Mechatronic System Design Project: A 3D Printer Case Study

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***Abstract*— a mechatronics project for designing a 3D printer prototype is discussed. The project work is part of a senior students' project class and is used as a case study to highlight the success of developing a fully-integrated engineering system that incorporates a mechanical plant, electronics, drivers, embedded controllers, and software interface. The project objective is to realize a 3D printer prototype with relatively simple design. The described work can be used as an educational reference for proper mechatronics design and as a hobbyist reference for designing desktop 3D printers.**

Keywords—3D printer; Mechatronics systems; Engineering education; Embedded control.

I. INTRODUCTION

3D printing technology is expected to have such a high impact on the industrial world that some engineers, analysts, and investors are calling it the new industrial revolution. 3D printing is an additive manufacturing process where products are built a layer-by-layer to make three dimensional solid objects [1].

Additive manufacturing have gained much interest in the academic and industrial worlds. This interest resulted in innovative research and development in the areas of products, process, and machines which in turn initiated re-thinking of manufacturing logistics and structures [2].

3D printing can have major effect on inventory management and supply chain. 3D printing will change the way that products are manufactured because it can reduce the supply chain management and reduce (or even) eliminate the shipping cost and lead time. 3D printing can also reduce the imbalance between export and import countries, lower manufacturing cost, and create new industries and new professions [3].

Conceptual, verification and functional models can be produced rapidly and with low costs for several purposes such as learning, researches and marketing. Customized designs are easy produced which encourage the producing of novel designs and in turn increase creativity.

Production of small batches with low cost can be achieved, because no initial cost for special tooling is required. Also the digital transportation of designs reduces the cost compared to transfer objects via traditional ways.

The ability of 3D printing to produce small production batches with easy-to-use technology can cause an industrial revolution that allows small companies to compete globally in manufacturing products. Consumers can work with their 3D printers at home and produce their customized products.

3D printing can play a major role in cloud-based manufacturing where a service-oriented network enables users to configure, select, and utilize customized product resources and services [5]. Already there is a 3D community that shares ideas and designs that can be downloaded with a simple internet link and sent to 3D printers.

In general, 3D printers are used for two purposes: Rapid prototyping (creating prototypes for traditional manufacturing and research purposes) and rapid manufacturing (creating products for short run custom manufacturing).

There are several methods for printing 3D objects such as Extrusion technique, Stereolithography (STL), and Digital Light Processing (DLP). A brief description for these methods is shown in Table I where the main principles for each printing method is discussed [4].

Selecting the printing method depends mainly on the following criteria:

- Print speed which is the time required to print a specific distance in the Z-direction.
- Cost of the parts used.
- Resolution which is measured in dots per inch (DPI) or the thickness of Z-layer.
- Accuracy between the printed object and the original model
- The number of colors
- Complexity of the mechanical structure and its electronics and user interface.
- The required post-treatment of the printed object.
- Availability of the system components and printing materials.

TABLE I. 3D PRINTING METHODS

Method	Description
Extrusion / Fused Deposition Modeling (FDM)	This process works by melting a thermoplastic material using a resistive heater and extruding the melted material through a nozzle according to the 3D data supplied to the printer. The first layer immediately hardens as it hits the heated plate and the next layers harden as it bonds to the previous ones.
Stereo lithography (STL)	A laser beam is used to harden photopolymer resins and thus producing a solid object.
Selective Deposition Lamination (SDL)	In this process an adhesive with different densities is fed to provide the function of bonding layers of paper together. The cross sections of object will have higher densities and others with lower densities are used as supports. After that the printing plate moves up to a heated plate and pressure is applied. Finally each layer is cut by an adjustable Tungsten carbide blade. Colorful objects can be produced by this method.
Digital Light Processing (DLP)	Similar to STL, but with more effective light source such as a deformable mirror device or an arc lamp with a liquid crystal display panel. The light is directed to the entire surface of photopolymer resin in a single pass, which provides faster printing.
Laser Sintering / Laser Melting	A laser is traced out to a powdered material which causes the powder particles to be fused. This method must be carried out in a completely sealed chamber of inert gas and at a precise temperature.
Electron Beam Melting (EBM)	This method is similar to laser sintering but differs in the heat source since it uses an electron beam and thus this process must be executed under vacuum conditions.
Binder Jetting	Initially a powder is fed by a piston after that an automated roller spread the powder onto build platform. Finally the print heads apply binder to the cross sections that form the object.
Material Jetting	Works by selectively jetting the printing material which is usually in molten or liquid state and supporting material through different jetting heads. However, the printing materials tend to be liquid photopolymers, so curing process is needed to initiate a chemical polymerization reaction which causes the plastic to dry and form a solid.

