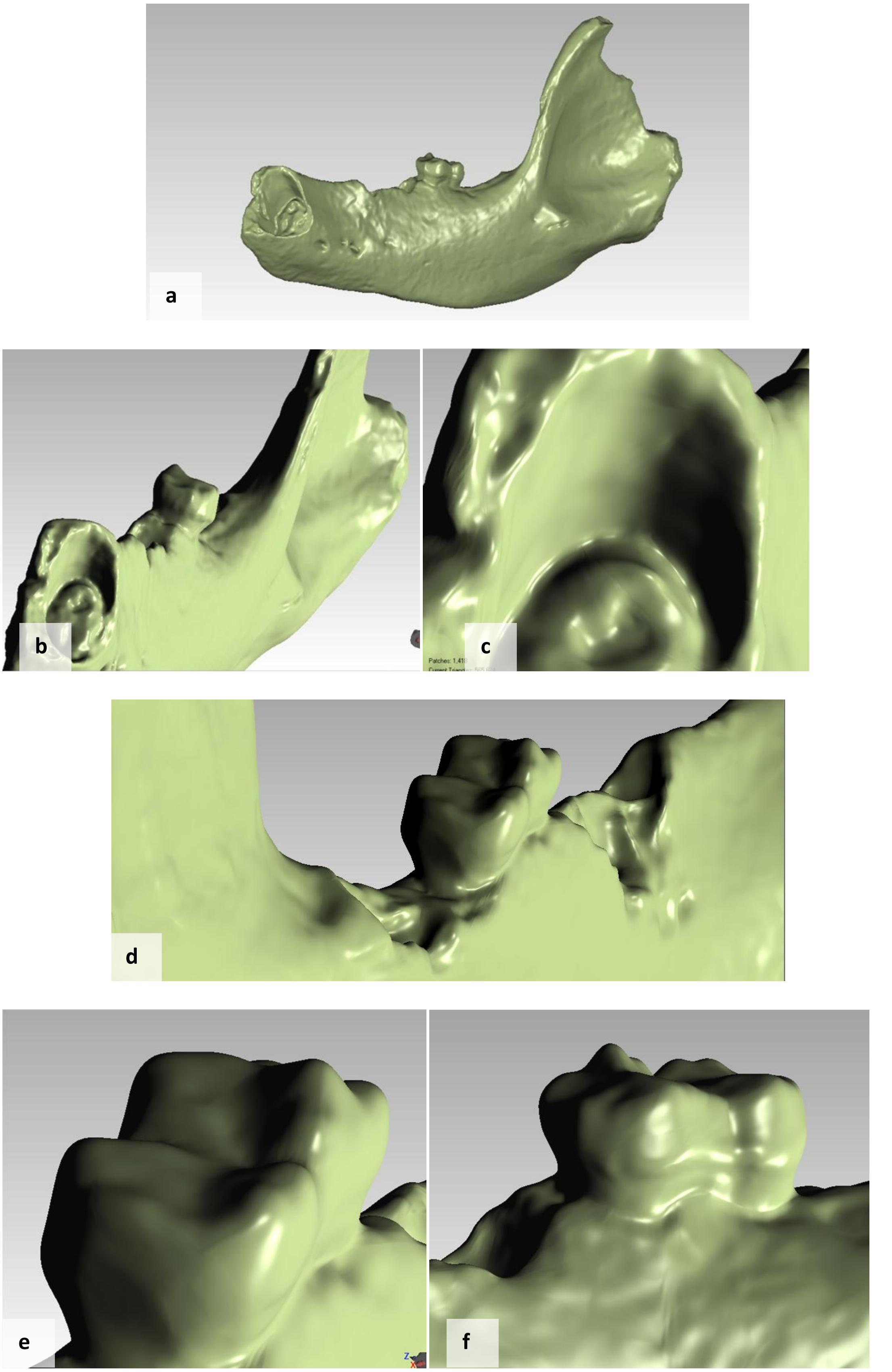



**Figure3.16.(a)**Display of model after surfacing**(b)** Display of front view **(c)**Magnification of front view **(d)** Display of side view **(e)** Magnification view of tooth **(f)** Side view of tooth displaying the generated surfaces.

## 3.10. Importing to Solidworks

The IGES files were imported to Solidworks software (Figure3.17). Solidworks was able to provide parametric design tools for further manipulation of the CAD models.

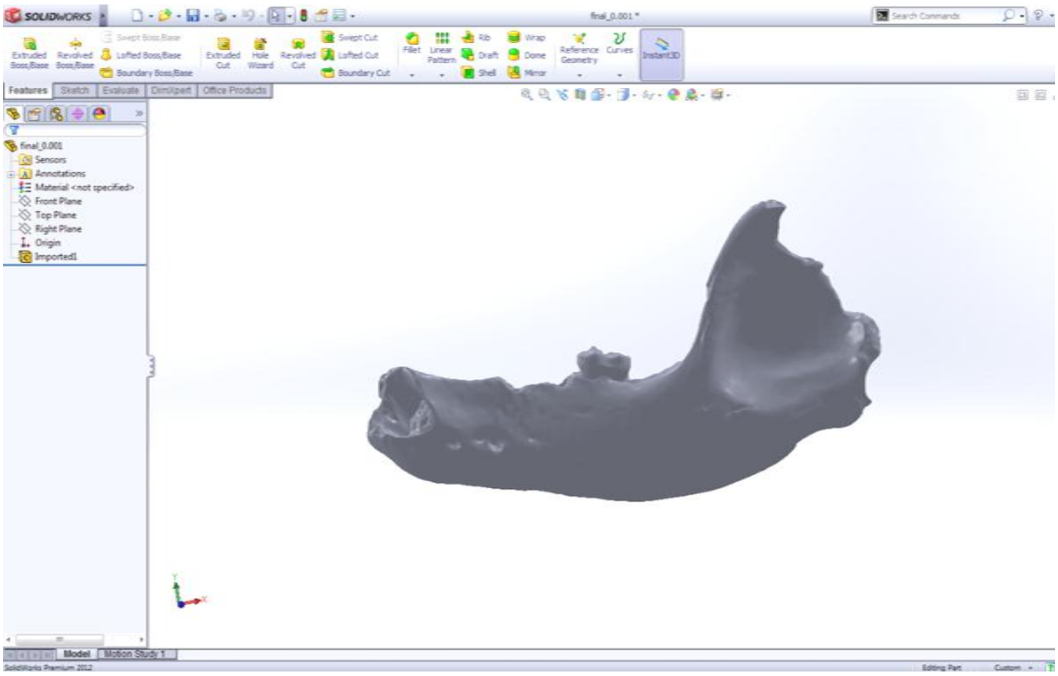


**Figure3.17.** Display of IGES file when imported into Solidworks interface.

## 3.11. Processing of CAD model

The parametric design software provided the necessary tools to divide the IGES model to 4 or 5 parts. Rivet slots were designed to the parts to make the assembly of the physical models easier. Each one of the 4 or 5 parts could next be converted to STL, OBJ, WRML, or any other format requested (Figures 3.18 - 3.19).

