COMPARISON OF IMAGE GENERATION
AND PROCESSING TECHNIQUES
FOR 3D RECONSTRUCTION OF THE HUMAN SKULL

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The purpose of this paper was to compare an unconventional 3D digitizer with an expensive CT-Scan for 3D reconstruction of a human skull.

A new method is proposed that will allow the reconstruction of a model from a cloud of points or images and in the same time, will allow the transfer of the reconstructed model in a FEA software.

Two models of a human skull were reconstructed, one was reconstructed using a 3D modeling software, *3D Studio Max*, from 3D coordinates generated by a 3D digitizer, *Microscribe*, and another one reconstructed using an image processing software, *Surfdriver*, from 2 dimensional CT-Scans. Both models were meshed in MSC Patran and subjected to stress analysis using MSC Marc Mentat 2000.

Additionally, a few image processing software were compared – OSIRIS, SCION IMAGE, EFILM, 3D DOCTOR, OPTIMAS and SURFDRIIVER - in order to find the best software that has a 3D reconstruction algorithm.

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CHAPTER 1 INTRODUCTION

Although in the last few years, the use of the non-invasive medical techniques for diagnosis and treatment has experienced a huge development, mainly due to advancement in technology, for research and education these methods are still elaborate, expensive and not readily accessible.

Two virtual models were designed for this study.

For the first model the 3D coordinates were extracted from a real skull model using a Microscribe 3D digitizing unit and then brought as splines into 3D Studio Max and U-lofted to form a solid NURBS model.

For the second model, the DICOM cross-sections were captured from an Image Works CT Workstation using the e-Film software and exported as Tiff images. The images were then processed using SurfDriver, an image processing software, to form a virtual skull. Both models were subjected to stress analysis using a Finite Element Analysis program. The results obtained from the two scanning techniques will be discussed and presented, including the pros and cons of using the more accurate and expensive CT-scans versus the inexpensive hand-held scanner.

For this study, different image processing software was investigated in order to find the best interface to capture, reconstruct and model body data. The features, availability, cost and user-friendliness of these software tools will also be presented.

A new method is proposed that will allow the reconstruction of a model from a cloud of points or images and in the same time, will allow the transfer of the reconstructed model in a finite element software for performing a stress analysis.

Because of the skull's complexity, the complexity of the analysis involved, the huge amount of time spent etc., not many studies investigate the skull and its finite element analysis. Some studies investigate the cervical spine, trying to develop a finite element model for the head and neck during impacts [1].

Other studies are trying to develop finite element models for specific bones, e.g. for first cervical vertebra, that will help understand the injury mechanism and the biomechanical response of the bone [2].

Usually, the majority of the finite element analyses on the human skull is approximate and has many assumptions. The internal structures of a human skull raise too many problems: the skull model must represent the exterior but also the interior, the brain, the fluid around the brain and so on. There are a few complex finite element models that contain all the anatomical features that are normally inside of the human skull, having an extra layer of brick elements that represent the brain, another brick layer that represent the space between the brain and the skull and another one to simulate the cerebral spinal fluid [3].

As it can be seen, all this can be modeled in a FEA software but only in an approximate manner. The majority of the skull models that exist now are much simplified and the analysis generates only approximate results. Sometime the skull is assumed to be a shell object [4], sometime a solid object [3]. However, the finite element analysis performed under these conditions can give us a fair idea about what force a skull can withstand, what is the maximum stress to which it can be subjected and so forth.

CHAPTER 2 THEORETICAL BACKGROUND

2.1 What is an image?

What is an image? According to the dictionary, an image is “a reproduction of the form of a person or object” anything that closely or exactly resembles another [5].

The images of an object may be:

- *Visible physical images* which are entirely real and are either transitory (optical) or permanent (paintings, sculptures) in nature;
- *Non-visible physical images* are optical images outside the visible range or images of an unreal nature (physical spectra, any physical parameter, tomography images);
- *Mathematical images* may be continuous (a function) or they may be discrete, digital (matrices). Such is the situation with purely synthetic images created by computer.

A mathematical image must be processed first in order to obtain an image as we know, an output image. Image processing generally means converting an input image in an output one for two different purposes: to improve the visual appearance to a human viewer and to prepare images for measurements of the features and structures present. [6]

There are two types of image processing:

- *analogue* (converts an input continuous image into another continuous image);
- *digital processing* usually carried out by a computer that converts a discrete input image into a discrete output image.

2.2 3D Reconstruction

Three-dimensional imaging (3D imaging) refers to capturing the 3D dimensions of an object followed by processing, displaying and analyzing those data until a complete and accurate 3D image is obtained.

Nowadays, in bioengineering, there is a great interest in developing 3D imaging because of its huge application in medicine, simply because it is very difficult to use 2D images for studying 3D models. 3D imaging can be performed *directly* by actually collecting a three-dimensional set of information all at once or *indirectly* by gathering a sequence of 2D images and then combining them [6].

There is also *multimodal imaging* which refers to the use of different imaging systems (CT, MRI) to acquire images of the same object providing complementary and more complete information about the object than can be obtained from any single image type [18].

Even if it the reconstruction is done by direct or indirect imaging, 3D reconstruction means basically rebuilding, putting back together the information in three-dimensional coordinates. 3D reconstruction has become a primary capability desired in order to deal with the complexity of human body. There are only two ways to visualize inside the human body: through surgically cutting and by computer-aided reconstruction. The advantages of 3D reconstruction as diagnostic and medical investigation tool are enormous; first of all it is a noninvasive, no life threatening risk method with all the benefits that derive from this.

A 3D reconstruction method can be used not only to study the human body or to diagnose a disease, but also in the treatment of a disease, especially in surgery. For

example, it will be much easier for a surgeon to visualize during the surgery the exact location and dimension of a tumor and the anatomical parts surrounding it.

3D biomedical images are often organized as collections of 2D images where the third dimension may be another spatial dimension, time or the same object imaged by different modalities. Most often, 3D images represent the object as adjacent planes through the structure. This result in a stack of 2D images called a volume image [27].

Reconstruction is the process known as the reverse of digitization. *A digitization* is converting an image from the continuous form to discrete one, which is transforming the image into an array or matrix of numbers then processing them as necessary by computer and transmitting them. However, this is a reversible process and the digital image can be converted back to a continuous image. Different kinds of devices can be used for reconstruction, such as a cathode ray tube or a photographic negative. They transform the array of numbers in the digital image and convert it into an analogue image, which is visible to the observer [7].

In this paper, the direct and indirect 3D imaging methods for reconstruction were compared and their results analyzed. For performing the direct method (3D coordinates input) the Microscribe tool and 3D Studio Max were used and for the indirect reconstruction method (2D CT scans input) SurfDriver, a 3D reconstruction and image processing software was used.

2.3 Microscribe Max – 3D scanning of the skull

Microscribe Max is a software 3D device that works in conjunction with the *Microscribe 3D digitizing unit* v 1.25 and *3D Studio Max* v. 2.5 developed by Ghost 3D and Immersion Corporation. The main purpose of the Microscribe Max is to permit the

digitizing of various 3D objects and to work with the resulting data input directly inside of 3D Studio Max.

Microscribe Max is designed to bring simple and quick operations for digitizing data inside 3D Studio Max. With this “raw” data, various 3D Studio Max modeling techniques can be used in order to produce complex 3D models [8].

2.3.1 The Microscribe 3D digitizing unit

The Microscribe (see figure 1) enables to construct complex computer models by tracing the surface features of a real physical object of any shape, size and material. The Microscribe has a precision mechanical arm with high performance sensors, which track the position and orientation of the stylus tip [9].

Fig. 1: The Microscribe 3D digitizing unit

This kind of device is used to collect data directly from the surface of the study object. The stylus tip is moved over the contour of the physical object following its

surface until the entire surface is digitized. Usually, points are drawn on the object's surface in order to facilitate the digitizing process. The Microscribe captures the physical properties of a three-dimensional object and accurately translate them into a 3D model on-screen.

