Design of Control System for 3D Printer Based On DSP and FPGA

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***Abstract*—3D printing technology is a rapidly-evolving field, which has seen an explosion of interest in the last decade due to the influence and great degree of maker movement and the rapid prototyping. A set of specialized print control systems is the basis for the fabrication of electronic technology. The use of closed-loop control to improve performance in robots is a well-established technology, by adding the necessary sensors and computational hardware, it is easy to establish a low-cost and efficient 3D printer system. Success of a motion control systems depends not only on the controlling algorithm but also on the control hardware structure. Compared with common robot manipulators, 3D printer system has a more open-ended structure, which needs the control system to be flexible to the flexibility in 3D printer system. Based on DSP and FPGA, unique flexibility and excellent control capability of the motion controller can be designed to fit the requirements of the flexibility in 3D printer system. In this thesis, a kind of closed-loop control structure based on DSP and FPGA for 3D printer has been proposed. The main contents include: (1) the analysis of mechanical parts of common low-cost commercial 3D printer and its requirement for control system. (2) FPGA and DSP can inherently handle processes in parallel, therefore a kind of closed-loop control system has been designed to execute G-code, compute curves and accelerations, and drive multiple stepper motors simultaneously. The thesis illustrates the frame of control system, and provides the design of hardware circuits and software architecture. (3) The linear acceleration and deceleration algorithms of multi-axes have been analyzed, and the simulation results of trajectory following by closed-loop control prove the efficiency of the work in this thesis. The limited contributions of this thesis include, (1) a kind of design of hardware and software for 3D printer system based on DSP and FPGA; (2) the analysis of motion control of the multi-axes implemented in this control architecture. The platform developed seeks to increase awareness of the potential for the integration of closed-loop control into existing open source designs and will help to improve the performance of the low-cost 3D printer system.**

***Index Terms*—3D printer, motion control, FPGA, DSP, stepper motor, closed loop**

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I. Introduction

Controlling our environment and the things around us has been one of the fundamental goals and one of the greatest achievements of the human endeavor. The motion controller acts as the brain of the driving system by taking the desired target positions and motion profiles and then creating the trajectories for the motors to follow, which is a numerical control instrument in general.

Unique flexibility and excellent control capability of the motion controller results in effective application of lots of industrial instruments. Benefit from the development of high performance and high speed processor such as digital signal processor DSP and programmable logic device FPGA, motion control technology is enormously enhanced [1].

A Field Programmable Gate Array (FPGA) based system is a great hardware platform to support the implementation of controllers such as PID controller, fuzzy controller, adaptive controller, optimum controller, FIR filter and even neuro network system [2], [3].

The system developed by Takahashi and Goetz [4] could run a current control algorithm with a Xilinx FPGA to increase the bandwidth of the current loop control. Tzou and Kuo [5] performed the vector and velocity controls of a PMAC servo motor by using FPGA technology successfully. Other works on FPGA based motion controls include Paramasivam [6], Bielewicz [7] PID control was used as the control algorithm in these works.

The controlling of speed is also one of the important portions in motion control. In particular, it refers to acceleration and (or) deceleration controlling. Daniel Carrica [8] has proposed a recursion algorithm for applied on FPGA, the algorithm proposed avoided the complexity in computations but at the same time increased the loads on digital device. Ngoc Quy Le [9] also proposed an algorithm for controlling variable speed and it has been implemented on DSP by using the closed-loop technique. For this algorithm, the control precision has been improved, but it was just tested in lab without any loads connected to the stepper motor, besides the

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speed curve generated by algorithm was not fine in continuity.

The above mentioned algorithms are somehow complicated with less efficiency. If we are to consider that the moving units would move with large loads t low speed, but at the same time demand high precise positioning and accuracy, which means more measured data to be in process. this paper chosen the trapezoidal curve speed control mode [10], by using motion control closed loop by adding a position feedback unit, then proposed a novel algorithm to directly control both speed and position which had been implemented on FPGA and DSP.