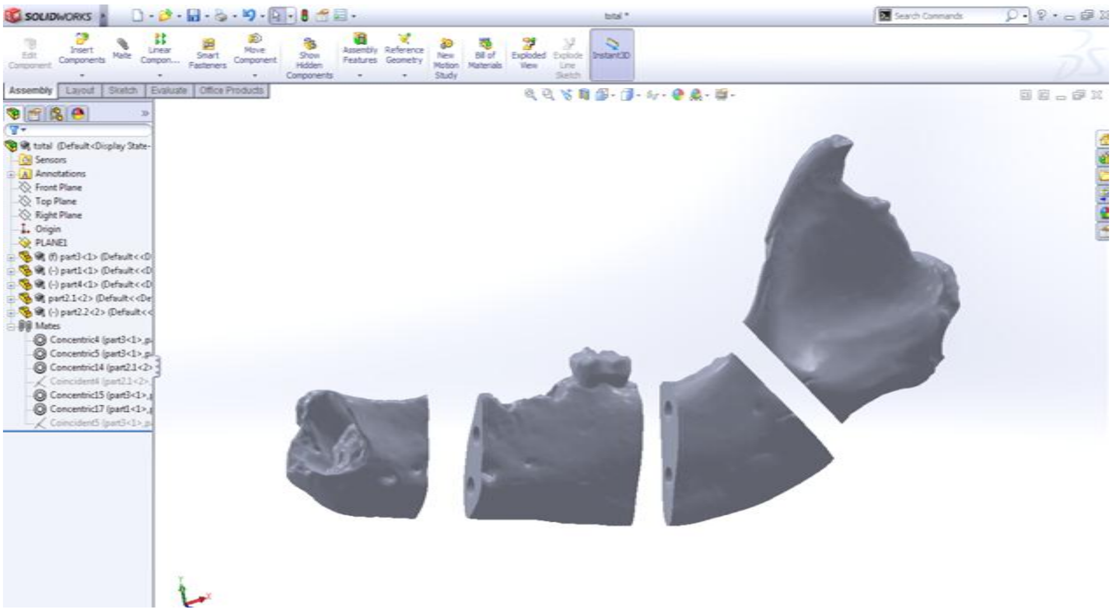


**Figure3.18.** CAD model divided in four parts.

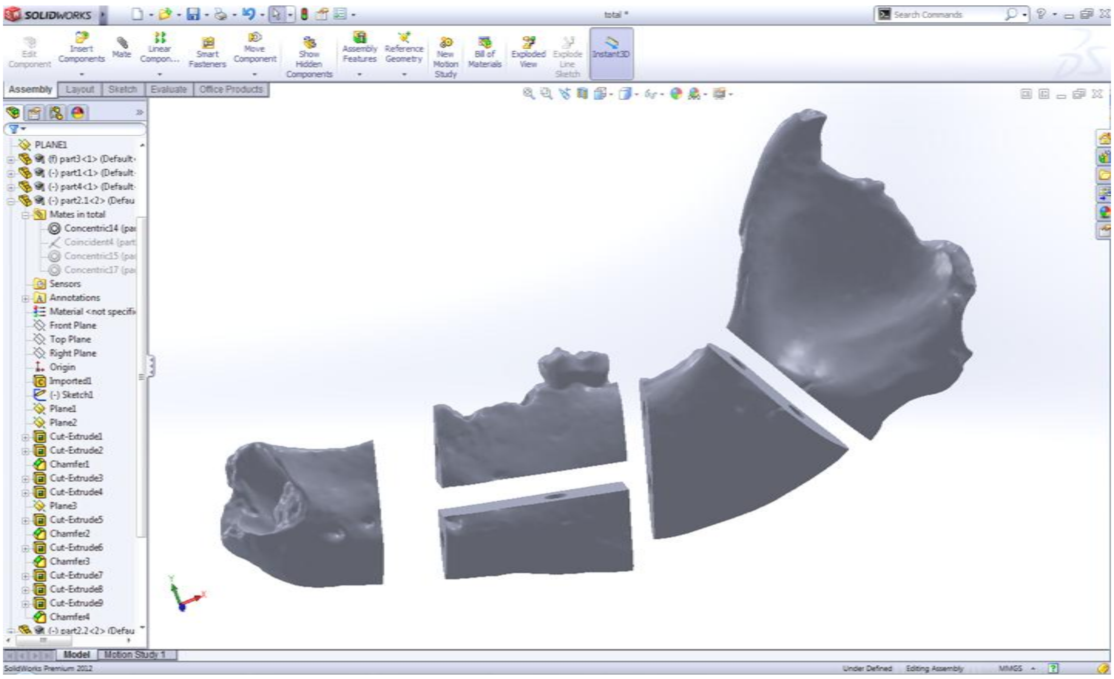


**Figure3.19.**CAD model divided in five parts.

## 3.12. Exporting STL files

The STL files for each part of the jaw-bone were produced.

## 3.13. Importing to Axon2 and generation of built files for FDM machines

The STL files, for the entire body and for the divided parts were imported to Axon2 software. The running parameters of the FDM machines were set up, such as the material, the temperature, the supports, and the raft. The built up files were created (Figure 3.20 - 3.21).

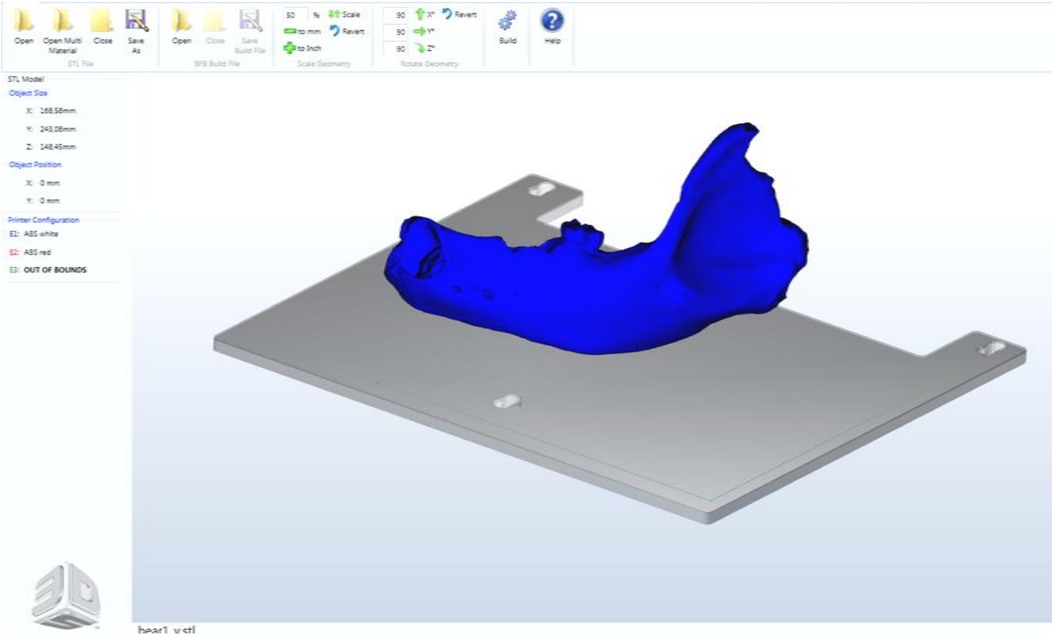


**Figure 3.20.** The Axon2 interface after importing the STL file for the entire body.

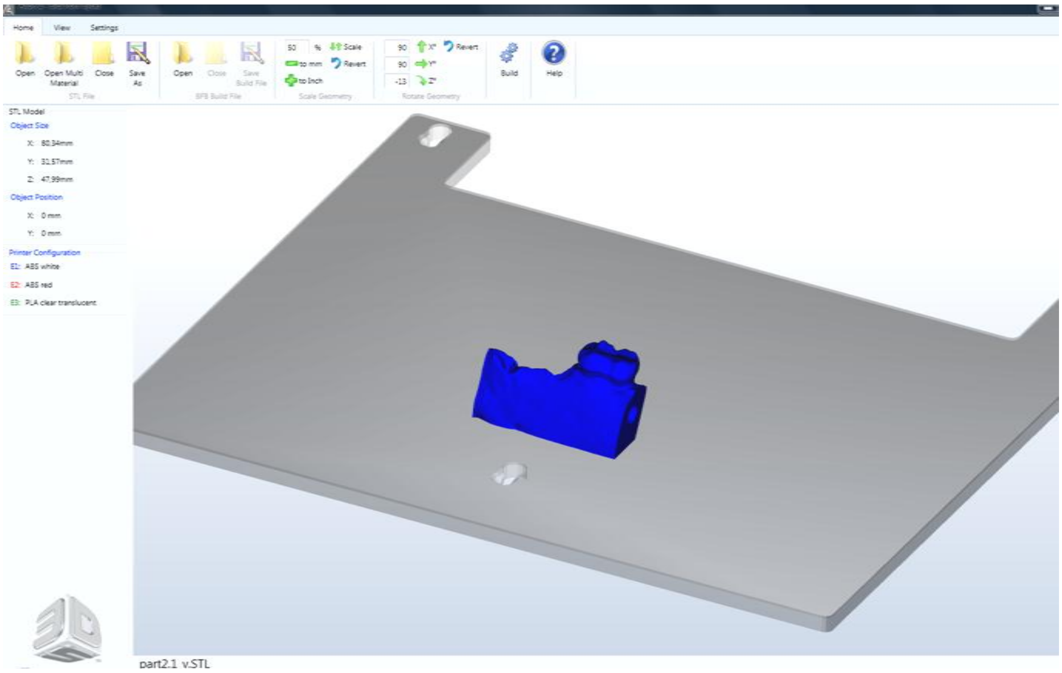


**Figure 3.21.** The Axon2 interface after importing the STL file for one of the parts of the body.

## 3.14. Generation of physical models with FDM technology

The built up files were transferred to the DFM machines (Figure 3.22) and the generation of the physical models was initiated. Finally the plastic models (Figures 3.23 – 3.24) were produced.