There are 3 major types of 3D digitizing technologies:

- Ultrasonic tracking: it is considered the least accurate, least reliable and most susceptible to geometric distortions. Ultrasonic digitizers transmit sound waves in 3D space using non-portable transmitters mounted in the wall or ceiling. Because the speed of sound depends on air pressure, temperature and other atmospheric conditions the performance of ultrasonic systems can vary with the weather. In addition these systems are susceptible to sound interference from air conditioning etc.
- Magnetic tracking: magnetic 3D digitizers work on the same principle as ultrasonic systems using a magnetic field as the signal medium to triangulate spatial locations (to divide into triangles). While not susceptible to distortions resulting from atmospheric changes, they are very sensitive to distortions resulting from nearby metal or magnetic fields. In addition, such systems cannot be used to digitize objects with metal parts.
- Laser Scanners: laser-based systems have many limitations even if they are the most expensive. Objects with reflective or transparent surfaces pose major problems for laser systems, as do large objects and objects with concave or other shape which obscure the direct path of the laser beam.

The Microscribe uses a mechanical tracking technology developed especially for hand digitization devices. The hand digitization devices are in high demand in human

kinematics studies, virtual reality applications and industrial robotic applications, activities where three-dimensional positional tracking is a requirement [10]. The Microscribe's arm combines graphite links for a lightweight structure and precision bearings for smooth manipulation. Each joint uses digital optical sensors, which are immune from any environmental noise and interference. It can be used on objects of any material and in almost any environment [9].

The Microscribe-Max interface allows controlling the performance and use of the Microscribe in 3D Studio Max. The *Microscribe Digitize* button must be activated first, because it establishes the data connection between the microscribe and the Microscribe-Max plugin. There are 3 possibilities for digitizing an object:

- Using the *Draw Splines* button. This button allows the user to begin a new spline or to add splines to the ones previously created (to do multiple splines). This command was used to digitize the model because it gives the most accurate result. Splines are created simply clicking the left pedal once for every point from the surface.
- Using the *Create Mesh Faces* button. This command allows the creation of a multiple mesh faces object or to input mesh faces into an already created object. The procedure of tracing points is the same as in the previous case; click the pedal once for every point on the surface. This method was also tried to digitize the human skull, but the final model wasn't so accurate, probably because of the natural complex structure of the model.
- Using the *Create Mesh Strips* button. This button allows to create a linear sequence or "strip" of mesh faces by defining two parallel lines (running in the same direction from start to finish) with the stylus [13]. The model created using this

command wasn't very accurate also, one possible reason being that "the mesh" drawn on the skull couldn't follow two perfectly parallel lines.

2.3.2 3D Studio Max

3D Studio Max R 2.5 is a software designed for modeling and animation. It has very powerful and advanced tools for organic modeling (people, plants, animals or any other freeform shape with irregular shape). Because organic models have usually complex shapes, they are more difficult to model. Visualization on the computer screen becomes more and more difficult as data are collected and the model is more complex. Because this becomes critical when collecting large numbers of points, Studio Max has multiple view options: perspective front, left and top views.

In 3D Studio Max objects can be created using *polygons*, *patches* or *nurbs*. Using these concepts, there are several modeling techniques:

- *Spline-based modeling*. By definition, a *spline* is a curved line that passes through several vertex dots in a 3D space [12]. Spline modeling takes the approach of creating 3D objects from straight or curved lines – splines – through a variety of methods (loft, extrusion). It is used usually for creating objects with special profiles and shapes [11]. Spline modeling is the simplest modeling method. One simple way of spline modeling is to build an initial structure using splines, then the splines are connected and a mesh is constructed. The model was designed by first using closed splines, and then by transforming them in Nurbs in order to obtain a more accurate final product.

- *Polygonal, mesh-based modeling.* Mesh modeling is used mainly for creating flat, planar objects. A polygon can be any closed shape bounded by three or more lines. A polygon is made of vertices, edges and faces (see figure 2).

Mesh modeling creates 3D objects from three- (*tris*) or four-sided (*quads*) *polygons* that have been joined together to form a more complex object.

Fig. 2: A simple polygon

It is the most popular modeling method because it allows any combinations of primitives to generate any 3D object [11].

- *Parametric modeling* is used when dealing with objects that have predefined attributes (radius, length, width) and their measures had to be adjusted, altered during the modeling process.

- *Patch modeling* is used for organic modeling, for modeling complex objects. By definition, a *patch* is made of several splines connected to each other that have a mesh of lines running between the splines [12]. The mesh is build using patches, which are “stretched” over an initial structure. At the end the patches are connected together. NURBS were used to build the model instead of patches because patch modeling is more time consuming and the result is not very accurate.

- *NURBS modeling.* By definition, NURBS (Nonuniform Rational B-Splines) are mathematical representations of 2- or 3-dimensional objects, which can be standard

shapes or free-form shapes. A *spline* is a usually curvy pattern used to guide someone shaping something large, such as a boat hull (figure 3). The B-spline is *Nonuniform*, that is, some sections of a defined shape (between any two points) can be shortened or elongated relative to other sections in the overall shape. *Rational* describes the ability to give more weight to some points in the shape than to other points, in considering each position's relation to another object [13].

Fig. 3: A point NURBS curve

NURBS modeling is the most powerful and advanced technique used for organic modeling, for creating models with complex curves. With NURBS, there are two basic approaches to modeling. One is to create *NURBS splines* and then create surfaces between the splines. The other is to create *NURBS surfaces* and then adjust the surfaces. NURBS curves were used in creating the first model, then the curves were transformed in NURBS surfaces in order to U-loft them (to surface the model).

2.4 Computed Tomography

For 3D reconstruction there are four imaging techniques currently used in medicine. These are: transmission computed tomography, emission computed

tomography (positron and single photon), nuclear magnetic resonance (imaging and spectroscopy) and ultrasound (see table 1).

Each of the four methods depicts different categories of information. For example, x-ray transmission reveals the attenuation of photons, which is related to tissue density, thus giving anatomical information. Emission imaging involves detection of radioactive isotope distribution, which reflect physiological and biochemical activity.

Table 1: Comparison of medical imaging techniques [14]

Method	Parameters measured	Medical applications
Transmission computed tomography	Density and average atomic number	Anatomy, mineral content, flow and permeability
Emission computed tomography	Concentrations of radionuclides	Metabolism, receptor site concentration, flow
Nuclear magnetic resonance	Concentrations, frequency shifts	Anatomy, edema, flow, chemical composition
Ultrasound	Acoustic impedance mismatches, sound velocity	Anatomy, tissue structural characteristics

Nuclear magnetic resonance imaging, MRI, gives information on the concentration and relaxation of nuclei such as the hydrogen of water, carbon-13 isotope, etc.

The contemporary magnetic resonance image reflects the concentration of water and the physical and chemical environment of the water molecules as well as

information on flow comparable to x-ray angiography. Ultrasound is used in determining blood flow by measuring the frequency shifts in the returning waves.

Other methods, such as biomagnetic imaging, neutron and charged particle transmission, electrical current source, electrical conductivity, and light photon absorption imaging are presently under research [14].

- Emission computed tomography – involves the detection of photons from radionuclide distributions in the body. There are two general classes of emission tomography.

Single-photon computed tomography (SPECT) involves the rotation of a photon detector array around the body to acquire data from multiple angles [14].

Positron emission tomography (PET) utilizes the fact that the photons arising from the positron-electron interaction are emitted 180° one from the other; a pair of scintillation detectors can sense positrons emission by measuring the two photons in coincidence. Topographic images are obtained by computer-assisted reconstruction techniques [15].

- Nuclear magnetic resonance, when used in imagining is denoted magnetic resonance imaging. MRI has undergone extremely rapid development because of the richness of the information available and the tissue contrast it provides.

The basic mechanism upon which MRI is based is nuclear magnetism. All nuclei with an odd number of protons, neutrons, or both exhibit nuclear magnetism. The vast majority of all clinical MRI uses the hydrogen proton primarily due to the large numbers present in most tissues [15]. When the body is immersed in a static magnetic field, the spins protons become aligned with the magnetic field than against it. At 25°C

the difference between these aligned populations of about one proton in a million produces a net magnetization. A rapidly alternating magnetic field at an appropriate resonant frequency in the radiofrequency range changes the orientation of the nuclear spins relative to the direction of static magnetic field. These changes are accompanied by the absorption of energy by the nuclei. The nuclei of different elements and even of different isotopes of the same element have very different resonance frequencies. Thus, the magnetic nuclei in the body, when placed in a static magnetic field, become tuned receivers and transmitters of radiofrequency energy.

