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Development of a 3D bio-printer using CoreXY mechanism and syringe-based extrusion

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ABSTRACT

3D Bio-printer is said to have potential in the applications of medical studies and tissue engineering. A 3D Bio-printer could be used to print the artificial organs for organs transplant and cell tissue culture for generating new cell tissue. It could help in future medical and biological research. This paper presents the development process, i.e. working principle of Fused Deposition Modelling (FDM), mechanical, electrical and related applied software, of a 3D Bio-printer using syringe-based extruder and Core XY mechanism. Up to date, FDM is a popular technique because it is easily implemented, precise and accurate. The printed product revealed high repeativity, where (sample mean, sample standard deviation) is (0.72, 0.2455) mm. The procedure could help future customized 3D Bio-printer.

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1. INTRODUCTION

The earliest 3D printing technique was first introduced by Charles "Chuck" Hull in 1986 in which the 3D printer solidify the ink using light radiation and print the 3D model [1]. There are types of 3D printers available in the market such as Stereolithigraphy (SLA), Digital Light Processing (DLP), Fused Deposition Modelling (FDM), Selective Laser Sintering (SLS), Selective Laser Melting (SLM) and etc. [2-6]. FDM-typed 3D printer is the most famous among all the 3D printers in which the printer build a 3D model layer by layer from bottom to upward [7]. The ink of the 3D-printer is molten layer of plastic that fused up together [7].

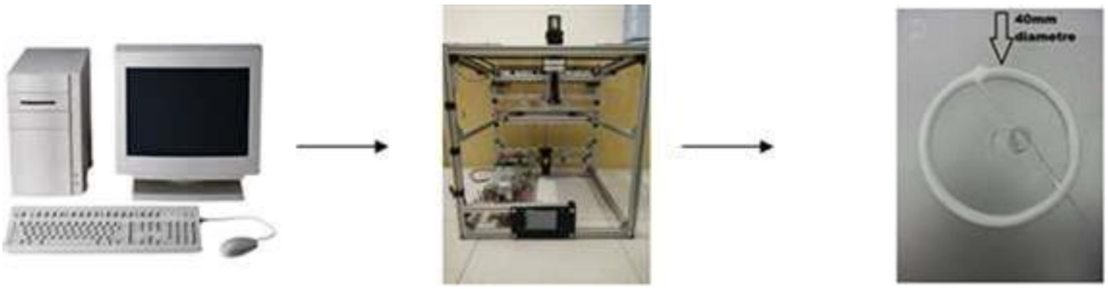
The 3D printer evolved rapidly in many fields nowadays and of the famous field is in medical. Lately, 3D Bio-printer became vital in medical fields in printing artificial organs, tissue, skins and bones [8-14]. Millions of patients are dying every year in the process of long term waiting for organ transplant. In medical treatment, there are difficulties in obtaining the healthy organs like the lack of organ donors, suitability of the organs on blood type, the condition of patients and the ages of the patients [15, 16]. 3D Bio-printer plays an important role to cover the shortage of healthy and suitable organ for those who may need them.

M. Ozturk et.al [17] described that there are three techniques of 3D Bio-printing commercially used today such as Inkjet-Based Printing, Extrusion Based Printing and Laser Based-Write. These facts are also support by the journal published by M. Calado et.al [18]. C. Ventola et.al [19] stated that 3D bio-printing are very famous especially in medical fields for research and study in many fields of researches such as tissue engineering, regenerative medicine and organ transplant since 2000s. The first 3D bio-printer [20] is introduced by Wake Forest Institute in year 1999 in which a fully functioned artificial urinary bladder was successfully printed. In year 2002, once again in medical field, 3D bio-printing produced artificial kidney that 100 percent replicated to the original one using ‘bio-ink’ technique. There are many other applications involving 3D Bio-printing such as Orthodontic which is one of the medical field that widely used of 3D Bio-printing in producing Invisalign Braces for repairing the teeth alignment [21]. The other application of 3D Bio-printing is on anatomical model and surgical preparation which give a big help in assisting surgery doctor [22-24]. Last but not least, 3D Bio-printing is applied in Pathology field, the 3D Bio-printing is used to print polypeptide model of the disease structure for diseases study purpose, type of disease and biological structure of diseases [25-26]. This paper intend to propose the development of 3D Bio-printer based on the Fused Deposition Modelling (FDM) using customized syringe based nozzle to print 3D Bio-model products.

2. RESEARCH METHOD

2.1. System Overview

The flow of the 3D Bio-printer system starts with creating a 3D model as the input of the system and was saved into a stereolithography (STL) file type. Then, a slicer program translates this model into individual layers. The slicer program named CURA was used to convert the model into g-codes which are transferred into a Secure Digital (SD) card. The g-codes list the instruction of functions and coordinates for the stepper motors to move synchronously. All these process were done in the computer. The SD card that contains g-code is inserted into the 3D Bio-printer controller. The 3D Bio-printer will execute and move according to the g-codes to print the desire 3D Bio-model. Figure 1 shows the overview on the 3D Bio-printer system.



