A Study of the dimensional accuracy obtained by low cost 3D printing for possible application in medicine

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Abstract. Low cost 3D printing' is a terminology that referred to the fused filament fabrication (FFF) technique, which constructs physical prototypes, by depositing material layer by layer using a thermal nozzle head. Nowadays, 3D printing is widely used in medical applications such as tissue engineering as well as supporting tool in diagnosis and treatment in Neurosurgery, Orthopedic and Dental-Cranio-Maxillo-Facial surgery. 3D CAD medical models are usually obtained by MRI or CT scans and then are sent to a 3D printer for physical model creation. The present paper is focused on a brief overview of benefits and limitations of 3D printing applications in the field of medicine as well as on a dimensional accuracy study of low-cost 3D printing technique.

1. INTRODUCTION

Three-dimensional Printing (3-DP) and/or Rapid Prototyping (RP) describes the creation of 3-D physical objects manufactured layer by layer. Since the 80's many RP methods have been developed and commercialized. Despite their differences, the majority of them uses the same methodology to construct a physical prototype [1-5]: Creation of a 3-D digital model; STL surface model creation; cross sections creation; generation of vector or raster data for machine tool control; creation of the physical model layer by layer; and finally post processing of the final physical model [6].

Although RP machines may use different kind of materials to construct a model (liquid, solid, powder) the procedure presented above is generally the same. The use of such a technology is becoming increasingly popular in the medical sector, especially in surgical planning and simulation. The need for surgeons to have a closer look at the patient's problem with noninvasive methods is imperative. Many of the processes initially developed for industrial reasons are now to be modified in order to serve medical science.

For the construction of a bio-model the main difference to an industrial model lays in the way the 3D data is obtained. In this case, a computed tomography scan (CT scan) of the patient is used in order to

create the virtual model. Depending on the conditions under which the CT scan is performed, the data may be altered. For example, movement of the patient during the examination may cause variations in the recorded dimensions. This may lead to dimensional discrepancies both in the virtual and the physical model that will be created. Therefore, it is essential to be really thorough during the CT scan to make sure that the data will be as accurate as possible.

The second step is the image segmentation that converts tomography into the 3D model. For intensity images (i.e. those represented by point-wise intensity levels) the most popular approaches are: the threshold technique; the edge-based method; the region-based method; and the connectivity-preserving relaxation-based segmentation method [5].

In the third step the physical model is created by using a 3D printing machine. Not all RP methods are suitable for the construction of a bio-model. The most suitable method is selected depending on the size, the materials and mainly the use of the bio model. The materials used are usually liquids, powders or solids such as resins, thermoplastics, polycarbonate, hydroxyapatite, metals etc. [7-9]. After the construction, post-processing takes place. All the support structures are removed and the bio-model is prepared in order to be touched by bare hands.

In the last few years various medical applications of RP have been developed [10]. This area is highly challenging because advances in this area require always a multidisciplinary approach and include a minimum of tasks related to medical imaging and 3D modeling, medical treatment and actual RP technology.

Prosthetic devices and implants have been developed a while ago using 3D printing. Recently, implants with optimized geometries have been fabricated directly in high-strength "final" materials using advanced processes such as laser powder forming.

Plastic surgery and reconstruction prosthetics are also very promising areas for 3D printing technologies. Breast and similar prosthetic devices are being investigated, as well as customized mandible substitutes and anatomically accurate prostheses for cranio-maxillo-facial reconstruction [11].

3D Printing can be used by surgeons to assist them in planning and analyzing complex operations, especially craniofacial and maxillofacial surgeries.