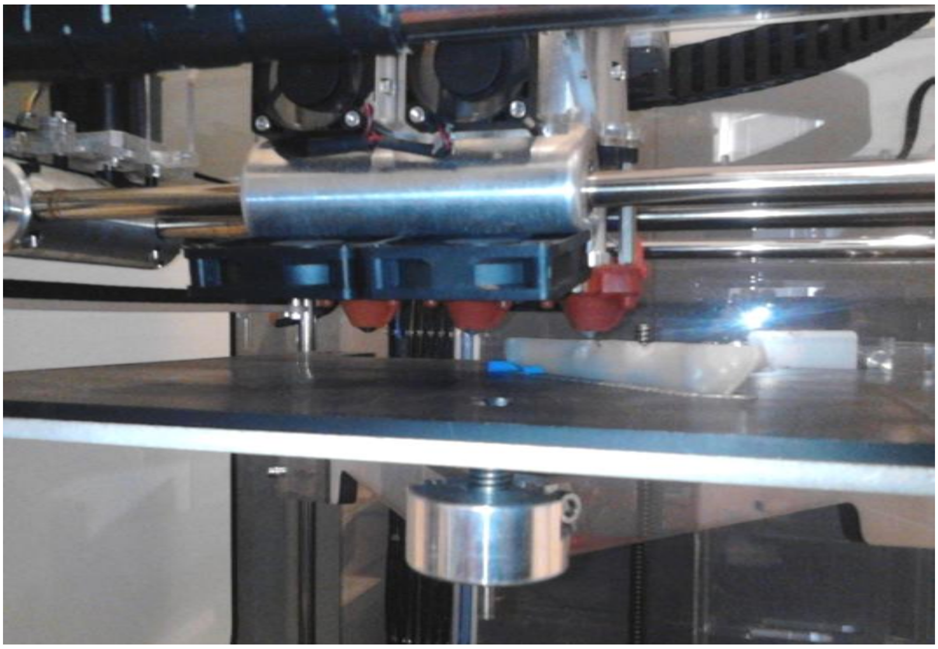


**Figure 3.22.** 3D touch bfb printer during operation.

**Figure 3.23.** Physical model of the entire body made of ABS plastic.

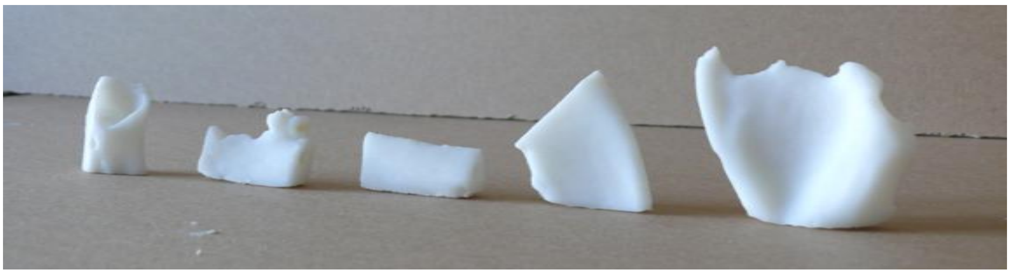


**Figure 3.24.** Display of the generated parts created separately.

## 4. Data analysis and Discussion

In this chapter a short analysis of the data derived from each phase, explained in methodology, is presented. The results and the choices made are discussed in order the reverse engineering method applied, to become more transparent and better described.

The scanning was completed in two sessions after 47 successful scans out of a considerable number of unsuccessful ones. The scans were implemented either as single scans or as scan families. The first data acquisition was taken in the International Hellenic University's 3d Lab – a controlled environment related to the ambient light and to the background of the field view-   by the NextEngine Scanner connected to a high performance desktop PC. The rest of the scans were completed in the ground floor of the Ephorate of Palaeoanthropology - Speleology of Northern Greece in the restoration lab with the aid of the same scanner but that time connected with a laptop of lower performance.

Due to the difference in the performance of the computers and in controlling the ambient light and background conditions differences in texture quality of scans were noticed (Figures 4.1 – 4.2). Minimizing the ambient lighting in the room improved the textures. Keeping the same distance after repositioning the object reduced color variations as well.

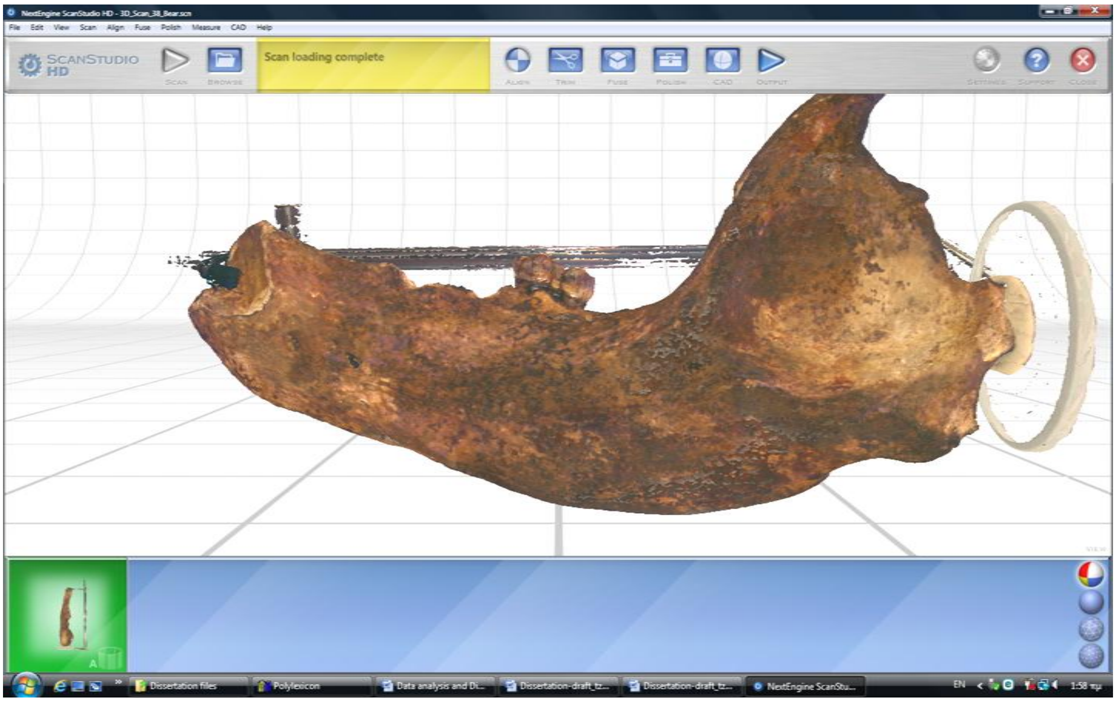



**Figure 4.1.** Texture display in given conditions of ambient light.

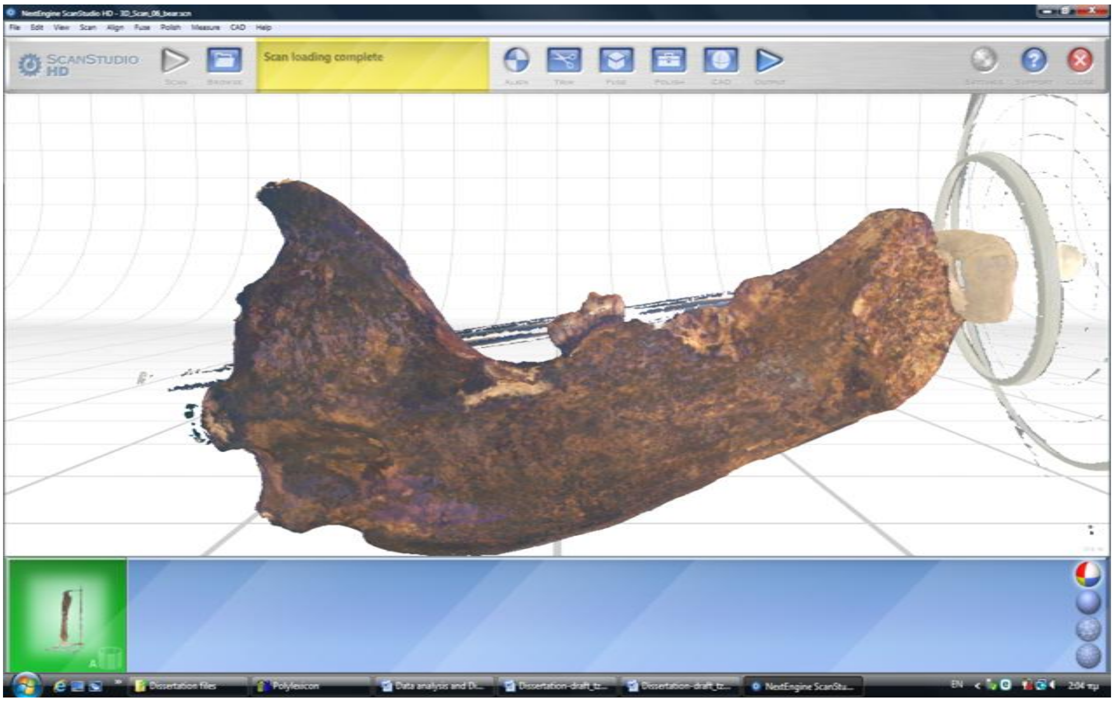


**Figure 4.2.**Texture display in given conditions of ambient light.

The point clouds of the selected scan families were trimmed next. The trimming was implemented by the *trim* tool of Scanstudio. The selection of the noise was done manually by circling or squaring the related points. The noise reduction resulted to finer and cleaner point cloud for each scan family.