For the linear translation levels using stepper motor, the motion control is typically implemented by computers and (or) programmable logic controllers (PLCs), using open loop technique, however, for high accuracy and efficiency applications, this would not be suitable any more [11], [12].

One of the biggest problems faced in any CNC machine or 3D printer is the missed steps while moving the tool head. In this paper we focus on low-cost 3D printers, generally with a price tag under 2000 USD. In general, for 3D printing electronics are broken down into 4 different areas, the controller, stepper motors, stepper drivers, and end stops.

Some authors designed dedicated embedded program for control system based on a modern and efficient STM32F4 microprocessor family that gave a substantial contribution to the development of a new branch of the three-dimensional printing. They used to 32-bite STM32F4 unit with popular open-source project called marlin and teacup for 3D printer [13].

In this project, we have designed an embedded system based on FPGA and DSP control board to control a 3D Printer. As we know, on a low level the basic operations and processes executed by a 3D printer are pretty simple. For example, stepper drivers need direction information, heaters need turning on and off and so on and this is straightforward for a microcontroller. However, what is hard for a 3D printer is the high level things. Calculating the acceleration curves to minimize time take, while maximizing the print quality. Tuning the PID loop for the nozzle and bed temperatures. Moving information to and from a computer or SD card. As we know Microcontrollers are not able to handle things in parallel what it means it can't execute several commands at the same time and also some microcontrollers couldn't fit all the mathematics and calculations into the available memory. Most microcontrollers-based designs will have slight delays when trying to drive everything at once and this would introduce some mechanical jitter.

II. Mechanical Analysis and Control System Requirements

The objectives and importance of the work can be described together as below:

Build the structure and assemble the parts of the 3D printer from a pre-designed model. Design and implement a flexible, compact, high-performance and closed loop control system based on FPGA+DSP to drive the various activities of a 3D printer being used.

The reason for the use of FPGA+DSP can be illustrated that: The traditional DSP uses a Von Neumann structure and some types of extension. This structure is essentially serial, which it cannot deal with. FPGA hardware can process in high speed, and can also process a large amount of data, just to make up for the shortcomings of DSP. DSP + FPGA system has the advantages of flexible structure, strong versatility, suitable for modular design, which can improve the efficiency of the algorithm; at the same time its development cycle is short, the system is easy to maintain and expand, suitable for real-time signal processing.

By using displacement sensors, the information of the actual motion along the X, Y and Z axes of the 3D printer are read and used as the inputs for the closed-loop controller which can modify the commanded position of the stepper motors to reduce the position errors. Analog to digital converter unit embedded inside DSP is used to read the sensors signals. Such system would improve the accuracy of the printed parts by correcting the mechanical error in the motors steps size, as well as catching and correcting missed steps, which enables the stepper motors to be tuned more aggressively and increase the speed of printing process. Thus the system is less cost, simple and easy to implement. In this system PWM technique is used to control the motors position precisely. The present work is also concerned with providing methods to the trajectory generator of the 3D-printer. FPGA and DSP are used as a control core to solve the path planning problems.

A. *Mechanical Analysis*

The model has been bought from the internet. The electronic parts such as the stepper motors and their driver circuits, and the mechanical components such as the metal rods and screws were purchased online from internet. These components include gears, mounts for various motors, the extruder housing, belt holders, and various other connectors.

Once all of the parts had been obtained, we began constructing the printer. The frame was assembled to form a basic rectangular frame. The printer after assembling in work place shows in "Fig. 1".

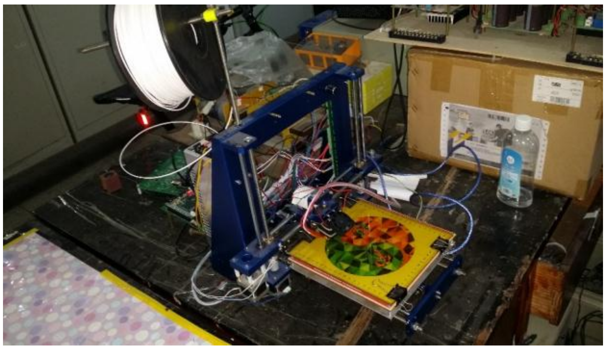

Figure 1. The structure of 3D printer after assembly.

