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Additive Manufacturing of Anatomical Models from Computed Tomography Scan Data

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Abstract: The purpose of the study presented here was to investigate the manufacturability of human anatomical models from Computed Tomography (CT) scan data via a 3D desktop printer which uses fused deposition modelling (FDM) technology. First, Digital Imaging and Communications in Medicine (DICOM) CT scan data were converted to 3D Standard Triangle Language (STL) format by using InVaselius digital imaging program. Once this STL file is obtained, a 3D physical version of the anatomical model can be fabricated by a desktop 3D FDM printer. As a case study, a patient's skull CT scan data was considered, and a tangible version of the skull was manufactured by a 3D FDM desktop printer. During the 3D printing process, the skull was built using acrylonitrile-butadiene-styrene (ABS) co-polymer plastic. The printed model showed that the 3D FDM printing technology is able to fabricate anatomical models with high accuracy. As a result, the skull model can be used for preoperative surgical planning, medical training activities, implant design and simulation to show the potential of the FDM technology in medical field. It will also improve communication between medical stuff and patients. Current result indicates that a 3D desktop printer which uses FDM technology can be used to obtain accurate anatomical models.

Keywords: 3D printing, rapid prototyping, CT scan data, anatomical modelling, FDM.

1 Introduction

Rapid Prototyping (RP) is an Additive Manufacturing (AM) technology rapidly developed throughout the 1980's and 1990's. Additive manufacturing allows to make prototypes or parts quickly on demand and any design modifications can be made without adding extra cost [1, 2, 3, 4, 5, 6]. MakerBot® company intended to democratize the rapid prototyping technology by offering an open source 3D

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FDM printer called MakerBot. The printer uses open filament system and as a raw material ABS and Polylactic Acid (PLA) plastic filament [7]. 3D printers are going to affect every face of life because any complex or customized parts can be fabricated in a short period of time and with less waste of material and lower carbon emission [8].

The following rapid prototyping techniques are the most commonly used systems. These are stereolithography (SL), selective laser sintering (SLS), (FDM), ink jet printing (IJP), laminated object manufacturing (LOM), 3D printing (3DP), and multi jet modelling (MJM) [9,10].

FDM technology is a layered additive manufacturing process which uses thermo-plastic material such as ABS and PLA to produce concept models, functional prototypes, manufacturing aids and low volume end-use parts. The FDM process begins by slicing 3D CAD data into layers. Then the data is transferred to a desktop 3D printer. The thermo-plastic material is uncoiled slowly and extruded through heated extrusion nozzle. The material is precisely laid down upon the precedent layers. Following each sequence the building platform is lowered down by the thickness of one layer while the extrusion nozzle continues to move in a horizontal X-Y plane. The process is repeated, adding layer upon layer, until the object is finished (see Fig. 1).

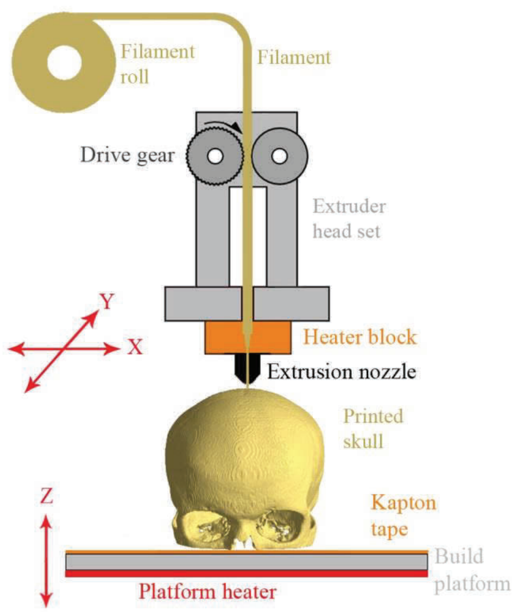

Figure 1: FDM method.

In this step, travel movements of the extrusion nozzle and if necessary support structure to hold the part upright position on the building platform and to support leaky connections, overhangs, cavities and bridges, are also generated. Once the part is completed these support scaffoldings can be removed off by hand. The slicing information is then exported to “gcode” or “x3g” file format that 3D FDM printer can understand to print the model. FDM technology is used in a wide range of industries such as automotive, aerospace, industrial design, consumer electronics, fashion, food and even in medical world [11].