STL and gcode generation Transfer gcode and print Printed product

Figure 1. Overview on the 3D Bio-printer system

2.2. Mechanical Design

The design of the 3D Bio-printer start with the software design where the SolidWorks was used to design the sketch for the customized 3D Bio-printer. SolidWorks is come in handy to sketch every component parts that are needed for building the 3D Bio-printer parts. The design of 3D Bio-printer includes the core XY mechanism in controlling movement of X and Y axis, Fused Deposition Model (FDM) printing technique and syringe-based extruder. Figure 2 shows the isometric view of the 3D Bio-printer. Its external dimensions are (X, Y, Z) = (500mm, 500mm, 500mm).

Core XY mechanism is one of the mechanism for 3D bio-printer techniques that is widely used by the researchers. The Core XY mechanism was applied in this project for customized 3D Bio-printer. Figure 3 shows the sketch of Core XY mechanism where the belting connected the stepper motor of the X axis plane and Y axis plane for movement. A Core XY is a parallel manipulator system that positions XY coordinates of the nozzle in Cartesian plane. Limit switches are installed at end of X and Y axis.

The Z axis plane mechanism is upward and downward movement and is controlled by a stepper motor attached to a ball screw and supported by two sliders as shown in Figure 4. The origin, (X, Y, Z) = (0, 0, 0), is defined at lower left corner and upmost position.

The customized syringe-based extruder as shown in Figure 5, is used to extrude the gel-type ink. A single axis drive attached by a NEMA-17 stepper motor, is used to step and push the syringe plunger, hence squeezing gel-type ink in controlled volume.

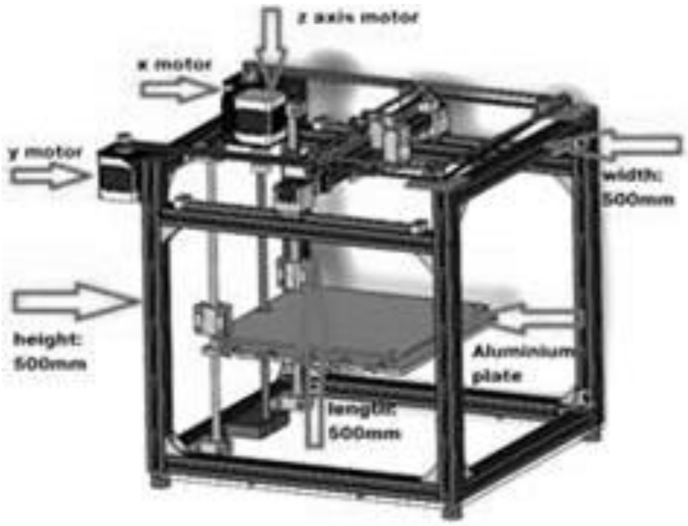


Figure 2. Isometric view of 3D Bio-printer

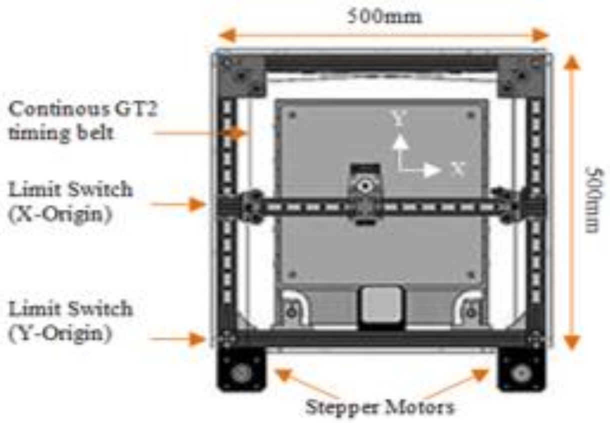


Figure 3. Core XY mechanism (Top view)