Following the frame's construction, the X, Y, and Z axis and their components had to be constructed and affixed to the frame in their relative positions. The Y axis was controlled by moving the bed of the printer forward and back, while the X axis was controlled by moving a suspended carriage that held our extruder left and right. Finally, the Z axis was obtained by moving that suspended carriage up and down. Below is an explanation of these aspects of the construction.

B. Stepper Motors

Unlike brushless DC motors which operate in continuous once they are supplied with power, stepper motors on the other hand would run in discrete step angles. So we could say that a stepper motor is a brushless motor that divide the full rotation cycle into a number of steps. The stepper motor contains of a soft iron shaft surrounded by electromagnetic stator. Both rotor and stator have poles. When the stator is powered the rotor moves to align itself with stator or rotor moves to have minimum gap with the stator. Thus to run a stepper motor the stators are powered in a sequence. Hence we provide pulses to motor driver that will create this sequencing.

The figure below shows a NEMA 17-size hybrid stepping motor can be used as a uni-polar or bipolar stepper motor and has a 1.8° step angle (200 steps/revolution). Each phase draws 1.2 A at 4 V, allowing for a holding torque of 3.2 kg-cm (44 oz-in).

Figure 2. NEMA 17-size hybrid stepping motor.

III. Hardware and Software Design of the Control System

We use the 3D printed model created with CAD software to get model of one real object. And to process the data through the host computer, which controls the peripheral circuit system. We run repetier software in the host computer to make STL file into G-Code in the end. The host computer handles the raw data and controls the lower computer. The lower computer, which based on FPGA and DSP, is the control core of the printing system. It is mainly responsible for the control of the X, Y, Z axis movement of the motor. Then Let the machine reach the specified location accurately and finally print completed object. The whole flow chart is shown in “Fig. 3”.

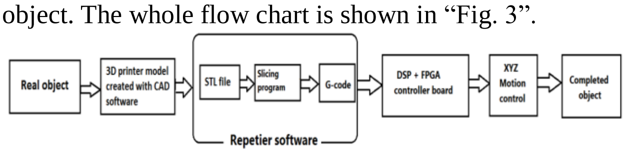

Figure 3. The flow chart of 3D printer.

A. Electronic Design

Once the printer had been fully assembled, all components had to be wired and tested to make sure they all functioned appropriately and had full functionality. Our 3D printing control board which shown in Figure 4 is controlled by using FPGA in combination with DSP. It can control up to 5 stepper motors with 1/16 stepping precision and interface with a hot end heater, a heated bed, a fan, a LCD controller, a 12V power supply, up to 2 thermistors, up to 3 end stoppers (Limit Switches), and serial communication with computer via RS232 protocol. We use DSP: floating - point processor TMS320F28335 and FPGA: ALTERA / Cyclone3 / EP3C5E144C8N.

The driver board is designed by Altium Designer software and it contains all the interfacing circuits which connect the FPGA+DSP board with the other components such as stepper motors, sensors, heaters, fans, and LCD.

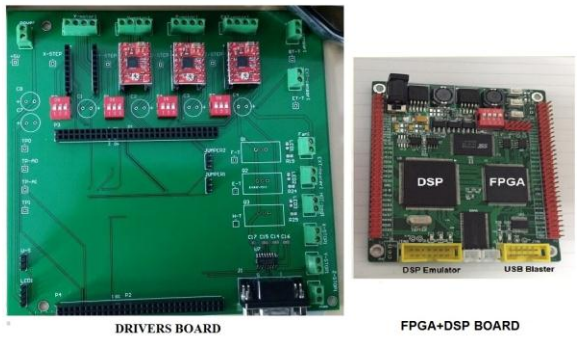

Figure 4. Control board.