The alignment and trimming of the scan families were executed manually with caution using the either the '*shade'* Figure 4.3 or '*color*' Figure 4.4 view depending on each case. Usually prior to scanning, alignment marks are made on the scanned object to make it easier to place pins and identify locations on the object during the alignment process. In this study that was impossible to be done for obvious reasons, thus the alignment was challenging.

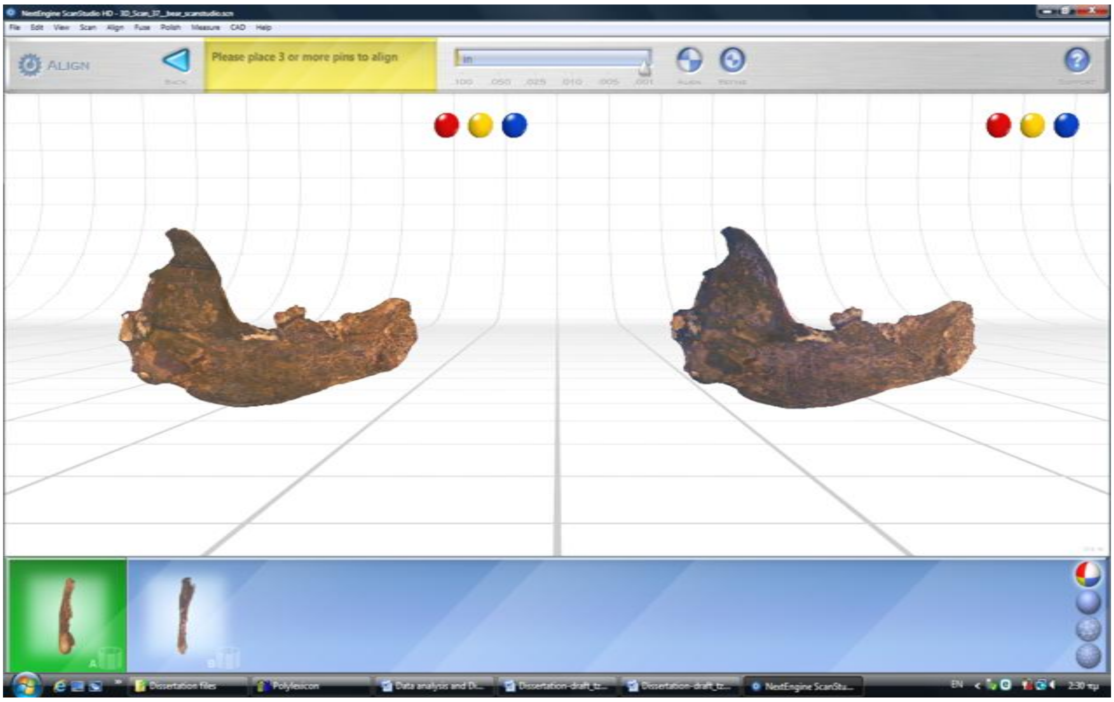


**Figure 4.3.** Color display of point clouds during alignment.

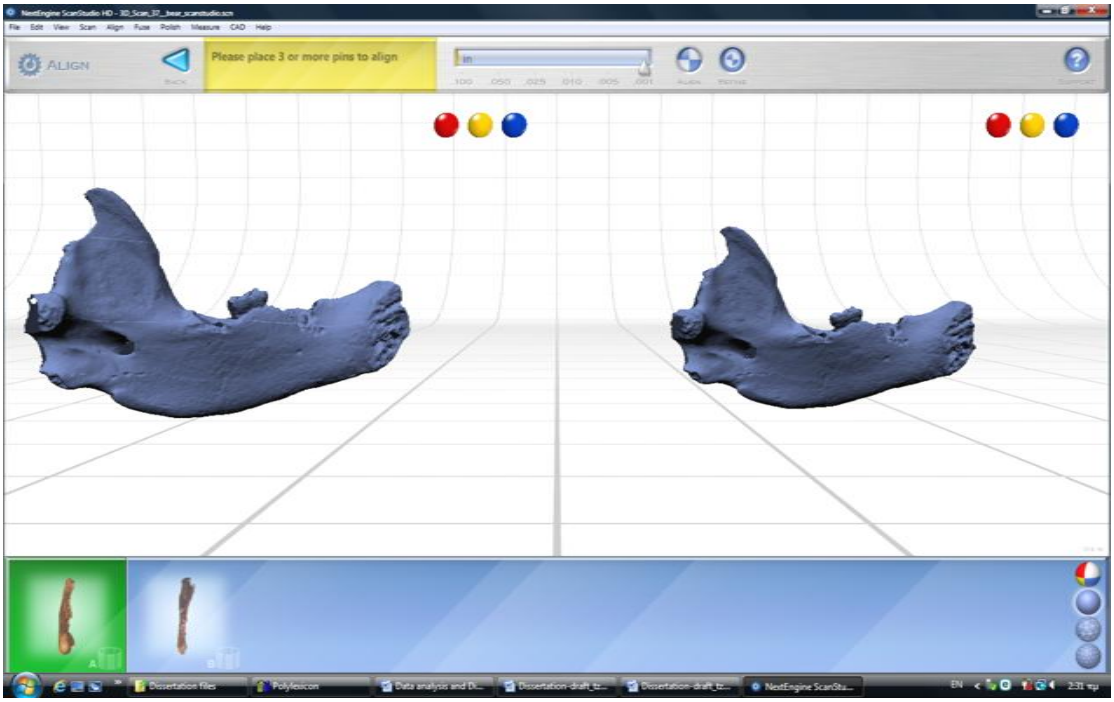


**Figure 4.4.** Shade display of point clouds during alignment.

The volume merging, remeshing, filling holes and simplifying have been accomplished by the use of '*fuse* tool'. In this phase the overlap from multiple scans was eliminated and the scans were merged into a single mesh. The procedure had been repeated with different settings since the optimal balance between simplification and number of triangles was required.

The scanned data were converted to STL files and PLY files (Figure 3.15) for the continuity of the study. Although at the time this study was held there was no CJP printer available there have been exported data in several of formats including PLY, STEP and WRML for future use. Following the optimization of the polygon models in STL files, an identical optimization of the generated PLY files is included in this study.

By the aid of corresponding software for data optimization an automatic examination for non-manifold edges, self intersections, spikes or small holes was executed. At this point there was some consideration in producing polygon models with thin shells that would provide thin shell CAD models (Figures 3.13 – 3.14) later on. A thin shell polygon model although it has less material requirements during materialization in rapid prototyping it has more polygons- almost double number- hence more triangles are created to geometrically describe the inner geometry. This problem had been resolved by reducing the triangles of the areas with low curvature as shown previously in methodology (Figure 3.12.b). Thus, a polygon model of the 500k triangles approximately has been edited to 350k triangles prior of shelling it, so as after the shelling, the number of shells to be again around 500k. A thin shell model created in this stage could be used for a future study in relation to the sensitive temperature behavior of polymer FDM products.

The generation of surfaces and CAD models had been followed and next the corresponding STL files were exported. Although with the data already collected the rapid prototyping could have been initiated. A further extension of the study had been implemented, resulting to a further edit and manipulation of the CAD model (Figures 4.5 – 4.10). The main target was new data to be produced enabling the materialization of the physical models in parts and not only as an entire model. This outcome could find many applications in the field of conservation, since it gives another solution of delivering copies of parts of scanned objects which can be used as accessional elements. Additionally, since the dimensions of the scanned object many times make impossible its prototyping to take place, 3D printed or FDM produced copies of parts of the object, would be a solution (Figure 4.13).

Practically that was done by importing the IGES files into Solidworks and by using the design tools and features provided. Rivet holes have been designed on each part which next had been assembled virtually (Figures 4.11 – 4.12).