- Ultrasound - ultrasonic imaging is the second most utilized diagnostic imaging modality today. Ultrasound denotes the use of acoustical waves at frequencies greater than 20 kHz. Generally, medical ultrasound is performed at frequencies in the range of 1MHz [14].

As an acoustic wave is launched into a medium, a mechanical disturbance of the medium is produced. Acoustic parameters such as pressure, medium velocity, medium displacement, density, temperature and sound speed respond accordingly and vary as a function of time and space. The following are some of the unique characteristics and advantages of ultrasound:

- Ultrasound is a form of nonionizing radiation and is considered safe to the best of current knowledge;
- It is less expensive than imaging modalities of similar capabilities;
- It produces images in real time, currently unattainable by any other methods;
- It has a resolution in the millimeter range for the frequencies being clinically used today;

- It can yield blood flow information;
- It is portable and thus can be easily transported to the bedside of a patient [15].

The technique is used to determine the location of surfaces within tissues by measuring the time interval between the production of an ultrasonic pulse and the detection of its echo resulting from reflections from those surfaces. By measuring the time interval between the transmitted and detected pulse, the distance between the transmitter and the object can be deducted.

- Transmission computed tomography. Today the most widely used imaging modality is the x-ray transmission intensity projection or radiograph (known as “x-ray”). The difference between the x-ray (a simple two-dimensional projection image) and the x-ray computed tomography (known as “CT”) is that the latter is the result of mathematically reconstructing an image of a slice through the body from multiple x-ray transmission projection images taken at multiple angles around the body. The CT scanner is basically an X-ray device that scans the objects from all angles and records the density and thickness of the analyzed materials.

The x-rays are generated by the interaction of accelerated electrons with a target material such as tungsten. The electrons are produced by a heated cathode and accelerated by applying a voltage between the cathode and a tungsten anode. The x-rays from tungsten are emitted from the x-ray tube placed one or more meters from patient. The x-radiograph is usually a film, not unlike a negative, which is darkened due to the interaction of the photons with the silver halide granules of the film. The image reflects the number or intensity of photons reaching the film but, as is the case for a conventional negative, the greater the intensity, the darker the radiography.

However, traditional x-ray technique has many limitations. First of all, this method does not permit the distinction between various tissues, because of the small characteristic differences in x-ray attenuation. It cannot distinguish, for example, between muscles, ligaments or vessels, therefore their image cannot be captured by this method.

Another major disadvantage is the superposition and compression of 3D information into a 2D image. Because of this, useful information is lost and the image detail of the analyzed object is only partially captured. The x-ray computed tomography is a more complete technique that adds a mathematical reconstruction theory of an object from its projections to multiangular x-ray scanning [18].

The x-ray CT machines use also an x-ray tube, but instead of being detected on film, the intensity is detected from an array of devices or tube systems.

The X-ray tube produces the x-ray energy that creates the CT image[16]. The tube rotates around the human body in order to perform multiple exposures in a short time and producing in this way a fan shaped beam (see figure 4).

Fig. 4: CT Scan

As x-rays pass through the body, they are absorbed or attenuated at different levels, creating a profile of beams of different intensities. A detector, that further transforms the profile in an image, analyzes this profile [17].

The computer tomography involves mainly the presence of a computer, which process the information received through the passage of an x-ray beam through an anatomical area. The CT creates images representing cross sectional slices of the exposed area. Each CT slice represents a specific plane, its thickness being called the *z-axis* [16].

X-ray imaging is mainly an anatomical procedure. The absorption of x-rays due to differences in elemental composition has an important effect for imaging bone or calcium deposits because this absorption process is proportional to the atomic number. The reason we can differentiate gray from white matter in the brain in CT images is that the H, C, O, P contents for gray and white matter and cerebral spinal fluid differ slightly. Very little contrast is observable between blood and muscle as the density and the elemental compositions are very similar. To provide image contrast between them, usually a dense fluid with elements of high atomic number can be injected or swallowed during x-ray exposures [14].

Many factors affect the quality of the CT image produced, some of those factors can be regulated, some cannot. One of the factors that can be regulated is the slice thickness. Slice thickness is extremely important in CT because for example, thinner slices produce sharper images and on the other hand, the thicker the slice, the more flattening is necessary. If the slice thickness is big, the inaccuracies will be pronounced because the system approximates a 3D volume (a cube) to a 2D image (a square).

Another factor that affects the quality of a CT image is the field of view. It is essential to choose a correct field of view otherwise the final CT image could be too small or too big, with abnormalities hard to detect and precious information lost.

An important role in obtaining an accurate CT image is played by the algorithm used for reconstruction, and this depends on the manufacturer of the tomograph [16].

Beside the conventional computer tomography method, there are a few other methods that are based on the same principle: Helical CT, Multidetector CT and Electron Beam CT.

The data acquisition process for *helical CT* traces out a spiral trajectory rather than a sequence of parallel ones; this method permits capturing a larger volume of the analyzed object in a very short period of time (figure 5).

Fig. 5: Helical CT

Multidetector CT method is similar to the previous one; it is in fact an improved helical CT. In this case, multiple parallel detector arrays record multiple beams simultaneously and allow multiple slice profiles to be acquired during a single spiral cycle.

Electron beam CT is a specialized imaging application used usually in cardiac imaging because it gives the possibility to image body parts in motion (figure 6).

Fig. 6: Electron beam CT

This it is possible due to the fact that there is no mechanical rotation of the x-ray source (gantry) like in all the previous cases.

Instead, the x-ray source consists of four parallel pairs of semicircular rings spanning around the patient. An electron beam is electromagnetically swept along one ring at a time, thereby creating a rotating fan beam of x-ray [18].

The CT process consists mainly of 3 parts: *data acquisition*, *image reconstruction* and *image display*. All the views that form an image are processed by the computer and stored for later use. Some of these raw data are used in the creation of image data. The raw data are refined and analyzed and transformed in what are called image data. These image data are further transformed and create the final CT image [16].

CHAPTER 3 APPROACH TO CREATE A SOLID MODEL

3.1 First model. Direct 3D reconstruction method

In order to obtain the final computer model using the direct 3D reconstruction technique, a number of steps were necessary. The following are the principal stages in making the final skull model:

- Preparation of the initial model;
- Designing a clamping device;
- Digitizing the initial model with the Microscribe digitizer;
- Modeling the skull using the 3D Studio Max software.

In performing the modeling process, some of the steps were known from the beginning and some of them – like the necessity of a clamping device - were discovered and introduced as the project progressed.

The initial model was a synthetic skull having real dimensions. In order to make the digitizing process easier, points were traced out on the skull's surface in a horizontal (every half of inch) and a vertical direction (every inch) forming a fine "mesh".

At the beginning, the 3D dimensions of the skull, recorded using the Microscribe digitizer tool, were not accurate, because the model was not fixed on a support and it was not completely immobile. The digitizing process was even more difficult because all the work had to be started from the beginning every time and finished in the same digitizing sequence as the reference points could not be chosen to be exactly the same every time.

Usually, the initial model is made of gypsum or a similar material and glued on a flat, immobile surface in order to be digitized. In this case this method could not be used because the skull model was an expensive model and more, all the skull' sides needed to be digitized, including the base of the skull.

Following this thought, a clamping device was designed that holds the skull model in place. The clamping device was designed in such a way as to keep immobile various skulls of different dimensions, from a very little skull - a possum skull - to a much bigger one – the human skull. It has various possibilities of adjusting its dimensions, three in vertical directions (lateral bars and the middle one) and two on the horizontal direction (lateral bars).

The device consists in a horizontal rectangular plaque of 20/45 cm on which two vertical metal bars and one middle vertical plastic support are mounted (see figure 7 and figure 8). The lateral metallic bars have inside smaller plastic bars that can slide up and down function of the height of the analyzed model.