Nowadays, there are many websites dedicated to 3D printing that include 3D printing companies, communities and hobbyists. In order to save time and focus efforts of others, we compared available information among 16 dedicated 3D printing websites, as shown in Table II. Also, we highlighted the three websites that were most beneficial to our work. The comparison was based on the following criteria:

- Methods. Does the website describe principles of operation for 3D printing?
- Design. Does the website provide detailed steps about building or assembling the mechanical structure of 3D printers?
- Implementation. Does the website include helping information about electronics, software, applying various tests, troubleshooting or CAD models?
- Products. Does the website sell 3D printers components?

TABLE II. COMPARISON BETWEEN 3D PRINTING WEBSITES

Web site	Methods	Design	Implement	Products
3dprinting.com	✓	X	X	X
explainingthefuture.com	✓	X	X	X
3dprintingindustry.com	✓	X	X	X
3dsystems.com	✓	X	X	✓
reprap.org	✓	✓	✓	X
hackaday.com	X	X	✓	✓
protoparadigm.com	X	X	X	✓
micron3dp.com	X	X	X	✓
gadgets3d.com	X	✓	X	✓
thingiverse.com	X	X	✓	X
plasticscribbler.com	X	X	✓	✓
makezine.com	X	✓	✓	✓
solusi3d.co.id	✓	X	X	✓
3ders.org	✓	X	X	X
3dprinterplans.info	✓	X	✓	X
pronterface.com	X	X	✓	X

In this project, an extrusion technique was selected because of its simple mechanical structure, parts availability, and low-cost technology. Furthermore, it is ideal for desktop printer and provides most practical prototype for educational purposes.

The contribution of this paper will is that it provides:

- A step-by-step approach to design a fully-integrated mechatronics system that can be used for educational projects.
- A review of available 3D printer designs and resources.

This paper will be divide into four sections. Section II discusses 3D printer software usage. Section III discusses the design while Section IV shows the implementation. Finally, Section V the conclusion of this paper.

II. SOFTWARE

3D printing follows the sequential stages of design, printing, and post production. 3D printer's software functionality can be divided into three steps:

- Generating CAD models with STL extensions.
- Slicing the 3D model into layers. The objects are built by laying out material layer by layer.
- Generating the G- code (a series of commands that drive the printer) and interpreting the commands via the firmware.

The firmware and G-code are then uploaded to the microcontroller. The microcontroller sends the appropriate pulses to the drivers in order to control speed and direction of axes motors. Feedback signals from thermistor are used to control heat generated by the hot end.

In 3D printing, the user-interface software is an important element that should be chosen carefully. This host software has several tasks that include creating 3D model, slicing objects and converting STL file to G-Code.

A wide range of programs exist to create 3D models and convert STL files to G-codes. Two program were selected for this project. *Thingverse* website [6] was used to download 3D models (it provides over than 400 000 3D model with STL extension) and *Pronterface* [7] was selected to convert to G-code because of its ease of use. It also provides interfacing with firmware without the need for other programs.

Pronterface, shown in Fig 1, is a graphical interface software that contains a built in software called slicer, which is mainly responsible for converting the STL file into G-code and slicing the 3D model. Slicer interface has four main tabs : plater where 3D models are sliced and converted to G-code, print settings contains the parameters that control the method of printing, filament setting where the filament information can be sets and finally, printer setting which contains the parameter that relate to the printer.