B. Control System of 3D Printer

The computer inputs control signals to the lower computer through outputting electrical pulses. The control system bases on FPGA and DSP as the master chip as shown in “Fig. 5”.

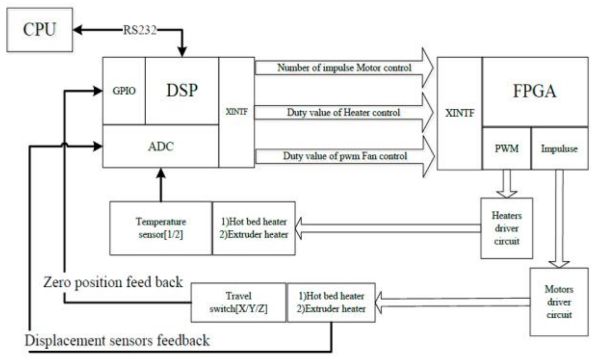

Figure 5. Structure of peripheral circuit.

The computer will send the instructions to the DSP chip through the circuit interface. And The DSP will send multiple PWM pulses to FPGA through XINTF. FPGA gets control impulses from I/O pins and sends control pulses to sensors of peripheral circuit. After that the peripheral circuit will send feedback signals to the DSP chip immediately. Through all this above, the whole system realizes a closed-loop control process finally.

FPGA controls the hot bed heater and extruder heater by controlling the waveform of PWM. And The temperature sensor tests temperature of those mentioned above and sends feedback signals to DSP. The DSP chip understands this data by Analog to Digital Converter, which was embedded in DSP chip. The same principle that the ultrasound sensor get the distance data and sends feedback signals to DSP, too. Moreover, travel switch can send feedback signals to the GPIO of DSP. In turn the DSP will control peripheral circuit by sending PWM pulses to FPGA. And the FPGA will control peripheral circuit directly. The system will remain in a dynamic equilibrium range.

C. Software Architecture

The process of 3D printing in the part of software is shown in "Fig. 6". Firstly, we confirm the model we want to print and extraction detailed parameters of his appearance. Then we create a 3D model, which repetier can understand, by programs like 3D MAX, Pro/Engineer, and Rhino. And we also can create the model on repetier directly. Then repetier will slice the model into thin layers and export the G-code, which contain the features of the model, into command, which the driver circuit can understand. In the end, the three motors will move orderly through the system.

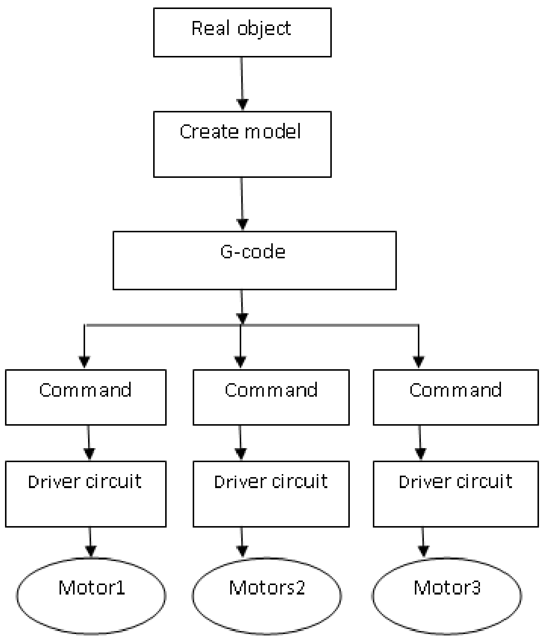

Figure 6. The process of 3D printer in the part of software.

The speed control of stepper motors flow chart is shown in the "Fig. 7". After the program begin, the MCU will get the speed set of motors. Then the MCU will calculate the pulse frequency we need and convert to clock cycle division factor. Then update the timer division factor, registration timer interrupt, generate pulses in the interrupt response in the end. The speed of the motor can be obtained from the beginning, if we want stepper motors work in a new set of speed, then the program will convert the pulse frequency, which can output appropriate PWM pulses to driver stepper motors the speed set, into the clock division factor. The coefficients are updated and pulses are generated in the interrupt function, then the motor correspond to the speed set. Then the system will judge the speed of motor whether is right. The wrong speed will be corrected by the control system.