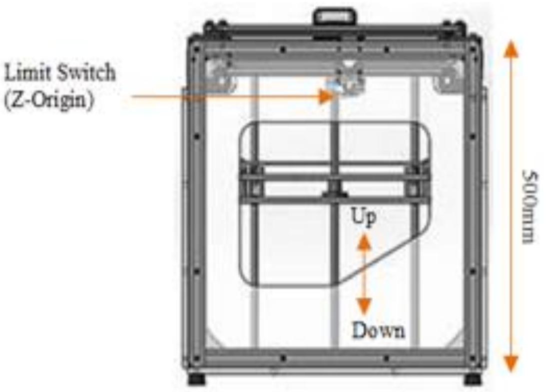


Figure 4. Z axis

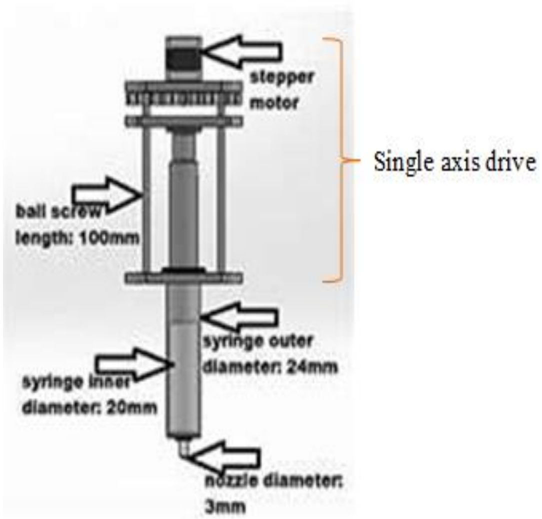


Figure 5. Syringe-based extruder

2.3. Electrical Design

For electrical design, a 3D Controller named as CHITU (http://www.cbd-3d.com/en/index.shtml) is used as the controller for the 3D Bio-printer that reads and translates g-codes into corresponding NC movements of the Core XY, Z axis and Extruder in printing process. Figure 6 shows the schematic diagram for connection between mechanical components, electrical parts and the CHITU controller. The schematic diagram shows the connection for power source, stepper motors for each axis (X, Y, Z) and extruder, and limit switches that define the maximum and minimum strokes in each axis, i.e. aslo the origin, [X, Y, Z] = [0, 0, 0]. The SD card slot is used to read from a SD memory card for the purposes of firmware flashing and printing. A 3.5” TFT colour touch screen provides an interface for monitoring and user instructions.

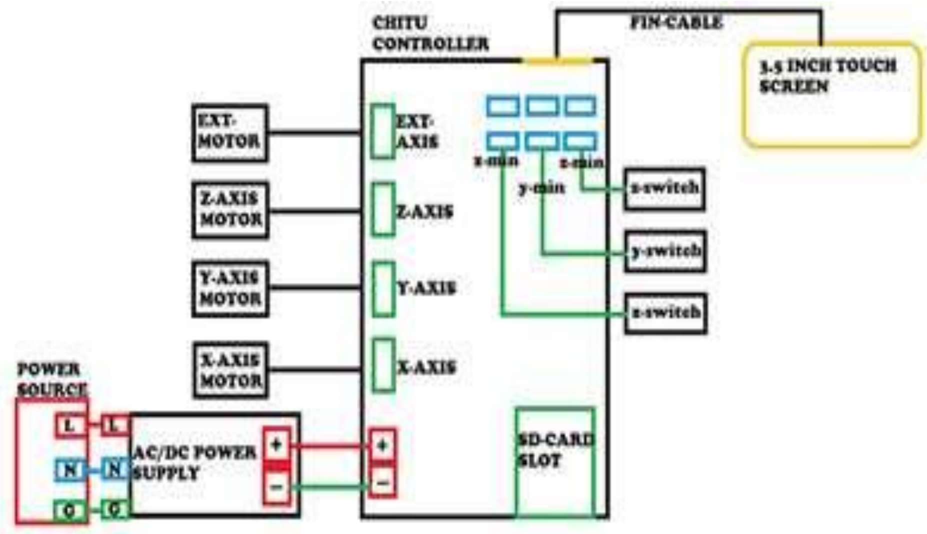


Figure 6. CHITU controller schematic diagram

2.4. Calculation on Axis Movement

Calculation for every single axis are vital to determine the suitable step size for each stepper motor. As shown in (1) is applied for the calculation. The step size are calculated and tabulated in Table 1.

$$Step\ Size = \frac{Distance\ per\ rev \times (Angle/Step)}{16 \times Step} \quad (1)$$

Table 1. Calculation on Step Size of X-axis, Y-axis, Z-axis and Extruder

Axis	Distance per revolution (mm)	Angle (°)	Angle/Step (°)	Step Size (mm/step)
X	40.64*	360	1.8	0.0127000
Y	40.64*	360	1.8	0.0127000
Z	5**	360	1.8	0.0015625
Extruder	5**	360	1.8	0.0015625

*** Core XY – 20 tooth GT2 timing pulley. Diameter = 2.032mm x 20 tooth = 40.64mm**
**** Ball screw pitch = 5mm**

2.5. Calibration

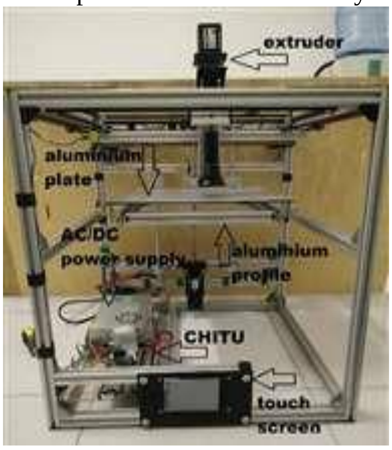
Calibration is the most important part of the research as it troubleshoots the problems occur while executing the 3D Bio-printer to reduce the error of the output. There are three types of calibration executed for X, Y and Z axis movements such as manual calibration, exercised calibration and extruder calibration.