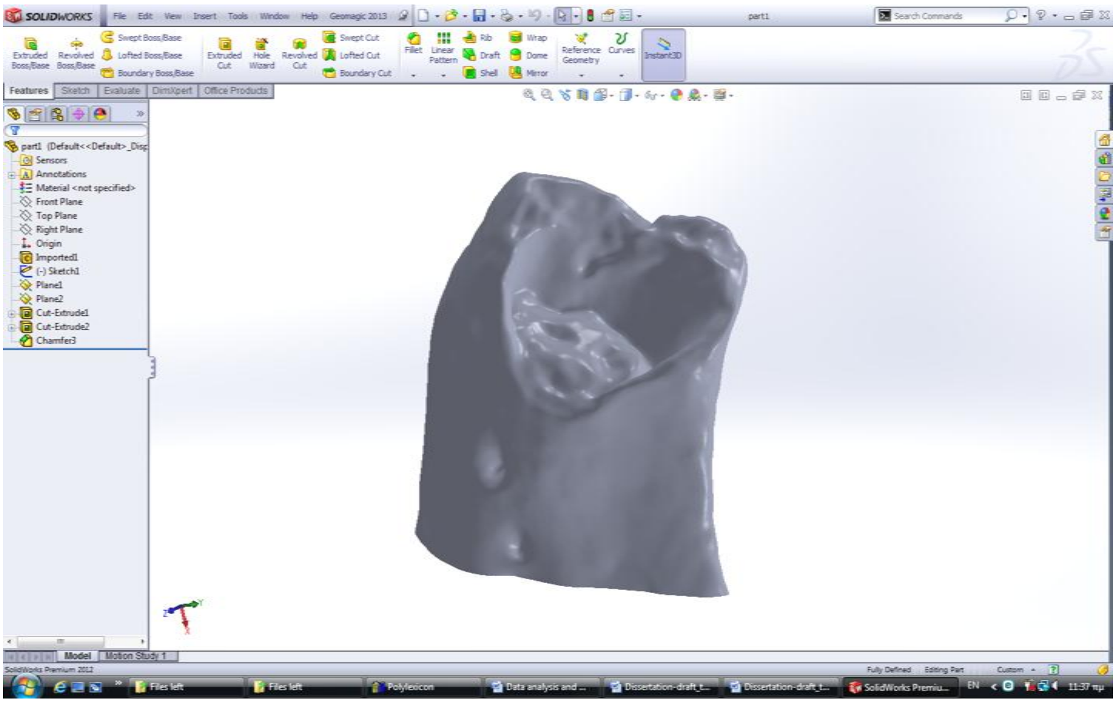


**Figure 4.5.**CAD model of part of the jaw-bone.

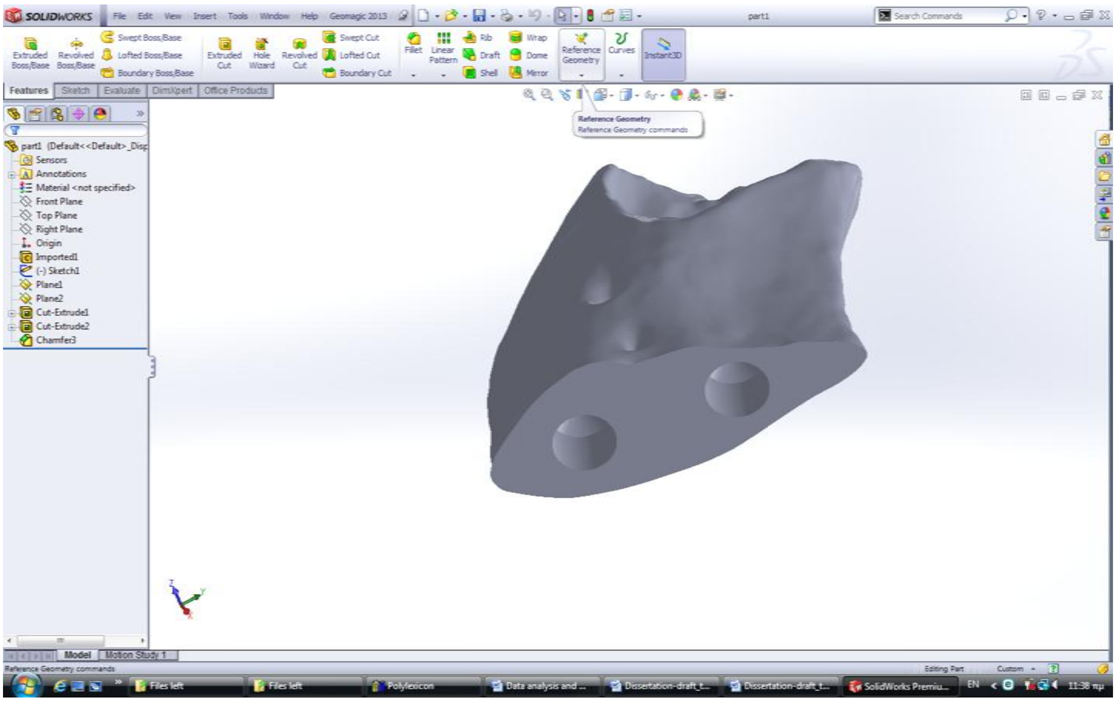


**Figure 4.6.**CAD model of part of the jaw-bone.

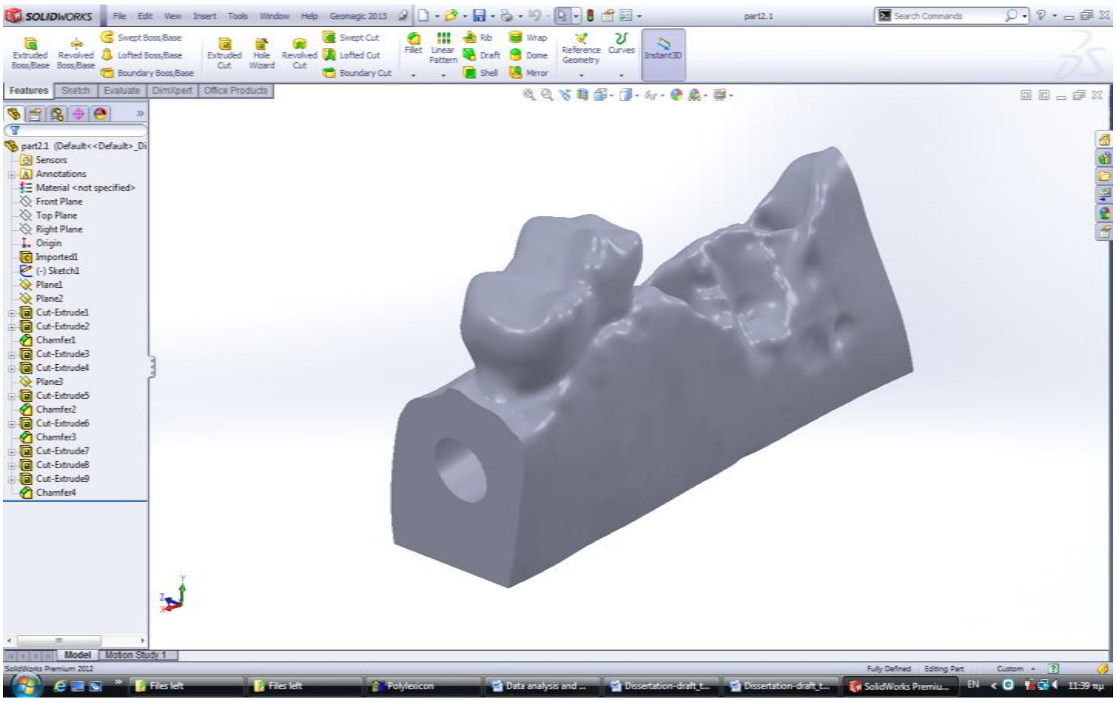


**Figure 4.7.**CAD model of part of the jaw-bone.

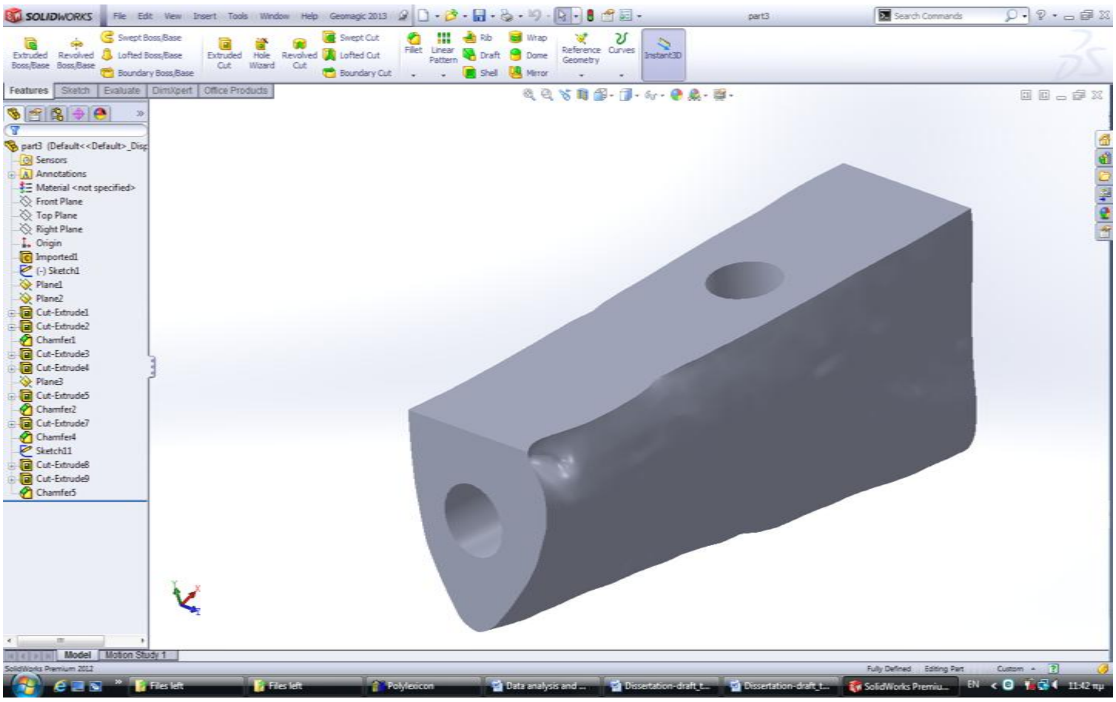


**Figure 4.8.**CAD model of part of the jaw-bone.

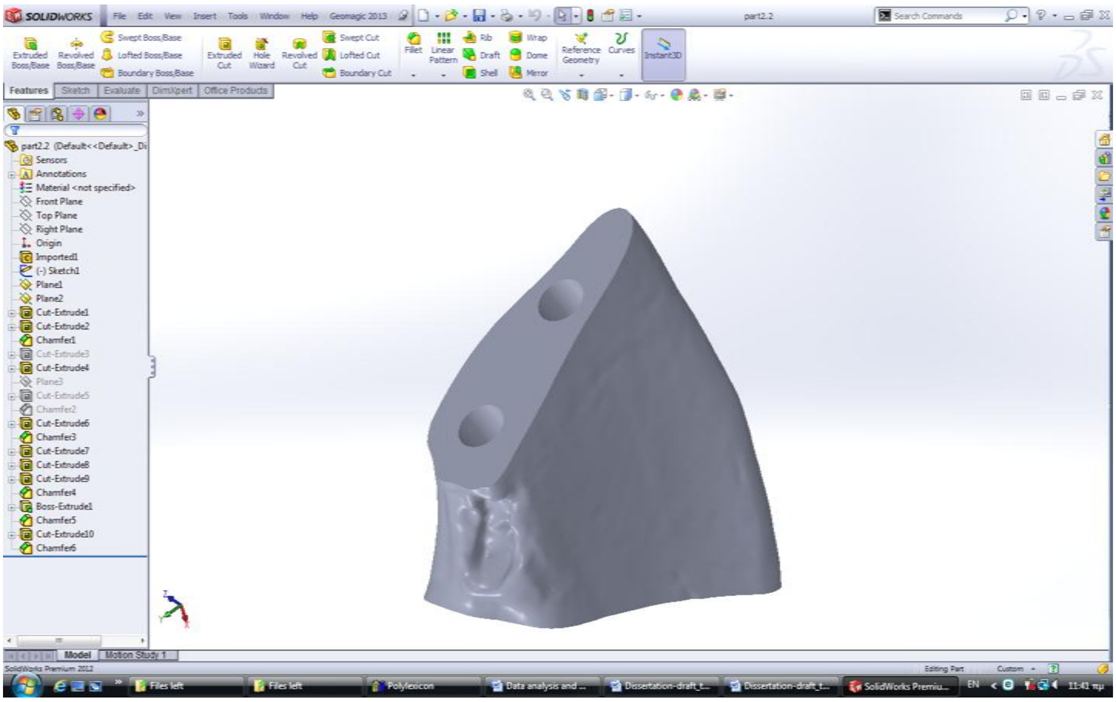