Perpendicular on the each plastic inside bar there is a cylindrical bar 1 cm in diameter that limits the lateral movement of the model. The horizontal cylindrical bars can slide left or right, towards the model, in order to keep it fixed. They have one sharp end and the other end is blunt so that they can be used alternately depending on the different surfaces of the model. The outside bar has one bolt on its vertical edge that immobilizes the inside plastic bar and one horizontal bolt that immobilize the horizontal cylindrical support.

The third support is placed in the middle of the plaque, consisting of two concentric cylinders. The outer cylinder, 4 cm in diameter, is designed with an exterior

bolt that immobilizes the inner cylinder. The inner cylinder, 2 cm wide, has attached a circular plastic plate at the upper end, 7 cm wide, which support the bottom of the model and takes almost its entire weight.

Fig. 7: Lateral skull positioning. Clamping device

Fig. 8: Frontal skull positioning. Clamping device

The digitizing process was the third step in making the virtual skull model. A Microscribe hand digitizer tool was used to record the 3D dimensions of the real skull.

As described in chapter one, there are three possibilities of digitizing with the Microscribe Max tool: draw splines, create mesh faces and create mesh strips. For modeling the virtual skull the draw spline option was used because it gave the most accurate model, that is, very similar to the real one. After the model was prepared and immobilized in the clamping device, the skull was digitized starting from the right temporal bone, following the frontal plane, towards the left temporal bone (figure 9).

Fig. 9: Skull seen in frontal plane.

Following every point previously traced on the skull surface, the entire skull was digitized with the microscribe' stylus drawing splines, from the very little splines (around the temporal bone) to very long and complex ones. In order to obtain a more accurate model, especially in the face region where there are many details that have to

be digitized more carefully, twice as many splines were traced as compared to the rest of the skull. The digitizing process was more difficult as splines became more complicated, having more points and more complex shapes. The possibility to see on the computer screen four different views (perspective, left, top and front) of every point digitized with the microscribe[®] stylus, was very helpful during the entire digitizing process and especially at the end when the model became very complex (figure 10).

Fig. 10: Half skull model splines

The virtual skull can be modeled by digitizing the entire skull or by digitizing only one half of the skull and then mirror it. For making the skull model both approaches were tested.

Digitizing the entire skull was a very difficult and strenuous process and the result was not very accurate. The points traced on one half of the skull were not exactly the same as the ones on the other half, so the final mesh was not identical on both sides.

The model became more and more complex with every line traced and much more difficult to be digitized and to be visualized on the computer screen. There were many other reasons that influenced the decision to model the skull using the second approach, which is to assemble the skull from two identical halves.

In the beginning, only one half of the skull was digitized using the same option, draw splines. The half skull was digitized using eleven closed splines and the MicroscribeSpline object was obtained (figure 11).

Fig. 11: The MicroscribeSpline object

After the splines were drawn in 3D Studio Max, in order to obtain a virtual skull model, the splines need to be transformed using the 3D modeling tools available. The initial MicroscribeSplines object had to be transformed in NURBS curves object and then in NURBS surfaces object.

The MicroscribeSpline object can be converted to a NURBS object by first drawing a NURBS point curve and then attaching the MicroscribeSplines object to the

NURBS curve. The MicroscribeSplines are transformed into NURBS curves only if the splines types are changed to Curve and the vertices are Smooth or Bezier.

Using the Mirror option, the first half of the skull can be copied. The two identical half skull parts are aligned and attached one to another forming a perfect skull.

Fig. 12: NURBS curves object

The entire skull is now a NURBS object that can be skinned any time to form a complete virtual skull model (figure 12).

In order to access the surface panel and surface the model, the NURBS model was transformed in a Nurbs Surface model by changing its status from the Edit Stack modifier, from Nurbs Curve in Nurbs Surface. The Nurbs Surface model was skinned using the U-LOFT surfacing option. U-LOFT surfacing means skinning multiple nurb curves. The final Nurbs Surface model can be seen in figure 13.

The software has another capability of skinning, named ruled surfacing, but it creates a surface only between two consecutive curves.

Fig. 13: NURBS surface object

Usually complex models made of multiple, successive nurb curves are surfaces using U-LOFT because it creates the most adequate result.

The final solid skull model designed in 3D Studio Max from 3D coordinates recorded by a Microscribe can be seen in figure 14:

Fig. 14: Solid skull model

3.2 Second Model. Indirect 3D reconstruction method

The model designed using the indirect reconstruction method was used as an etalon because the 3D reconstruction from 2D CT slices, using a reconstruction algorithm, is now widely used and well acknowledged as being the best modality of reconstruction from 2D images. Usually, the two-dimensional slice data from the CT scanner are used as input for the three dimensional reconstruction.

The skull was modeled in two stages: acquire the CT scans and use a 3D reconstruction software. Two other reconstruction methods were also tried using a software to extract the boundary of each slice, using another software to obtain the x, y coordinates and another one to reconstruct the skull.

The CT scans were taken at the O'Bleness Memorial Hospital, Athens, OH using a GE Helical Hi Speed – FX/i scanner (figure 15).

Fig. 15: Helical CT scanner

The images are captured and analyzed using the Image Works Workstation, which is a multifunctional, stand alone, single user workstation. The Image Works Workstation supports image display, film manipulation and composition functions, image analysis and manipulation. Beside film, image analysis and manipulation, the Image Works Workstation supports also 3D reconstruction from 2D slices.

The same synthetic skull used in the first part of the study, for modeling the virtual model, was scanned with the helical CT scanner following both sagittal and frontal planes. The interslice distance was set at being 3 mm. 48 CT slices were obtained for every analyzed plane.

A 3D skull model reconstructed by the Image Works Workstation can be seen in figure 16:

Fig. 16: Image Works Workstation 3D reconstruction [14]

The 2D images were imported as DICOM files in eFILM medical image manipulation software and then exported as TIFF files. The second skull model was then reconstructed using **SurfDriver**, a 3D reconstruction program. SurfDriver allows the creation of a complete 3D object from 2D serial sections in a few easy steps. The reconstruction concept is based on tracing the outline (contour) of the object on each 2-D image and then SurfDriver will surface the object created (figure 17). The final model, ready only in a few minutes, can be exported for analysis as DXF, IGES to a FEA software. For all 48 CT sections, contours were created using the pencil tool.

The Pencil tool was used, even if the Magic Wand tool is easier to use - just click inside the object - because sometimes the contour could be really intricate and the pencil tool gives a better control on how the vertices will be placed.

Fig. 17: CT section contour in SurfDriver

After all the contours are traced, the process ends and the object is surfaced. The final model can be adjusted (slice translation, rotation, copy etc), measured, rotated, edited (delete polygon, delete vertex, make polygon). The second model reconstructed following this route can be seen in the next figure:

Fig. 18: Second model. 3D reconstruction in SurfDriver

The model was then transferred in MSC Patran as an IGES file to be meshed. It was transferred as surfaces and successfully transformed into a 3D solid in order to be analyzed. The process is described in detail in the FEA chapter.

3.3 Other 3D reconstruction methods

Two other methods of reconstruction were tried for making the second skull model. Both methods were designed in such a way as to fulfill the two most important

requirements: to do the 3D reconstruction of the skull and to transform the initial DICOM files in any file compatible with an engineering software for analysis (STL, IGES, etc).

The first step was to convert one by one all the 48 CT images from DICOM files to TIFF files using eFilm software. The first method used Adobe Streamline, an image processing software, mainly to import the TIFF files and to export them as DXF files. Streamline software was used also for extracting the boundary of every section and export them as DXF files compatible with Unigraphics Solid Edge software. From here, the model would be reconstructed and transferred in Algor. The method could not be used because the DXF files could not be transferred successfully in Solid Edge.

Another method was based on extracting the coordinates (x, y) of every CT section, using a special function in Optimas image analysis software – Point Morphometry – and to bring these coordinated in Solid Edge.

A Visual Basic program was developed to convert the extracted coordinates to closed curves. The converted boundaries from Optimas into Solid Edge can be seen in figure 19.

Fig. 19: Curves in Solid Edge

To obtain the final model, the external boundaries of each cross section would be lofted using the Loft Protrusion command and then the final model would be transferred in Algor for analysis.

This second method could not be used either because of several problems. It is extremely difficult to reconstruct a model from many cross sections in an engineering software, especially a complex model like a human skull, because the contours have different dimensions and intricate shapes.