The displacement control of the stepper motors is shown in the "Fig. 8". We Firstly, control the motor to run at a defined speed, and then calculate the time of this motion and driver the motor, starting the timer at the same time, When the time run out stop the motor, so as to achieve displacement control. This part of is mainly for providing interfaces in the axis linkage system later. Finally, we will measure the place of motors by sensors, the wrong displacement will be corrected by the control system.

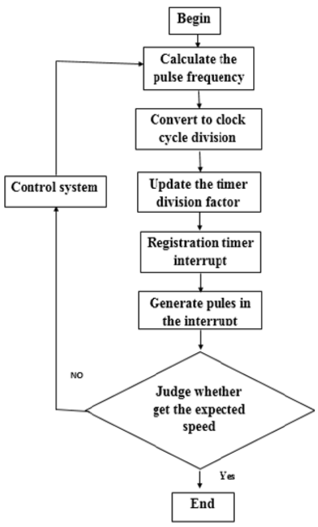

Figure 7. Flow chart of motors speed control.

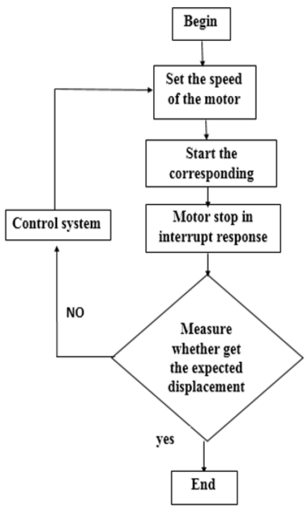

Figure 8. Flow chart of displacement control.

We choose Quartus II as the development platform for this project. Quartus II is one kind of development software, designed by Altera, which is competent to comprehensive PLD / FPGA, schematics, VHDL, Verilog HDL and AHDL (One language that Altera Hardware Support) and other design input forms, embedded in the existing synthesizer and emulator. We can complete designs of PLD flow chart into the hardware configuration.

A. Linear Acceleration and Deceleration Algorithms of Stepping Motors

The control system chooses the trapezoidal acceleration/deceleration algorithm to control the motion of each stepping motors. Trapezoidal algorithm is a straight line acceleration and deceleration, which can run stably, and meet the rapid changes of motors of the speed and positions. At the same time, the algorithm is easy to implement, the control is simple and the calculation is effective. The curve of the trapezoidal acceleration / deceleration algorithm is shown in "Fig. 9".

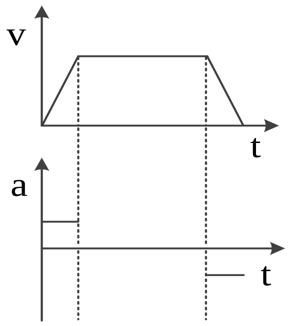

Figure 9. Trapezoidal acceleration and deceleration.

From the above figure we can see that the process of stepper motor speed change is in three stages: acceleration, uniform and deceleration. Its displacement of the acceleration and deceleration can be expressed as:

$$S_a = S_b = \frac{v_{\max}^2}{2a} \tag{1}$$

B. X-Y- Axis Simultaneous Motion Algorithm

Since the hot end heater of 3D printer are moving on the work surface following the printing path, it is necessary to control the motors to move at the direction of X-Y-axis simultaneously. Because of the trajectory of the stepper motors can be decomposed into a large of discrete points, and the movement of motors in adjacent discrete points can be described as a linear motion. So the X and Y axis displacement can be decomposed into two linear motion, as shown in "Fig. 10" below, Where the coordinates A and B are adjacent coordinate points, and the hot end heater will move from point A to point B.

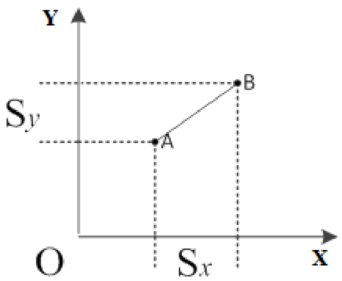

Figure 10. The movement of hot end heater.