Manual calibration is the process that steps each axis manually and performs manual inspection using a ruler. Stepping length was entered and each axis stepped separately. Exercise program calibration is the calibration that involved with predefined g-codes with know movements. Several g-codes were coded to exercise three axis in performing point-to-point, linear paths, ramps and circles. The purpose of exercised g-code programs is to ensure the system works harmonically together. Extruder calibration is the calibration made for customized extruder only. The purpose of calibration is to check the movement of pushing the plunger into the barrel of syringe. Manual adjustment of the speed and step size settings could be done to determine the extruded result.

2.6. Hardware Assembly

Figure 7 shows a completed customized 3D Bio-printer hardware with specification. All the main components are attached to the aluminium strut 20x20mm as the main frame of the 3D Bio-printer. Core XY and Z axis also are placed precisely inside the main frame. All electrical parts such as NEMA 17 Stepper motors and CHITU controller are wired accordingly.

Completed Hardware Assembly



Specifications

Type: Fused Depositioning Modelling (Bio-Printing)
Dimension: 500 x 500 x 500 mm3
Weight: 12 kg
Controller: CHITU Controller
Extruder: Syringe based
X and Y axis mechanism: Core XY type

Figure 7. Completed hardware assembly and specifications

3. RESULTS AND ANALYSIS

A 3D CAD design is needed before any 3D Bio-printing is executed. Figure 8 shows the full process on the CAD design of a ring-shaped 3D Bio-model. Firstly, the CAD drawing of the sample is designed by using SolidWorks with desired diameter value and shape as illustrated in Figure 8(a). Next, the CAD drawing file will be saved in STL file format as illustrated in Figure 8(b). Next, a STL file will be read by the Slicer software called CURA (https://ultimaker.com/en/products/ultimaker-cura-software) and the model is virtually sliced into multiple layers as illustrated in Figure 8(c). Every single layer contains streams of g-codes which will be executed by the 3D Bio-printer.

Table 2 shows the measured and error values for every single samples. The average measured value is 40.72mm which is a difference of 0.72mm to the target value. Meanwhile, the average error value is 0.72mm because the printed product is collapsed due to the viscosity of toothpaste ink. The standard deviation for measured and error values is 0.2455. One of the factor for this error could be the relative flow rate by nozzle size. The nozzle size has a diameter of 3mm which might not be suitable for the usual flow rate setting. The vibration occurred in printer itself when printing may contribute to the error in printing. The vibration might cause the toothpaste to collapse and spread horizontally.

Table 2. Samples Results (target value = 40mm)

No. of Samples	Measured Values (mm)	Error Values (Measured-Target) (mm)
1	41.0	1.0
2	40.5	0.5
3	40.7	0.7
4	40.8	0.8
5	40.4	0.4
6	40.6	0.6
7	40.7	0.7
8	40.5	0.5
9	40.8	0.8
10	41.2	1.2
Average	40.72	0.72
Standard Deviation	0.2455	0.2455

In this experiment, ten samples of the ring-shaped 3D model with 40mm diameter (inner) as shown in Figure 9 were printed. Tootepaste is used as the gel type specimen since it is the cheapest and easily available. All the samples are measured and calculated for data analysis.

(a)

(b)

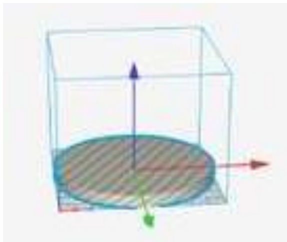
(c)


Figure 8. Full process on the CAD design of the ring-shaped 3D Bio-model; (a) Sample design in SolidWorks; (b) Sample design in STL format; (c) Sample design in CURA

Figure 9. Printed product using toothpaste

4. CONCLUSION

The development of the customized 3D Bio-printer was a success in terms of software or hardware design. The customized 3D Bio-printer was able to function properly and print out the 3D Bio-model successfully according to CAD design with accepted error. This 3D Bio-printer can be further improved by implementing a more precise and accurate calculation on the alignment of the Core XY, by adding up the number of Limit switch used for more accurate positioning in Core XY and Z plane. The 3D Bio-printer can be further upgraded by using WiFi as communication system to transfer file from a computer terminal to a 3D Bio-printer wirelessly.

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