The transparency of the model and recent developments in color resins allow distinct visualization of tumors or other anomalies within the surrounding tissue or bone. High-cost applications in comparison to CNC modeling techniques have been a restraint and therefore rapid prototyping has been used in the past only in cases where the benefits obtained justify the extra expense. However, the advent of lower- cost RP systems and full color capability in recent years, in addition to the growing need for awareness in the medical community is likely to result in a wider use of such models [12]

Nowadays, RP applications are involved in many manufacturing procedures and there is a need for educating individuals belonging to various scientific backgrounds. Moreover, many types of prototypes, like bio-models, can be used to educate medical students in the terms of the technologies and the methods used to construct models, moulds and finally implants. Typical applications are illustrated in Figs 1-4.
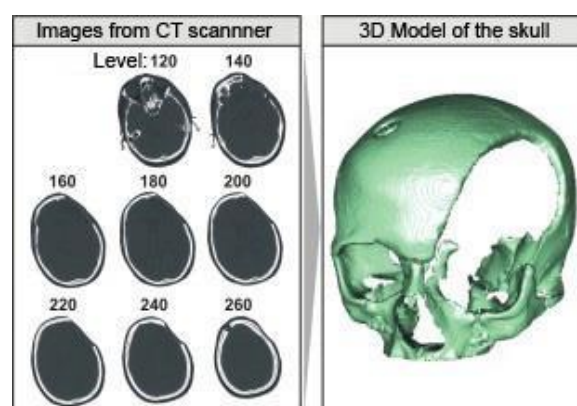

Figure 1. Images from CT SCANNER and 3D digital model [13].

Figure 2. 3D printed skull [13].

2. LOW COST 3-D PRINTING

Low-cost 3-D printing is frequently referred to the application of semi-professional printers. A typical equipment of this category is the Wanhao Duplicator 4X; a 3D printer operating under the Fused Filament Fabrication (FFF) technique, which is one the most common 3D-Printing technique today.

The Duplicator 4X is a 3D printer with dual extrusion up for 1.75 mm filament (Fig. 3). It has a protective cover around the printer to ensure a stable temperature during printing. The layer alignment results in a 100 μm resolution. The drive system was designed to give the optimum positioning accuracy. The entire system has a sturdy 3/8″ diameter linear shafting. The bearings, which are made of sintered stainless steel, are self-aligned. The Z-axis construction consists of a stepper driven, cantilevered stage. The speed of the Z axis ranges from 150 mm/minute to 1.000 mm/minute.
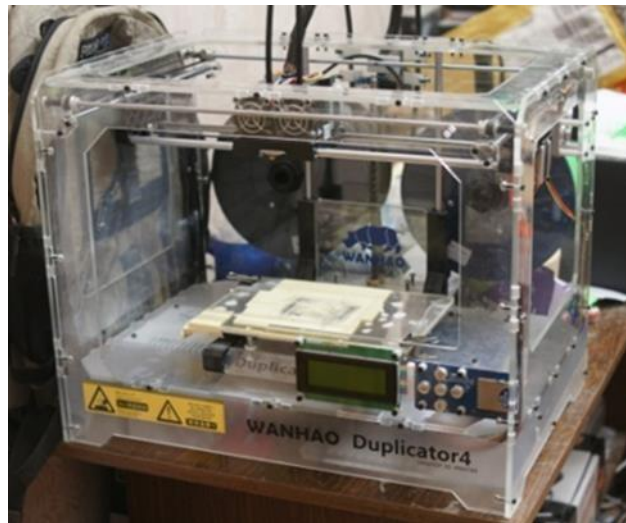

Figure 3. The Duplicator 4X 3D Printer.

Dimensional accuracy of the parts produced by using rapid prototyping technologies and the relevant factors affecting it, are major issues of investigation in the literature. The main parameters influencing dimensional accuracy were found to be layer thickness, infill, number of shells, printing and movement speed.