We must ensure that the stepper motors of X and Y axis run and stop at same time. Assuming that the displacement of X-axis is Sx, its velocity is Vx, the displacement of Y axis is Sy, its velocity is Vy, and the following relationship exists:

$$\frac{v_x}{v_y} = \frac{s_x}{s_y} \tag{2}$$

C. Simulation of Trajectory Following by Closed-Loop Control

We use a PID controller (proportional–integral–derivative controller) to get precise trajectory. The system and controller are assumed to take the form shown in "Fig. 11".

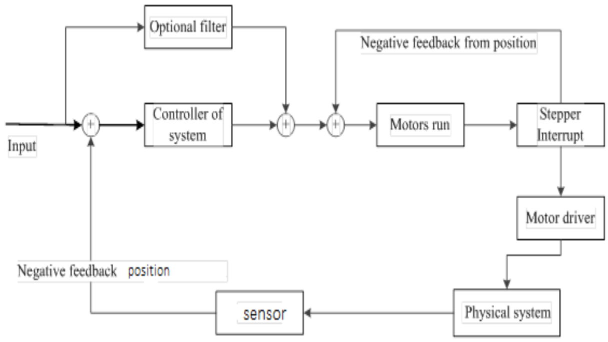

Figure 11. Controller block diagram.

Through Matlab simulation, we analyze the feature of PID controller. A better test of performance involves measuring the system's ability to follow a series of move commands. Formulated as G-Code, these commands replicate motions found in a real-world print. "Fig. 12", shows the system's performance in following a circular trajectory composed of linear segments, both in command trajectory and closed-loop. the trajectory was generated as G-Code and run at 30 mm/s. The mean trajectory error (the distance between each data point and the command trajectory location at that point, then average these quantities) is given as the following expression:

$$e_t = \frac{1}{N}\sum_{i=0}^{N}\sqrt{\left(x(i)-x_t(i)\right)^2+\left(y(i)-y_t(i)\right)^2} \tag{3}$$

The PID closed-loop controller has a mean error of 0.07 mm, so PID controller can make system work better surely.

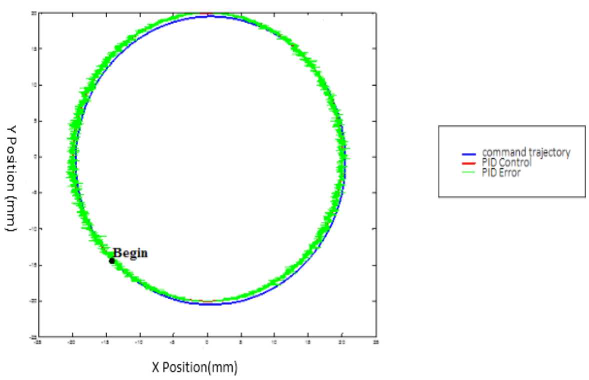

Figure12. PID circle tracking and tracking set.

IV. EXPERMENTAL WORK

We import 3D model (cube) that created with CAD software, which repetier can understand it and makes STL file. Repetier slices the cube model into thin layers by slicer as is shown in "Fig. 13".

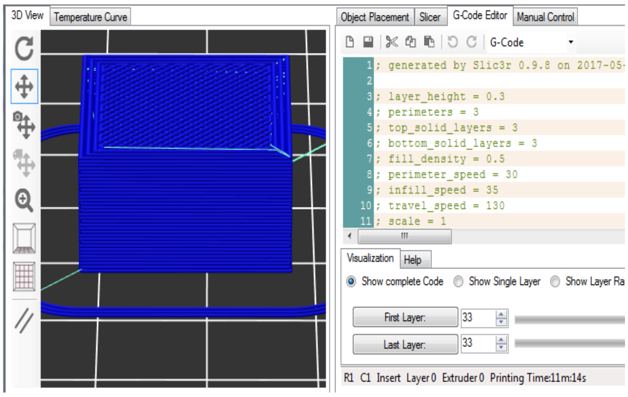

Figure 13. The slicing.