**Figure 4.9.**CAD model of part of the jaw-bone.

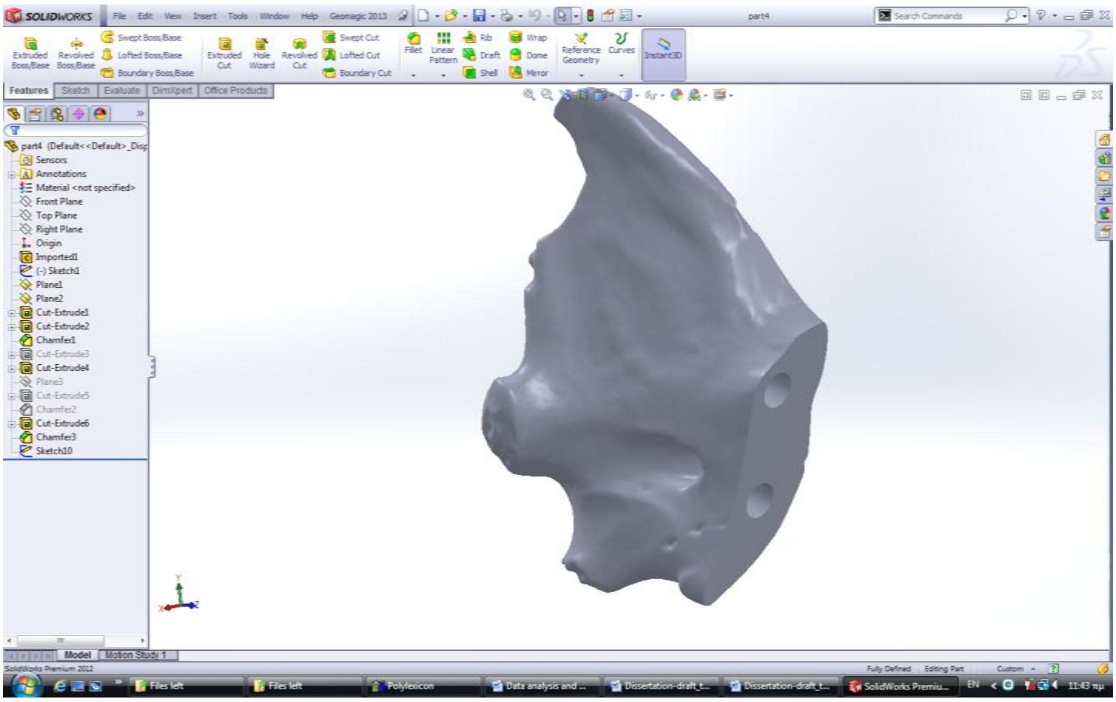



**Figure 4.10.**CAD model of part of the jaw-bone.

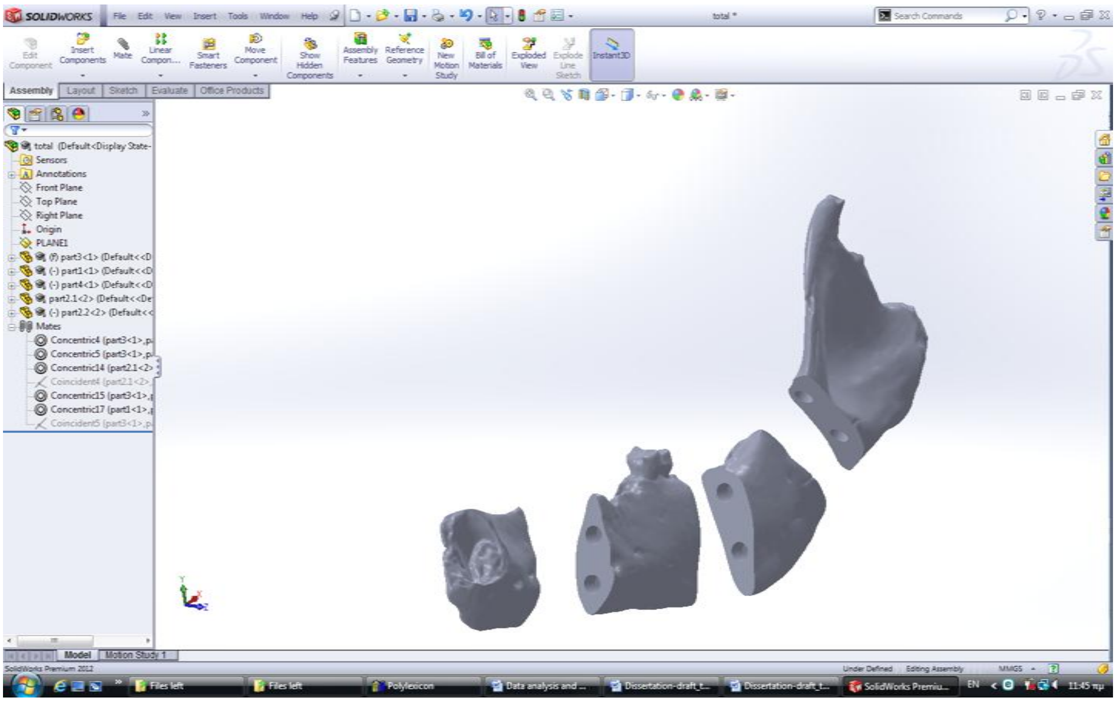


**Figure 4.11.**Assembling parts in Solidworkd interface.

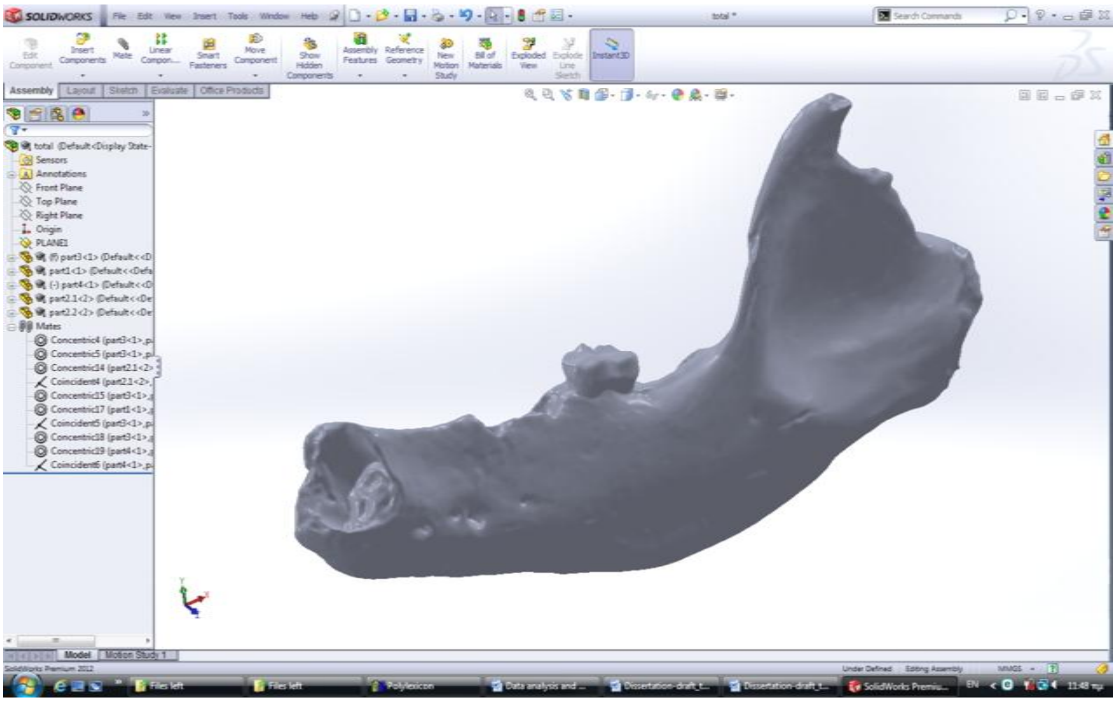