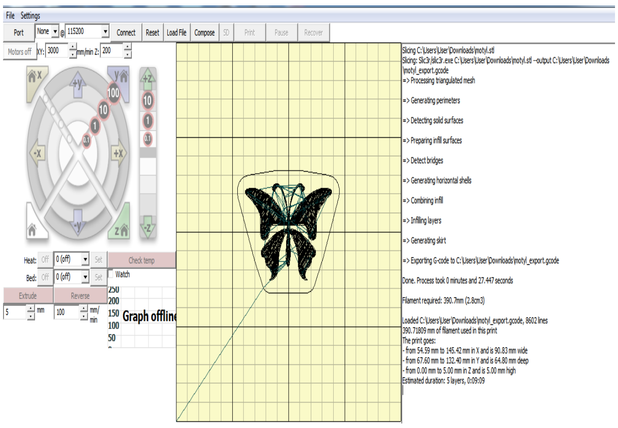

Fig. 1. PRONTERFACE INTERFACE [7]

Firmware is the code that is installed in the microcontroller memory. It provides the interface between other software and controller and must be written in a language that is compatible with controller. In this project, an open source *Marlin* firmware was used.

III. DESIGN

3D printers are considered mechatronic systems because they involve mechanical parts that are controlled by embedded controllers and driven by power electronics. The design of mechatronic systems is a challenge because it involves many interacting subsystems from different disciplines. In such systems, concurrent design is used to maximize the performance and minimize the time [8].

This section will discuss important design issues: system specifications, system diagrams, mechanical design, component selection, and electrical circuits. The design process incorporates the following 7-steps:

1. Define the Problem
2. Gather Information
3. Propose Solutions
4. Study the Solutions
5. Analyze and Design the chosen solution
6. Implement the Design
7. Evaluate Performance

An essential part in the problem definition is initiating the system specifications. These specifications were based on the objective of implementing a low-cost and simple design for a desktop 3D printer as shown in Table III.

TABLE III.SYSTEM SPECIFICATIONS

Printing Material	PLA (Polylactic Acid)
Layer Thickness	0.35 – 0.5mm
Filament size	1.75 mm
Print Size	152 × 152 × 152mm
Printer Weight	13KG
Printer Size	300 × 500 × 430mm
Nozzle size	0.35mm and 0.5mm
Extrusion Temperature	185°- 220°
Velocity	15mm/sec
Acceleration time	0.2 Sec
Resolution	.03mm/step

Design steps 2 (gather information), 3 (propose solutions) and 4 (study solutions) were done via analyzing existing designs and doing an in-depth comparisons among the solutions. These steps were documented in section I.

A. System Diagrams

The concept design was initiated by drawing the block diagram as shown in Fig. 2. The system has five outputs (four motors and one heater) and eight inputs (six for positioning the axis, one for temperature, and one for detection).