"Fig. 14" shows The G-code that contains the features of the cube model, and this G-code exports into commands which the driver circuits can understand.

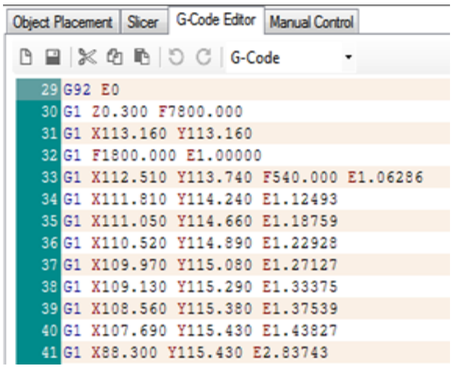

Figure 14. The G-code.

Finally, the driver circuit sends the commands to X, Y, and Z motor which in turn moves as linear motion and prints the cube model layer by layer until finish the whole shape as we see in "Fig. 15".

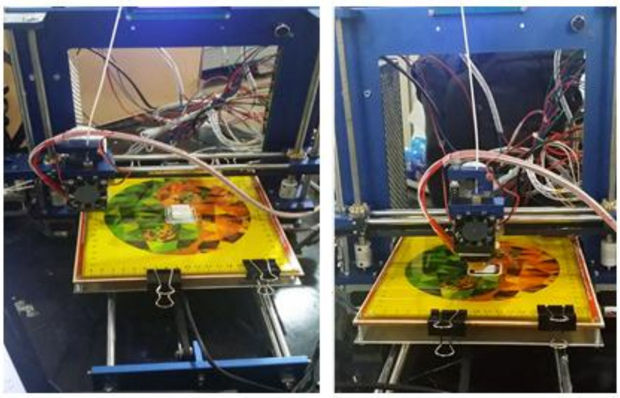

Figure 15. The printed cube in work place.

V. Conclusion

The main works are about a design of control system based on FPGA and DSP for 3D printer. By the usage of a powerful logic function and open system scalability, reconfigurable features, an open-ended control structure can be established. Although it's different in the number and type of axes as well as the type of programming and internal control system, the requirement of multi-axes motion control is similar and can be combined into a unique architecture. The main works in this paper include,

- Build the structure and assemble the parts of the 3D printer from a pre-designed model. Through the analysis of mechanical parts of common low-cost commercial 3D printer and its requirement for control system, then a kind of control system architecture based on DSP and FPGA has been proposed.
- The thesis clarifies the frame of control system, and supplies the hardware circuits design and software architecture. based on that FPGA and DSP can treat the processes in parallel inherently, the mission of motion control of multi-axis can be split into many parts according to the architecture of software, and the closed-loop control system has been designed to execute G-code, compute curves and accelerations, and drive multiple stepper motors simultaneously.
- The process flow of the closed-loop control system has been provided, and the control strategies of acceleration and deceleration of multi-axes has been designed with the path planning method to explains that how to control the 3-axis and how the endpoint trajectory is generated based on the control of each axis. the simulation results of trajectory following by closed-loop control prove the efficiency of the work in this article.

This article has completed the overall design of 3D printing, but the lack of individual experience in personal practice, coupled with the limitations of time and laboratory conditions, in the whole process there is still some problems and the system are not good enough. The following points are suggested for further developments:

- Further development of high-precision motion control system (which can use dedicated motion control board), so that the movement system and inkjet printing system do not need to interfere with each other, to facilitate better maintenance updates and further upgrades.
- The slicing algorithm can be refined and refined into the 3D printer within the master control system, in order to achieve the computer and the printer into one.
- The foremost area of future work centers on the development of more accurate, better-performing control algorithms. Getting the more complex controllers described here and elsewhere in the literature will be a major step towards realizing all that closed-loop control is capable of.

Acknowledgments

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