Van Nunen et al. [12] fabricated stereolithographic skull models for five patients to be used in the surgical planning and as a result they demonstrated that the models had improved communication to kins and supported the training of residents. Sinn et al. [13] are also used SL method for craniofacial surgery because it provides highly accurate models and additional information in treatment planning. But they mentioned that stereolithograpic process added extra cost for the procedure and this is to be a hindrance to its widespread acceptance in clinical pratice. D’Urso et al. [14] fabricated the biomodels by using SLS method. They also reported that biomodelling is facilitated diagnosis, operative planning and communications between medical stuff and patients. On contrary, they pointed out that manufacturing time and cost are high. Sailer et al. [15] manufactured 20 patient’s craniofacial biomodels with selective laser melting method and they mentioned that main disadvantage of the process is expensiveness and the models are thin and fragile and when the models are taken apart and reassembled for simulation purposes the originalty of the model is definitively lost. A 3D desktop printer costs around $1000 is used in this study. The cost of consumable material used for the production of parts is so cheap and 1kg filament of ABS is as low as $29. 1: 2 scaled model of the skull can be produced in 6 hours. Anatomical skull models previously fabricated with variety of additive manufacturing methods but in this study, as a new, the skull model is manufactured with FDM technology both in a short period of time and very cheaply.

2 Building the anatomical model

The term “CT scan” is a representation of multiple X-ray images of structures of a human body on a display. The word “tomography” comes from the Greek word “tomos” which means slice and the word “graphein” means write [16]. It is possible to manufacture three dimensional tangible examples of anatomical models of human body with the developments in medical based modelling technologies. Anatomical model of a human body organ can be generated by collating of attained CT scan data. These digital models can be manufactured with rapid prototyping methods and these tangible models can be used for preoperative planning, diagnosis, therapy choices, teaching purposes, surgical simulation and medical device prototyping. These physical models could be very useful for planning very complex surgeries. Moreover, it is quite easy to manufacture a customized implant if there is 3D tangible anatomical model of a human organ [17].

In this paper, the manufacturability of anatomical models from 2-D DICOM CT scan data via converting those to 3D STL data by a desktop 3-D FDM printer is evaluated. A case study is also enclosed to show that how intangible digital medical data comes to life as a tangible object through the FDM method. The geometry of the anatomical skull is quite complicated and cannot be manufactured with classical cutting processes such CNC milling or extremely difficult to produce because it has intricate details. In this point rapid prototyping technology can be helpful. Fabricated anatomical physical model of a skull facilitate surgery planning, rehearsal of the operation by marking, drilling, cutting and so on without having time pressure. Having physical object in hand is not only useful for communication between medical personnel but also useful for presentation of the operation details with the patient and its kin [10].

The process of manufacturing of anatomical models from CT scan data via 3D FDM printer has six steps. They are;

- Data acquisition via CT Scan,
- Generating a 3D model from CT scan data and solid, shell or hollow CAD design of the model,
- Exporting the CAD model to STL file format,
- Slice the model into layers, generate the travel movements and support structure if necessary,
- 3D print the anatomical model,
- Remove the support material and apply finishing process [18, 19, 20].

2.1 Data acquisition via CT scan

As input data, a conventional hospital CT scanner's data are used. For the purpose of medical visualization, CT scan can provide detailed information about the anatomical structure in a layered format. First step generating a correct anatomical skull model is to strip bone structure from CT scan data. CT scans of an anonymous patient's skull are obtained. The thickness of the slices of the CT scan is 1 mm in average. Size of DICOM data files are 515 Kbytes.

2.2 3D modelling of the skull from CT scan data

160 DICOM files are processed in InVesalius v3.0 software during the skull stripping process (see Fig. 2). InVesalius, which is a multi-platform free and open source software package for visualization and medical imaging, is used for elimination of soft tissues and stripping of skull bone structure [21]. In order to strip the skull structure from soft tissues correctly threshold value is chosen as 246. InVesalius has exporting facility of 3D models as STL file format that is rapid prototyping's standard data transmission format to fabricate physical object of an anatomical model by using a rapid prototyping technology. The ".STL" file is further processed in open source MeshLab processing and editing of unstructured 3D triangular meshes software in order to remove floating substances not attached to the anatomic model and for smoothing (See Fig. 3) [22].