**Figure 4.12.**Five parts assembled as one.

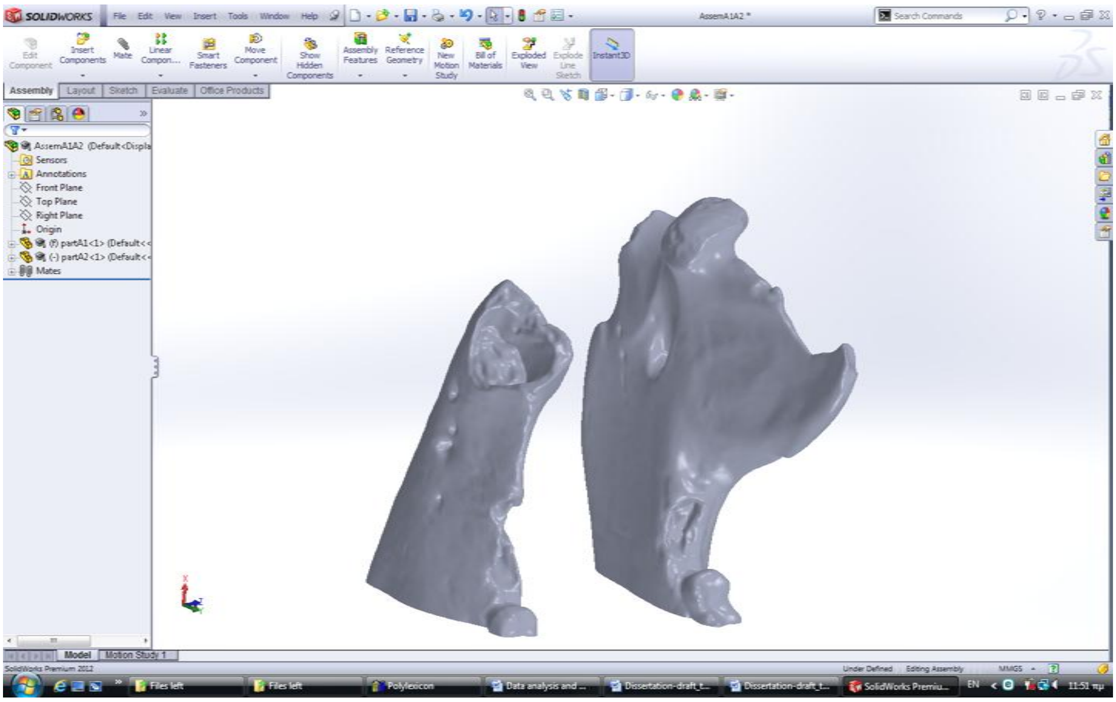



**Figure 4.13.**Scanned object divided in two.

After the conversion to STL format and the importing to the Axon2 software, the generation of the appropriate files, used from the FDM machines for the prototyping process, was implemented.

The generated physical models made of white ABS polymer are shown in (Figures 4.14 – 4.17).