Efforts were made to choose the coordinates to be approximately the same for all the sections, to start with the same y or the same x, to choose the same number of points for every cross section and so on. Loft Protrusion command could not be used for the entire set of contours. The command could be used for only 5 consecutive sections but for more than that, it gave an error answer saying that the geometries are intersecting somewhere, even when the distance between the slices was significantly large.

3.4 Medical image software

For this study a few image processing software were compared in order to find the best interface between medical (OSIRIS, SCION IMAGE, EFILM, OPTIMAS, 3D DOCTOR, SURFDRIIVER) and engineering software and to perform the 3D reconstruction of the skull model.

OSIRIS, a free medical image manipulation and analysis software, was the first software analyzed. The Digital Imaging Unit at the University Hospital of Geneva, Switzerland, developed the OSIRIS software as part of the Geneva PACS project [15].

At the beginning of this study OSIRIS was used in order to perform the 3D reconstruction from 2D slices. The program allows the image display in a single window as stack mode and tile mode and has many image display and manipulation functions (zoom, adjusting the contrast, filters). From an engineering point of view, OSIRIS is a very robust and stable software.

It is also very easy to use and easy to learn how to use even if the user has no previous experience working with medical image software. The software has a command called *Multiple ROI Volume*. Using this command, a contour volume is reconstructed from all the 2D slices. The boundary of the slice needs to be picked first, that is, tracing a region of interest (ROI). All the slices are then displayed in tile mode and then the Multiple ROI Volume command becomes active.

The problem occurred when the work had to be saved/exported. The program can import/export PYPYRUS 2 and 3, DICOM and TIFF files but the 3D volume can be saved only as .txt (data window).

Fig. 20: OSIRIS - Multiple ROI Volume command

Osiris was developed for medical image manipulation and analysis and it works very well for this. The difficulty arises when the purpose of its use is extended toward other fields of study, such as engineering. Using Multiple ROI Volume, a 3D contour is generated as seen in figure 20.

It is true that it can import DICOM files and export them as TIFF, but this is done by almost all the other image processing software. The next analyzed software was **Scion Image** for Windows. Scion Image is the Windows version of NIH Image, a Macintosh program, written at the National Institutes of Health. Scion Image may be used to capture, display, analyze, enhance, measure, annotate and output images [16]. Scion Image has a much better, professional look; the commands are easily accessible (buttons on the screen), easily recognizable from their icons, even if you are not a frequent user, and the most important thing, it has many commands other software do not have. Scion Image has multiple possibilities to process and analyze an image (binary, arithmetic, plot profile, calibrate etc) and to edit an image (select, scale, invert, rotate, flip, zoom etc).

Scion Image is a very modern and professional software, which gives the user a lot of choices in attaining a specific goal through the multiple possibilities it offers. The software was tested in order to make the 3D volume reconstruction using the *Stacks* command Scion Image has.

Scion Image supports the organization and manipulation of a series of 2D images as a 3D array called a stack. The procedure is extremely simple, all the 2D images are opened and then from Stacks the Windows to Stack option is chosen, which means converting a set of 2D images into a stack (a stack contains a set of related 2D

images, such as a movie loop or serial sections from a volume). When all the pictures are in a stack, a new slice can be added, deleted, navigate between them, make a movie, animate them, and finally make a project. Another advantage of the Scion Image software is that it has several possibilities to transfer an image, it imports/exports as DICOM, BMP, TIFF, LUT and ROI files.

As the Scion manual says, *Project* does volume rendering, useful for visualizing the internal structures of 3D images, but this is only a simple projection and is not by far a volume reconstruction or even a contour reconstruction (figure 21). *Project* is a very useful command for other investigations. The user can set the slice distance, the angle, the orientation and one can see and rotate every slice, but for 3D reconstruction from 2D slices, it was not enough.

Fig. 21: Projection in Scion Image

The next analyzed software was **eFILM**. Efilm is a relatively new medical imaging software developed by eFilm Medical Inc. which specializes in the development of medical imaging information systems and software. The software can

be used in any health-imaging environment, including hospitals, clinics, dental offices, veterinary clinics, and related educational institutions [22].

One of the most important features of eFILM software is its image retrieval feature. eFILM was used to transfer the CT data, as DICOM files, from the CT workstation to our computers. Another important feature of eFILM is its export/import capability. The software allows the import of DICOM files, for example, and exports as TIFF, Jpeg, and Bmp files. This was a very important feature when working with different software and when data need to be transferred from a medical software into an engineering one. Efilm software has a very friendly interface; it is easy to use and easy to work with. In the main window there are more than 50 buttons which are very easy to use, and cover almost any function one needs to use: measure, browse through images in a series or through series, flip, rotate, invert, filtering (figure 22).

Fig. 22: EFILM software

One unique command and an extremely useful one is the 3D cursor. The program not only easily allows the display of the CT images in any format (the user has the possibility to determine how many rows and columns are displayed) but it also locates a point in 3D space using the 3D cursor capability (Tools - Multiplanar – 3D cursor). The software has also a stacking function that allows a quick and easy movement through the images of a stacked series. This is extremely useful for making a movie out of all the images (cine function). However, for reconstruction purposes this function cannot be used.

Efilm does not have any function that will do the 3D reconstruction or at least create a contour from 2D slices. Despite the fact that it couldn't be use for the present research, it has by far the most original features and many other capabilities that makes it a very good medical image software.

Another very powerful medical image software is **OPTIMAS**. OPTIMAS is a 32-bit software for image analysis for Windows (95/98/NT 4.0), designed by Media Cybernetics. Optimas is different from the other software analyzed so far not only because it is the only one presented in this paper that involved a substantial cost, but also because it is a software for image analysis and laboratory automation. It offers powerful processing and measurement capabilities, output to files or Excel, scripting, programming, hardware compatibility, and monochrome or color images. It supports high bit depth, image sequences, complex regions of interest, advanced morphology, Visual Basic, networks and more [23].

Optimas has many possibilities to analyze an image, from the most common and simple ones (common measurements) to very complex and powerful ones (mark points,

trace line, area, circular area, rectangular area, find points, lines, area, extract measurements etc). A very important feature is Data Menu in which one can access a point, line and area morphometry feature, generate particle count, find percent area, do a volume analysis etc. Regarding the reconstruction capabilities, Optimas does not do 3D reconstruction. The only capability that it is close to the reconstruction feature is the volume analysis option. This command is designed to measure the volume of specific structures in a 3D series of images. The images are selected using Sequence Acquire from the Image menu and then the images are superposed using Volume Analysis from Data menu (figure 23).

The result is a movie. In this paper, Optimas was used for the second skull model to import the TIFF images and to extract the X, Y coordinates of each cross section using the Point Morphometry option. A visual basic program was developed to convert those points to closed curves under Solid Edge software.

Fig. 23: Optimas software

Optimas cannot be used for reconstruction purposes but it is by far the most complex and powerful image processing software presented in this paper.

The next software that was analyzed was **3D Doctor**, the trial version. 3D-DOCTOR is an advanced 3D image rendering, processing and analysis software developed by Able Software Corp., a software developer specialized in image processing, rendering and visualization applications. 3D-DOCTOR is developed to provide a set of tools to visualize 3D image data (CT, MRI, Microscopy and other types), to extract object boundaries using both fully automatic and interactive 3D image segmentation, create both 3D surface and volume rendering [24].

3D doctor has many advantages, the most important one being its capability to visualize images in most file formats. It imports and exports files like DICOM, TIFF, BMP, JPEG, Raw Image Data and other 3D formats. The most important aspect is that it export 3D rendering data in DXF, 3-D Studio, VRML, raw triangle object, XYZ and other 3D graphics file formats and as can be seen from the previous analyses, this is an extremely useful and rare capability for an image analysis software.

Another very interesting feature of 3D doctor is its display function, a 3D image can be displayed in a *plane view window* to a slice, in a *montage window* where all image planes are organized side by side, in a *3D volume rendering window*, in a *3D surface rendering window*, or all the windows can be used at the same time.

The 3D doctor provides automatic *3D surface rendering* from extracted boundary data, direct *3D volume rendering* (see figure 24) by combining object boundaries and image voxels together or by projecting voxels with the highest intensity values and even *3D image restoration and reconstruction*.