An investigation of the dimensional accuracy of parts produced by Wanhao Duplicator 4X 3D Printer is presented by performing nine (9) printing operations. In order to achieve randomized experiments the L9 Taguchi orthogonal array was used. The selected part geometry has been prepared in STL format. The part designed and its specifications are presented in Fig. 4.
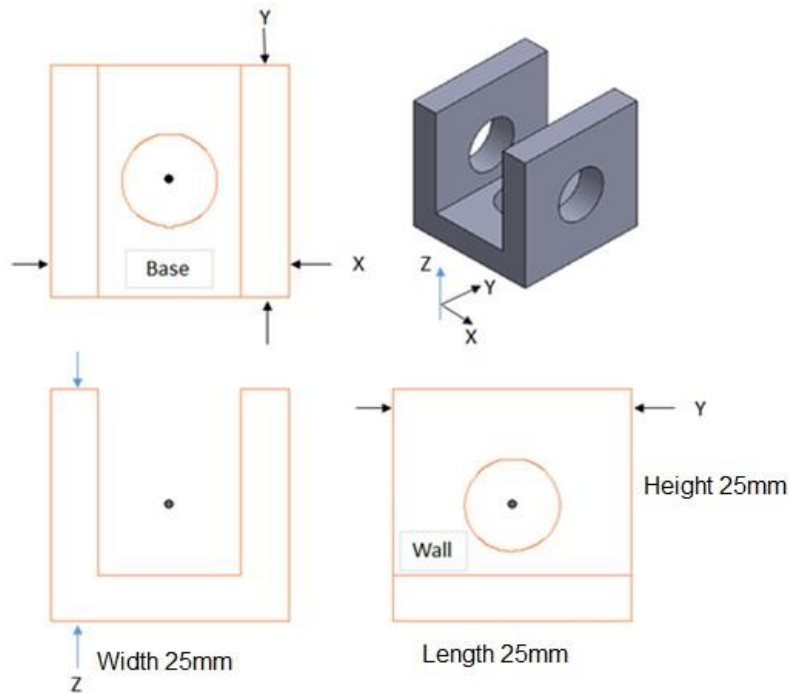
Figure 4. STL part specifications.

The process parameters used were the Printing Material (PM), the Infill Rate (IR), the Number of Shells (NS) and the Layer Height (LH). The Printing Material is defined by the control factors Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA). For the Infill Rate, three levels equal to 20%, 50% and 70% of the solid model were selected. The Number of Shells stands for the number of outlines printed on each layer of the object and is defined by three levels equal to 1, 2 and 3. Finally, for the Layer Height three values for the thickness of each layer were considered, 0.1, 0.2 and 0.3 mm. The process parameters and their respective levels are summarized in Table 1.

Table 1. Parameter Design.

No	Process Parameter	1	2	3
1	Printing Material (PM)	ABS	PLA	-
2	Infill Rate (IR)	20%	50%	70%
3	Number of Shells (NS)	1	2	3
4	Layer Height (LH)	0.1 mm	0.2 mm	0.3 mm

Average linear dimensions in X, Y and Z direction for each experiment have been measured with a digital caliper with an accuracy of 0.01 mm; see Figure 5 and Table 2).

Figure 5. The 9 test parts.

Table 2. Measurements in X, Y, and Z directions.

No of Exp.	PM	IR	NS	LH		X	Y	Z
1	1	20	1	0.1		24,84	24,69	25,085
2	1	50	2	0.2		24,94	24,685	25,145
3	1	70	3	0.3		25,11	24,79	24,9875
4	2	50	3	0.1		24,97	24,74	25,19
5	2	70	1	0.2		24,87	24,6825	25,2
6	2	20	2	0.3		25,00	24,895	25,08
7	1	70	2	0.1		24,96	24,555	25,12
8	1	20	3	0.2		25,05	24,745	25,075
9	1	50	1	0.3		24,77	24,57	24,5
					average	24,94	24,71	25,04
					Max	25,11	24,90	25,20
					Min	24,77	24,56	24,50
					Range	0,34	0,34	0,70
					σ^2	0,089168	0,088	0,364675

3. CONCLUSIONS AND FUTURE CHALLENGES

Since the need for bio-models and implants is imperative and the role of RP technologies is essential in their construction there are many promising studies that might help to overcome all the arising issues. In the present study a dimensional accuracy investigation of low-cost 3D printing was carried out and the results were tabulated on Table 2. The physical models manufactured by this low- cost 3D printing can be used for medical application after optimization of the process in order to achieve dimensional accuracy superior to the accuracy of the CT scan data.

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