**Figure 4.14.**Physical model of the entire body made of ABS.

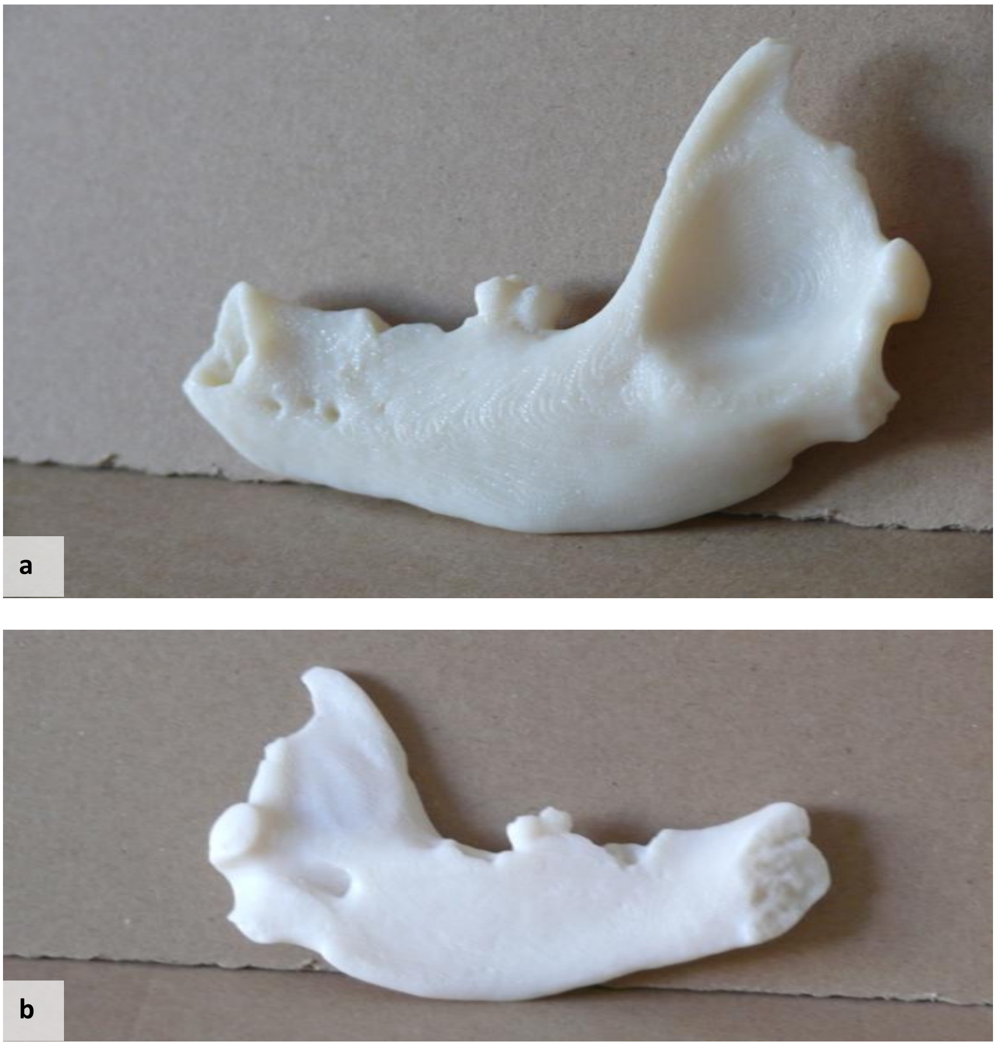



**Figure 4.15. (a,  b).** Views of the physical model of the entire body made of ABS.

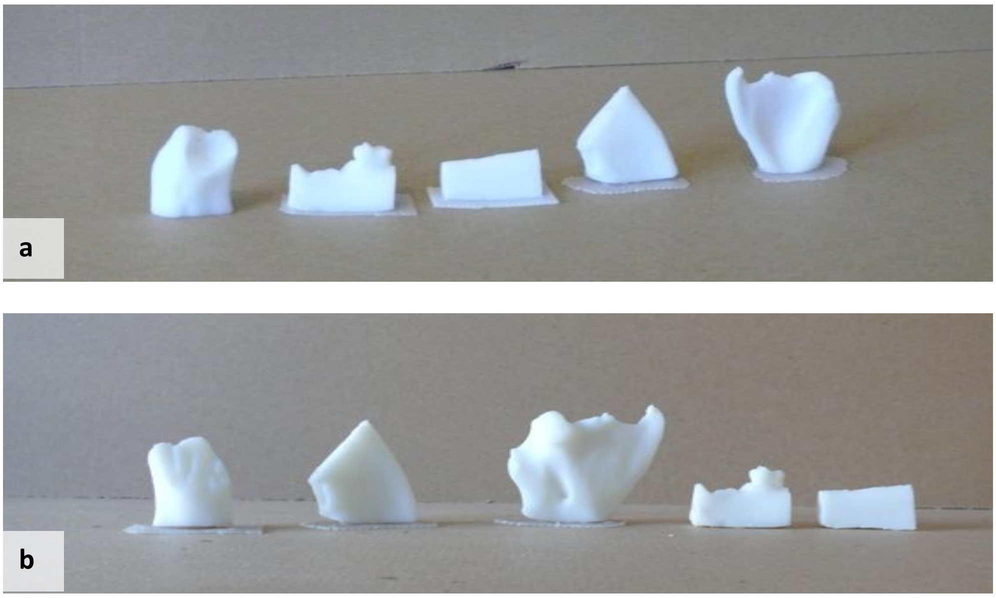



**Figure 4.16. (a, b).** Views of the five parts of the physical model made of ABS.

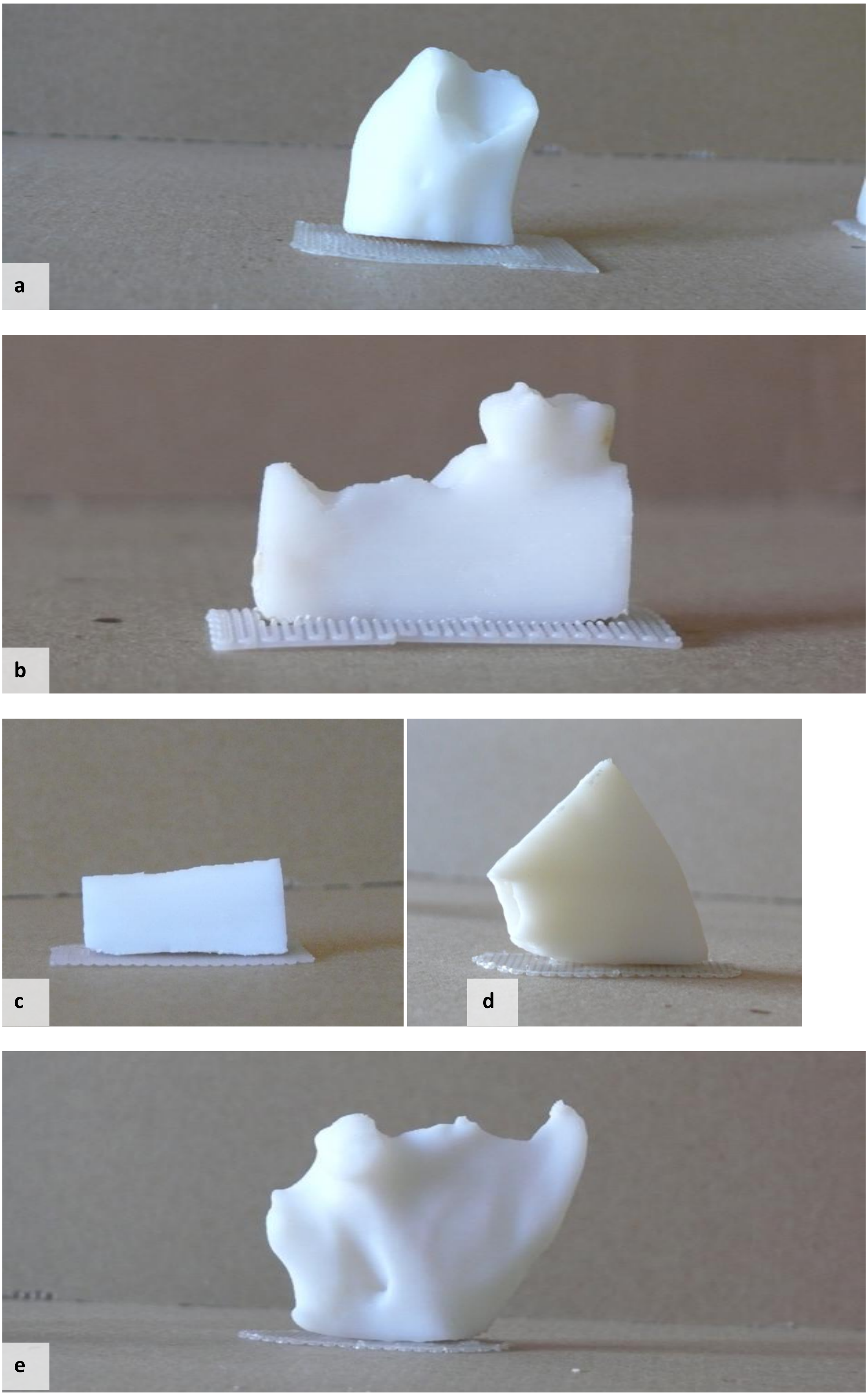



**Figure 4.17. (a,b,c,d,e).** Views of each of the five parts of the physical model made of ABS.

## 5. Conclusion

With the generation of the physical models produced by the FDM machines, the feasibility study of reverse engineering and rapid prototyping of the referred paleontological find was finalized.

This thesis was initiated from the requirement of an authentic copy, for exhibition purposes due to the fact that the original find would be very sensitive to the conditions of light, temperature and humidity existing in the cave of dragon in kastoria where is to be placed. The copy of the jaw bone from the ABS plastic will be handled to Ephorate of Palaeoanthropology - Speleology of Northern Greece in order to further process its surface with primers and colors, so to emulate the physical find.

The current work was essential in order to demonstrate a step by step approach taken for a real case study. The workflow from the scanning, the generated point cloud, the resulting polygon mesh, to surface modeling, to CAD modeling and ultimately to the materialization of physical exact copies was not the only outcome delivered.

The generation of the PLY files and the thin shelled CAD models are considered results of great significance. The PLY files can be used by a 3d printer of Colored Jet Printing technology as the Project 860 Pro and a colored authentic copy of high quality can be delivered and compared with the current plastic prototype after the surface modification from the Ephorate of Palaeoanthropology - Speleology of Northern Greece is achieved. This statement consist one of the recommendations offered by this research.

## 6. Future Work

The thin shelled CAD models can be used as the initial raw data for a new research related to the improving of the FDM product by CAD modeling. A further study about the temperature behavior of these polymer models can be initiated depending on the wall thickness variations and the improvements in part design.

Practically after the supply of the CAD models derived from the RE techniques a number of relative queries are raised:

What other strategic product development could be followed based on the data gained from the specific research?

Could –possibly– this study be applied in modern conservation methods or in creation of new products and services from any related museums? The answers will come in time.

But for now what can be proposed is that apart from making virtual products and exhibitions, the RE and RP techniques can be used in educational purposes. The relatively low cost polymer models can serve a specific population that has vision problems or it is young of age and it experiences objects mainly by touching them. Imagine the possibility of giving them the opportunity of seeing -through touch, historical artifacts and sculpture.

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