Fig. 24: Volume Rendering in 3D Doctor

Unfortunately the reconstruction is not supported in the trial version. 3D doctor is a very modern and powerful image analysis software and it seems to fulfill the analysis' requirements: to have an export function that could export files compatible to an engineering software and to have a 3D reconstruction function.

SurfDriver is a surface reconstruction program, a tool for developing detailed morphological reconstructions of anatomical features using sequential image [25].

A SurfDriver trial version was used for this project and unlike the 3D Doctor trial version, the SurfDriver trial version allows 3D reconstruction from 2D slices as well as the transfer of the newly created files as IGES and DXF files. The application is extremely easy to use and the results are impressive.

The central option window, called the Command Palette, has seven functions. The user has the possibility, from the beginning, to choose to create a new object, to edit, to process, to view an existing object, to adjust the image orientation or to calculate

volume and surface area. To create a new object, the user has first to specify the slice characteristics (width, thickness, slice interval), and then, using the Tool Palette, one places and manipulates the vertices.

For making the contours the Pencil tool was used. After the contours were completed for all the 48 CT sections, the user has the option to surface the object immediately or to perform the surfacing later. The surfacing process basically connects the vertices that were previously traced. This is shown in figure 25.

Fig. 25: 3D reconstruction from 2D slices using SurfDriver software

The model can be moved, rotated (free, constrained and stereoscopic rotation), or displayed as a wire frame, a simple box, or full-framed object. The software has also three rendering possibilities, view wire frame, no texture mapping or full texture

mapping. SurfDriver has many other capabilities that are very interesting and useful for any image processing analysis. One of the most important features of this software is that it permits the export of the files created as DXF, IGES and Morphologika. SurfDriver is an excellent (fast, accurate, non expensive) tool for 3D reconstruction from 2D slices and as it can be seen from the figure, the results are impressive.

CHAPTER 4 FINITE ELEMENT ANALYSIS

Finite element analysis is a method widely used for finding a solution to a complicated problem by replacing it with a simpler one [26]. The technique is based on the concept that any complex engineering problem can have *an approximation solution* by subdividing the problem into more manageable, simpler elements. The problem will have only an approximate solution and not an exact one, because a complex geometrical shape is divided in smaller elements that only approximate the original shape.

The most famous example in literature given for a better understanding of the finite element method is the circle example. Ancient mathematicians found that measuring the perimeter of a circumscribed or inscribed polygon to a circle can approximate the circumference of that circle (see figure 26). Each side of the polygon is considered to be a finite element. It was observed that increasing the sides of the polygon, the approximate solution converges to the exact solution [26].

Fig. 26: Finite element method illustration.

Finite element method is used today in almost all engineering disciplines because it allows solving complex equations from any engineering field by reducing them to

simple linear equation. It is successfully used in aerospace (static analysis of aircraft, rocket, spacecraft, missile structures, stability, design), automotive (mechanical design, crack and fracture problems, stress concentration etc), biomedical (stress analysis, impact analysis, biomechanics), geomechanics (analysis of excavations, soil structure, stress analysis), civil engineering (analysis of trusses, roofs, walls, propagation of stress waves), electrical (steady state analysis, eddy current), hydraulic and hydrodynamics (heat conduction, analysis of potential flow, viscous flow, wave propagation), nuclear engineering (analysis of nuclear pressure vessels, temperature distribution in reactor components) [26],[27].

Usually, a linear static stress finite element analysis consists of:

- Designing the model or importing it from other software;
- Meshing the model;
- Adding constraints, loads;
- Defining its characteristics (materials properties);
- Checking the model;
- Performing the analysis.

The most important, difficult and time-consuming parts in a FEA analysis are designing the model and meshing it. The stages in doing a finite element analysis are interconnected and strongly dependent one to another.

If the geometry of the model is not perfect, the model cannot be meshed and when checking it, the software will generate a geometry error. The analysis becomes even more complicated when the model is imported from another software, even if the two software are compatible, because geometry transfer problems can easily appear.

The transfer of the model from one software to another was done as a STL file for the first model and as an IGES file for the second skull model. The STL file exported from 3D Studio Max was further imported in FEA Algor software in order to be transformed also in an IGES format.

Another difficult part is meshing the model. Depending on the geometry of the model and on the type of the model, a proper mesh is chosen. There are many studies that compare several meshing generation methods in order to propose the best one [30], [31].

Usually any FEA software provides many mesh capabilities for every 2D, 3D analysis. A three dimensional model can be meshed using tetrahedrons, pentahedrons, hexahedrons or a combination of these (figure 27).

Fig. 27: The most common three-dimensional finite elements [33].

After designing the two skull models, they were meshed and then transferred in a FEA software for analysis.

4.1 FEA - First Model

4.1.1 First Approach

The first model was successfully imported in **Algor v.12**, (FEA software developed by Algor Inc.) as a STL file, using the Import option as can be seen from the following picture:

Fig. 28: Algor Skull Model

The chosen analysis was a linear static stress analysis. The Model Data was completed choosing Brick as element type. First, the skull model had to be meshed before the analysis. The method used for trying to mesh the model was FEA Mesh: Solid Mesh Generation.

A geometry error occurred when the meshing started. The Mesh Enhancement capability was activated but it also generated a geometry error. As figure 29 shows, the

model had 2 regions that raised problems. The model could not be meshed until the geometry was corrected in the two red zones (around the ear and on the lower jaw).

One attempt to improve the geometry was to delete the “wrong” points from the red zones, but the effort took a long time and the result was even worse, because now, in addition to the known geometrical problems, new errors, such as *gaps*, were detected.

Fig. 29: Algor model. Geometry problem zones

Because the model was extremely complex and nothing much could be done to improve its geometry, another software was considered to mesh and analyze the model.

The skull model was transferred in **Hypermesh 3.0**, created by Altair Engineering, a high performance finite element pre- and post- processor that enables the creation of finite element and finite difference models for analysis and engineering simulation [34].

HyperMesh was not able either to create a tetra mesh or any mesh for the second skull model. The main problem that appeared was that there were a lot of free edges and these correspond to areas where elements are simply missing (figure 30). Therefore the model is not enclosing a volume and cannot be meshed.

Another concern was that more than 65 - 85% of the elements failed simple checks, due to the presence of distorted elements, inside - out elements, elements with different normal orientations etc. Therefore, even if a mesh could have been generated, it would have probably ended up with very bad quality tetras that could have created many problems to a FEA analysis.

Fig. 30: HyperMesh model with free edges indication (red)

The model was then transferred in **MSC Marc Mentat 2000**, produced by MSC Software, a nonlinear finite element solver with powerful mesh and mesh enrichment capabilities.

As in the previous applications, the model was not transferred very well and a lot of information was lost through the STL transfer (see figure 31).

The majority of elements were distorted, inside out, upside down and generally, the geometry had many geometry problems. As can be seen from the figure, the distorted elements, represented in blue, were almost 50% from the entire number of elements.

Because of this complex and “wrong” geometry, the mesh could not be created.

Fig. 31: MSC Marc model with distorted elements (blue)

The model was then transferred in **MSC Patran 2000** as an IGES file. MSC Patran is a CAE software used for performing simulation on mechanical products, developed also by MSC Software.

The model could not be transferred directly from 3D Studio Max to Patran because 3D Studio Max does not have any export option compatible with Patran import option, so a lot of information was lost.

The model was transferred initially as an STL file from 3D Studio Max in Algor and from here exported as IGES file in Patran (figure 32).

Fig. 32: Transfer process

MSC Patran allowed the import of the model as curves model. The model has more than 50.000 curves (represented by a yellow color in Patran), see figure 33. However, the “skin” created in 3D Studio Max, the corresponding surfaces, was not exported.

This was happening because the model is made from *a cloud of three-dimensional points*. Unfortunately, none of the software investigated had an option that allows the reconstruction of a model from a cloud of points (usually resulted after 3D digitizing processes).

Fig. 33: First skull model in MSC Patran

The model had to be reconstructed from the beginning, by rebuilding the surfaces, transforming the model into a solid and then meshing it.