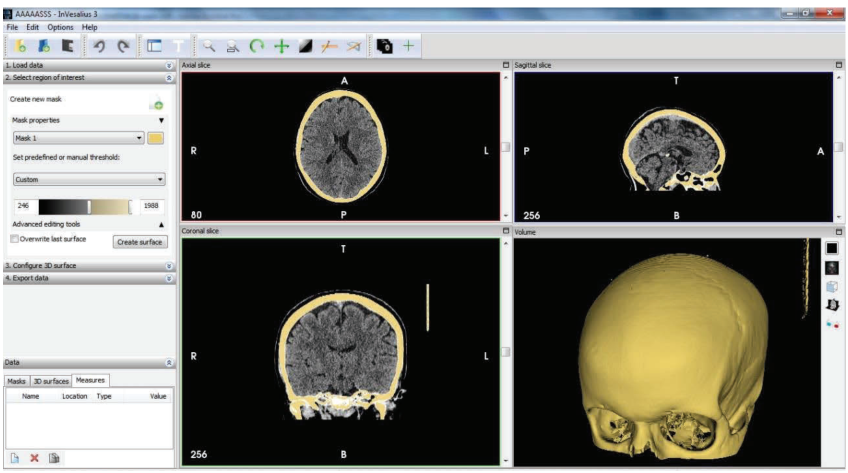

Figure 2: Skull stripping in InVesalius medical image program.

3 Manufacturing the anatomical model

The anatomical skull model is printed on a Flashforge Creator dual extruder 3D FDM printer in the department of mechanical engineering of Balikesir University. Its dimensions are 467 x 320 x 381 mm and small enough to use on a desktop in an office room. Building volume of the printer is 225x145x150 mm. Layer thickness can be changed between 250 μm and 100 μm. As a building material either ABS $(C_8H_8)_x(C_4H_6)_y(C_3H_3N)_z)$ or biodegradable PLA $(C_3H_4O_2)_n$ thermo plastics can be used. It uses open filament system and works with filaments 1.75 mm in diameter. Open source ReplicatorG 0040 or MakerBot® MakerWare™ v2.4 can be used

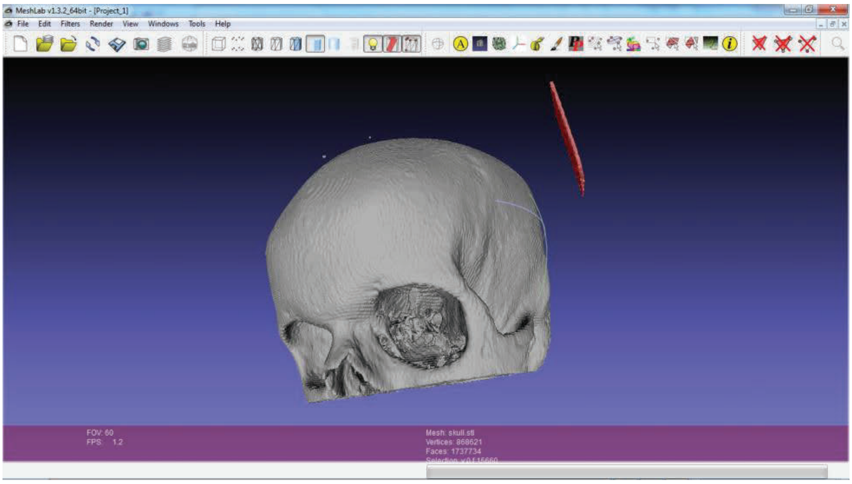

Figure 3: Removing of floating substances not attached to the anatomic model in MeshLab.

as slicing software. MakerBot® MakerWare™ program support ".STL" file format and can load it without any problem [23]. MakerWare™ 3D printing software is used for pre-processing and slicing of the anatomical model. Initially, the skull model is located on the build platform, scaled to 1:2, and orientated. In the slicing step of the anatomical model, MakerWare™ slices the 3D model into finite number of layers. For this study, 344 layers have been generated by the MakerWare™ software (see Fig. 4).