This could not be done for such a complex model because most of this work has to be done *manually*.

4.1.2 Second Approach

Because of this, a simpler model made only from seven splines was designed in 3D Studio Max. The geometry was modeled without the frontal part, “the face”, because this is considered the most intricate and problematic (figure 34).

Fig. 34: Simplified skull model

The model was transferred from 3D Studio Max into MSC Patran following the same route. Even so, the model was still too complex to be analyzed.

4.1.3 Third Approach

In order to reduce the geometry to a much simpler one, another way of designing the model was investigated. The splines were obtained by scanning the skull with the Microscribe. They were imported in the same file, as simple splines, without making a model out of them, that is, without converting them into curves, their corners into Bezier corners, etc. (see figures 35, 36).

The splines were modeled in such a way as to have the same number of segments, the same initial points (3D coordinates).

It is extremely important to keep constant the number of points, with the same location on each spline because this helps a lot the surfacing process.

Fig. 35: Lateral view of the 5 splines

Fig. 36: Frontal view of the 5 splines

The points were traced approximately at the same distance and location on each spline. Every spline had 14 points, 15 segments and almost the same shape except for the first one.

Fig. 37: The first spline has with 14 nodes, 15 edges and 12 surfaces.

In order to recreate the model from these splines, the entire geometry must be recreated *manually*. For example, the first point of the first spline must be connected with the first point of the second spline, then with the first point of the third spline and so on. At the beginning, 12 surfaces were created for the first and the last spline, using the *Create – Surface – Edge* path. Each surface was created from 3 *Edges* using the pattern shown in the figure 37. Then, the surfaces were created between two consecutive splines using *Create – Surface* with the 2 *Curves* option. The final model was verified with *Verify – Surface – Surface Boundary* option, to detect any irregularities such as free edges.

The model was successfully created, without any free edges, and was ready to be transformed into a solid.

There are two kinds of solids in MSC Patran:

- *Parameterized solids* that have only 5 - 6 faces.
- *B-Rep solids* that can have more than 5 or 6 faces. This means that the solid is defined just by its boundary surfaces. A B-Rep solid can only be meshed using Tet elements because they do not have any mesh paths defined inside the solid [35].

The model reconstructed (“the frame” of the model) used this approach – connecting each point with the next corresponding point - can be seen in the following picture:

Fig. 38: Reconstructed model (lateral view).

The Tet meshing algorithm works in the following way.

- It meshes the faces with 2D triangular elements;

- It equivalences to tie all the surface elements together;
- It verifies that all element normals are facing outward;
- It then fills the volume inside with Tet elements [34].

After the geometry was successfully done, the model was easily transformed in a solid (B-Rep solid) and then automatically meshed using a solid Tet mesh with a global edge length of 2 and a Tet 10 mesh element (figure 39).

Fig. 39: Simplified solid model

4.1.4 Fourth Approach

The model was designed by combining the two direct and indirect methods. This is the best method to reconstruct a model and to transfer it for FE analysis because it combines the advantages of both methods, 3D coordinates input and automatic surfacing using a reconstruction software.

The five original splines obtained using the Microscribe were transformed in NURBS object in 3D Studio Max. The file was saved as a STL file, transformed into an IGES file and finally imported into SurfDriver software. The fourth simplified model was reconstructed from surfaced splines following the same technique through which the second model was reconstructed from CT scans. The model was successfully reconstructed as can be seen in figure 40 and can be transferred into MSC Patran for analysis.

Fig. 40: MicroSplines model in SurfDriver

4.2 FEA – Second Model

The second model was first imported as an IGES file from Surfdriver into **Algor** software. Because of the IGES transfer between software, some of the information of the second model's geometry was lost. The main problem resulted after the transfer was that the Algor model had many gaps, missing elements, and therefore the model was not a closed volume as can be seen in figure 41.

Meshing the second skull model was impossible in these circumstances, unless the gaps were closed.

Closing the gaps can be a very difficult process especially when the model is so complex, when it has more than 10.000 elements and a few thousands faces. Therefore, it seemed a better approach if the model would be meshed in another meshing software.

Fig. 41: Algor second model

The second model was transferred as an IGES file in **Hypermesh** but the software could not process it; it gave more than 4000 errors. The errors could be caused by the IGES file transfer combined with the complexity of the model.

MSC Patran, v. 2000 r2, was the only software that imported successfully the second model, as an IGES file. The imported model can be seen in figure 42.

Fig. 42: Patran solid model

The Patran imported model had a total of 4664 surfaces. The model was transformed into solid in Patran using the *Geometry – Create – Solid – B-Rep* path. The resulted B-Rep solid had created 552409 nodes and 392273 elements.

Fig. 43: MSC Patran TET solid mesh

The solid was then meshed using the *Element – Create – Mesh – Solid* path using a TET mesher with TET 10 elements (figure 43).

The finite element analysis was done in MSC MARC Mentat 2000. The models were transferred from MSC Patran in MSC Marc as .DAT files.

The model reconstructed from CT scans could not be analyzed because of its huge geometry. Three simplified models were designed in SurfDriver, using 14, 9 and 7 CT scans, but none of them worked as expected. For example, the model designed with the minimum possible number of CTs (7), when transferred in Patran, gave a total of 708 surfaces. All of the simplified models resulted in a large number of surfaces (and consequently elements). Furthermore, it takes a long time for those models to be processed, if they can be processed at all.

4.3 FEA Analysis

For this study, a linear stress analysis was performed. Even if the bone is an anisotropic, nonhomogeneous, nonlinear material and a nonlinear analysis will be more appropriate, in biomechanical studies, for simplicity, the bone is considered an isotropic material and a linear analysis is usually done.

For simplicity, the models presented in this paper are considered to be solid inside. In a biomechanical study this will be an important factor to be considered because it will have an important impact on results. In this case however, the main purpose of this paper was to compare the two models and to design a method rather than do an exact measurement of the stress or strain involved in the analysis.

The data for the bone material were taken from a study investigating the calvarial bone [29]. The calvarial bone represents the upper domelike portion of the skull without the lower jaw. It is used often for craniofacial reconstruction surgery and bone transplants.

In this study, the analysis was performed linearly and post processed for obtaining the strain. They determined and proposed a Young's elastic modulus of 20.685 GPa and a Poisson's ratio of 0.22. Other studies investigating the human bone, usually the lower extremity bones, proposed a Young's elastic modulus of 19 GPa with a Poisson's ratio of 0.3 [32].

First, the boundary conditions were set using fixed displacement in all directions. The skull was constrained in the occipital region as seen in figure 44:

Fig. 44: Boundary conditions. Occipital constrains.

The load was applied in a single point in the middle of the frontal bone as a *Point Load*, perpendicular on the skull, with 50N in magnitude.

The value of the force was initially chosen to be 25N because this represents the average mass of an average dimension skull (2.5Kg). The 25N force was considered to be too small to create a visible change so the magnitude of the force was increased to 50N. The 100N magnitude seemed to be too big so a force in the range 25-100N should be chosen.

The bone was considered an isotropic material, having an Elastic Modulus of 200000 MPa, a Poisson's ratio of 0.22 and a mass density of 0.0002 lbm / in³.

The geometrical properties were set next: the entire model was considered to be 3D solid made of tetra 10 (127) elements. Figure 45 shows in bright red the stress accumulated in the point where the force was applied (the middle of the frontal bone).

Fig. 45: Equivalent Von Mises stress

Figure 46 illustrate the maximum stress in the occipital area, the area in which the skull is totally constrained.

Fig. 46: Component 11 of Stress

CHAPTER 5 RESULTS AND COMPARISON

The two models were designed primarily for finding a simple and non-expensive method of 3D reconstruction and for comparing two very different methods.

The first model, obtained by collecting real three-dimensional coordinates, was designed using an unusual, unconventional technique and this is considered maybe even more important than its analysis' results. Creating the model combines working with a relatively inexpensive 3D hand - held digitizer and processing the results in a 3D modeling software. The whole process takes very little time and the cost involved is insignificant. On the other hand, the second model obtained using the indirect method required collecting data from a CT scan, which is very expensive, and the use of another software to reconstruct the model which could be costly or time consuming.