The thickness of the each layer for the model is 150 μm. This slicing step not only contains slicing procedure but also consists of generating travel movements for the extrusion nozzle and model support structure that holds the model upright position and prevent the leaky connections, overhangs, bridges, internal cavities. The anatomical model requires support structure because it has overhangs, bridges, cavities, and delicate details (see Fig. 4). For the creation of the model 23 gr (including support material) ABS thermo plastic was used and building time took 10 hours. The building platform of the 3D printer is heated to 110 ^{o}C before printing because ABS plastic does not stick on to the building platform even though platform is covered with kapton tape which adheres to ABS very well and prevents ABS parts from warping. On the other hand, the extrusion nozzle heated up to 230^{o}C in order to make flow the ABS plastic smoothly. During the printing process, extrusion nozzle moves along the X-Y axis and the building platform goes down in Z axis. The skull model fabricated in the department of mechanical engineering of the University of

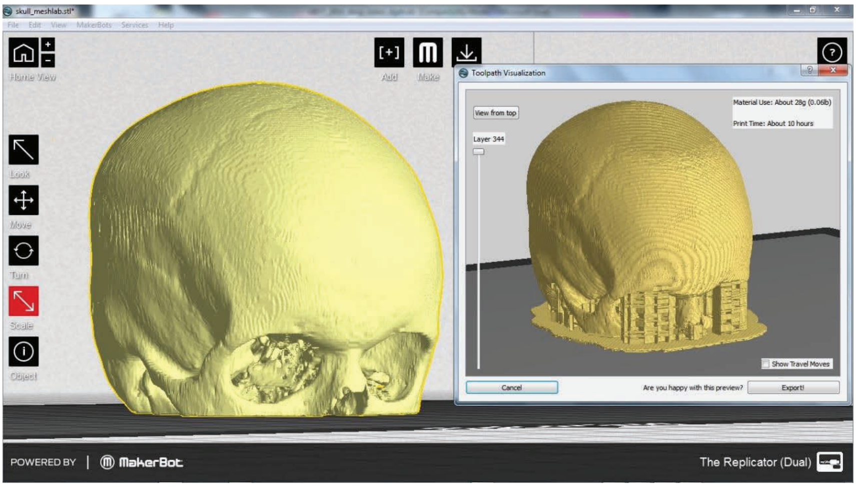

Figure 4: Slicing of the skull in MakerWare™ slicing - printing software.

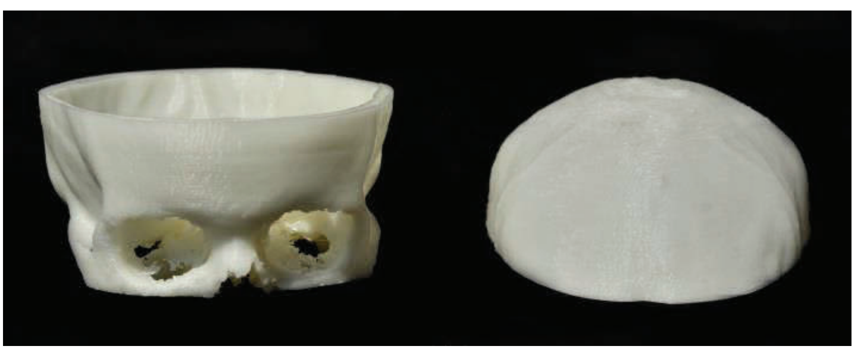

Figure 5: Tangible FDM printed case study skull.

Balıkesir is presented in Fig. 5. Following the production of the anatomical model, support structures removed by hand.

4 Conclusion

The main goal of this study was to validate the manufacturability of anatomical models from 2D DICOM individual CT scan data via converting those 3D STL data by a desktop 3D FDM printer. The case study showed that intangible digital medical data also comes to life as a tangible object through the FDM method. Even though anatomical skull models previously fabricated with variety of additive manufacturing methods, the cost of the models was high and fabrication time was longer than the FDM one. Moreover, approved materials, which can be sterilized, are available for medical use in FDM technology [24]. In this study, as a new, the skull model is manufactured with FDM technology both in a short period of time and very cheaply. Seeing this bio-model by the patients can help them to improve their understanding of the surgical operation.

It can be concluded that rapid prototyping in medicine is an emerging technology and has enormous potential for variety of medical applications like preoperative planning, diagnosis, therapy choices, teaching purposes, surgical simulation and medical device prototyping. However it is not used in everyday clinical practices yet because of its current limitations such as the time that needed for producing a 3D anatomical object and very important in emergency cases. Fabrication time ranges between couple of hours to couple of days. Of course this is no acceptable for emergency cases. But in near future it will increase its utilization in medical field hugely and also academic research activities will expand.

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