As it can be seen in table 2, the two skull models differ greatly. The only aspect that they have in common is that they are both in the end transformed into solids (TET solids) using the same software (Patran) and the same technique (solid TET mesh).

The resulted skulls models are so different because they are designed using different reconstruction methods (indirect vs. direct), using different tools (Microscribe, CT scanner) different software inputs (points, surfaces), different file transfer (STL, IGES), different FEA software inputs (curves vs. surfaces) etc.

When comparing the two models, the second one, created from CT scans, was definitely reconstructed better and resembles closely with the real model.

The first model, although reconstructed with lesser details, is created from real 3D coordinates, therefore, at least theoretically, it should be more accurate.

Table 2: Comparison between the two skull models (similar and distinct features)

	MODEL 1 (Unconventional)	MODEL 2 (Standard)
Original input	Cloud of points (3D coordinates)	2D images (CT – scans)
Tool	Microscribe - Max	CT Scanner
3D Reconstruction Method	Direct	Indirect
3D Reconstruction Software	3D Studio Max	SurfDriver
Software input	Spline	CT scans
Software output	NURBS model	Surface Model
Transfer	STL file	IGES file
FEA software input	Curves	Surfaces
FEA model	Make surfaces <i>manually</i> Make a solid Make solid mesh	--- Make a solid Make solid mesh
FEA software output	Tet Solid	Tet Solid

Two 3D reconstruction methods were described and compared in this paper: the direct and the indirect methods. Both of them have advantages and disadvantages as shown in table 3. Both of them were used in this study for designing a model and for analyzing it. The indirect method is more efficient than the direct one. This is not a surprise conclusion as the indirect method is the standard method, widely used today for 3D reconstructions.

What is the most important conclusion is that the direct method is comparable in any aspect with the standard CT method. For now, the standard method is by far the best method for 3D reconstructions but just because other options, like the Microscribe option, were not enough investigated. Microscribe – Max is mainly used now for 3D modeling purposes but this paper proves that it could be a very powerful and practical tool with multiple applications, including biomechanics and medicine.

Two main problems were encountered using the unconventional method:

- No IGES export from 3D Studio Max v. 2.5 (newer version which supports IGES export);
- Cloud of points export (FEA software with option to convert a cloud of points).

As previously seen, the problems were usually created by external factors that had nothing to do with the proposed method, which is an extremely innovative and powerful one. The fourth approach described in this paper, that is combining both the direct and the indirect methods seems to be the most suitable method because it uses the best features from both of them, cloud of points input capability of the unconventional method and the reconstruction capability of the indirect method.

Table 3: Comparison between the two methods (pros and cons)

	Direct 3D Reconstruction <i>(Microscribe – 3D Studio Max)</i>	Indirect 3D Reconstruction <i>(CT Scans - SurfDriver)</i>
Advantages	<ul style="list-style-type: none"> ▪ Easy to digitize; ▪ Non expensive; ▪ 3D coordinates input; ▪ Little amount of time spent: <i>minutes</i>; ▪ IGES, STL files output. 	<ul style="list-style-type: none"> ▪ No initial model preparation required; ▪ Surfaces output; ▪ SurfDriver – easy to use; ▪ No manual reconstruction of the model ; ▪ Best 3D reconstruction.
Disadvantages	<ul style="list-style-type: none"> ▪ Initial model needs extra preparation; ▪ Cloud of points output; ▪ Splines/Curves output; ▪ 3D Studio takes a long time to learn how to use it ▪ In FEA software, the surfaces of the model have to be reconstructed manually. 	<ul style="list-style-type: none"> ▪ Expensive; ▪ Time consuming (CT appointment, long procedure, data transfer etc): <i>days</i>; ▪ Scanning is done by somebody else; ▪ 2D coordinates input (CT scans); ▪ DICOM files output – needs converter.

Another important part of this paper was to determine, from an engineering point of view, the features, availability, cost and user-friendliness of various medical image processing software available today, regarding the 3D volume reconstruction from 2D slices. A comparison was drawn and some of the results are presented in Table 4. Opinions presented as “features” in table 4 are those of an inexperienced user, mainly based on personal experience with each software.

The six medical image software analyzed in this paper - OSIRIS, SCION IMAGE, EFILM, 3D DOCTOR, OPTIMAS and SURFDRIIVER - are designed for medical use. Each of them has at least one command that make it unique and extremely useful in various medical fields but the most important aspect, in my opinion, is that they facilitate the access to medical files and ease the possibility of sharing information.

In finding the best software to do the reconstruction, two major criteria were followed. The best software will not create a contour, projection or rendering but a real 3D reconstruction. The second criterion was the ability to export this reconstructed volume in an engineering software for analysis and as can be seen in table 4 only one of the investigated software has this feature.

For this study, only one of the six free available medical image software and the free trial versions could be use: SurfDriver software. As seen in table 4 column four, only SurfDriver has the 3D reconstruction capability. That is why, designing the second model could be even more expensive; in addition to the cost of CT scanning, it may involve either spending a lot of time trying to find the best software to do the reconstruction or spending a lot of money to buy such software.

Table 4: Comparison between various images processing

	Features	Import / Export	3D Reconstruction	3D Command	Cost
OSIRIS	Easy to use; Robust, stable software.	Papyrus 2,3 Dicom, Tiff	Creates a contour volume	“Multiple ROI Volume”	Free
SCION IMAGE	Professional look; Multiple possibilities to process and analyze an image.	Dicom, Tiff, etc	Makes a projection	“Project”	Free
EFILM	Medical image and information system; Image retrieval, 3D cursor	Dicom, Tiff, Jpeg, Bmp			Free
3D DOCTOR trial version	Reconstruction, DXF, 3D Studio export (not available in demo version); 3D rendering.	Dicom, Tiff, Jpeg, Bmp, etc	Makes a 3D image	“Volume rendering”	Free
OPTIMAS	Excellent measurement functions; Automatic data output.	Tiff, Bmp, Jpeg, Gif etc			Aprox \$7000
SURFDRIVER trial version	3D Reconstruction; DXF, IGES export.	DXF, IGES (type I, II, III), Morphologika	3D object	“New Object”	Free

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDIES

The objects obtained by using the Microscribe-Max tool can be transferred in a FEA software and analyzed using:

- Splines - with the same number of points, the same point location on the spline and equal number of segments.
- NURBS - that are transferred in SurfDriver.

The best feature of the first model, designed using the direct unconventional method, is that is reconstructed from *real 3D coordinates*. The worst aspect is that it exports the model as clouds of points. Using and FEA software with an option to convert the points will solve this problem.

The models reconstructed from CTs can be transformed in FEA objects using:

- SurfDriver 3D reconstruction software.

The method proposed in this paper allows the 3D reconstruction of a model from any input data (cloud of points or 2D images) using SurfDriver and allows also the transfer of this model in a FEA software.

This method can have multiple applications: haptics and telemedicine, virtual surgery, virtual education and training etc. Studies have already been made in telemedicine combining the benefits of the Microscribe with 3D ultrasound [36]. This project was initially developed by the US Army to support medical operations in Bosnia. The central idea was to create a network - based tool that will allow sharing medical information.

Another extremely important field in which a microscribe model can be used is haptics. Haptics is the science based on the sense of touch [5]. Haptics gives the user the sense of touch and force from virtual computer models. The model created with the Microscribe and the 3D Studio Max was used for a demonstration within a haptics project that is going on now at Ohio University. In this project, the PHANToM software is used to create a virtual environment. The main objective is to create a tool for medical education. Medical students for example, can be trained in the art of palpation using virtual reality, before performing it on human subjects.

These models can be successfully used for virtual surgery applications, the doctor can practice the medical procedure and “perform the difficult surgery” before actually opening up the patient.

For this study, a simple FE analysis was performed on the simplified model just to demonstrate that the reconstructed model could be successfully analyzed. The entire model could not be analyzed because of its huge proportions and the amount of time and work involved. A very interesting future work could be to perform the analysis for the both models and to compare the results. Another future work can be to find a method to compare the actual accuracy between the two virtual models and the real skull model.

As can be seen, there are multiple applications in which the method proposed here can be successfully used. However, for now, the direct unconventional method is slow and hard to use. With so many benefits, a new technology based on this method will probably emerge soon.

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