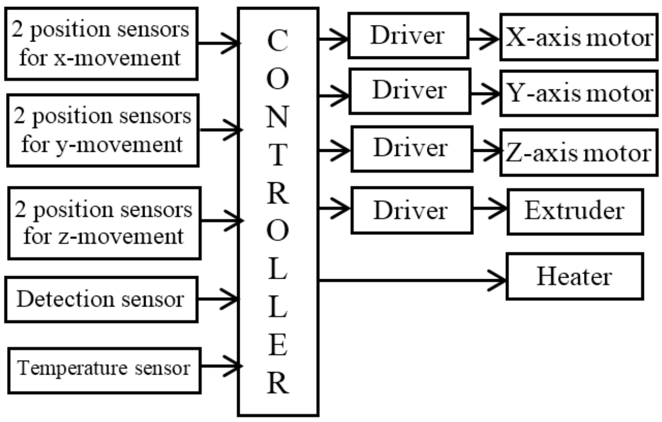

Fig. 2. SYSTEM BLOCK DIAGRAM

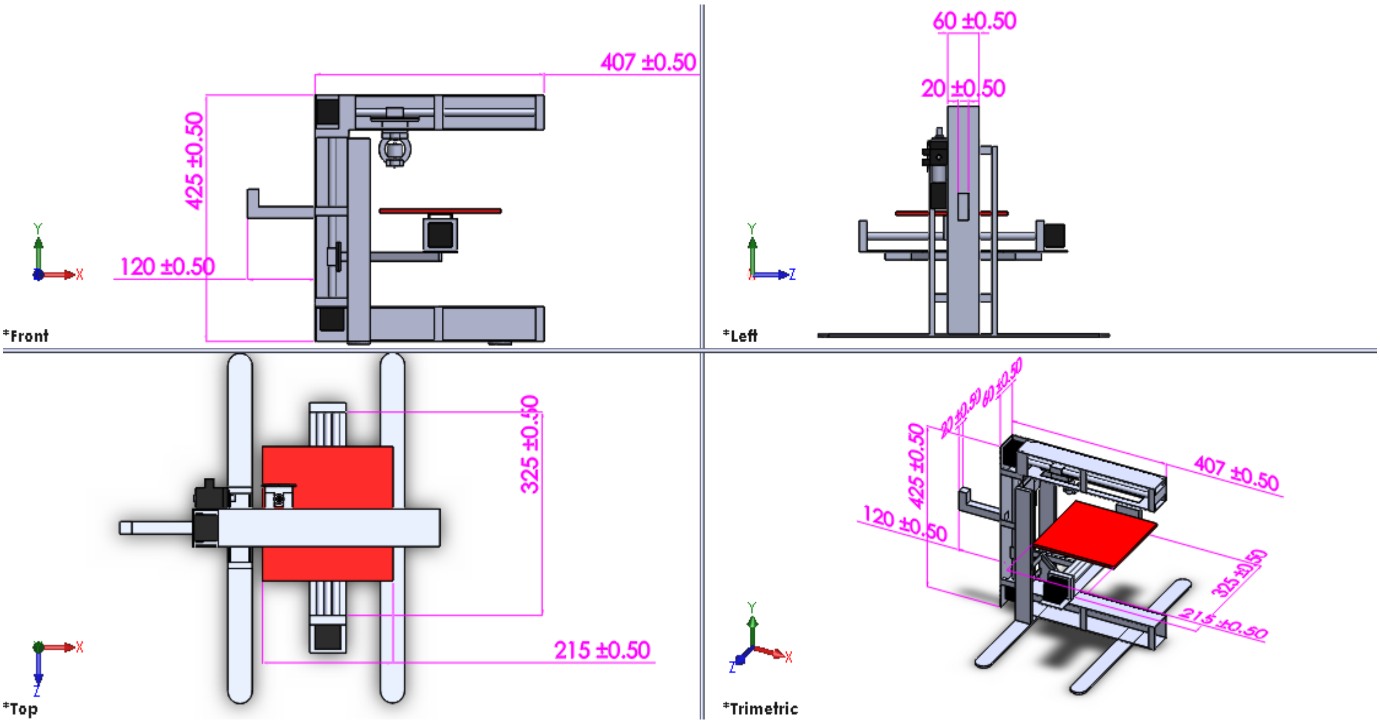

Fig. 3. MECHANICAL DESIGN (all dimensions are in mm)

B. *Mechanical Design and Calculations*

The mechanical structure was based on the Eventorbot printer [9] as shown in Fig. 3. The x-axis moves the extruder left/right and the printing plate is moved along Y and Z axes.

The main equations (used in the design calculations) are presented next in order to provide insight that can be used for educational purposes. All the variables are defined in Table IV.

The linear acceleration (for the axis movements) can be calculated as

$$a = \frac{\Delta v}{\Delta t} \qquad (1)$$

Therefore the required motor angular velocity and angular acceleration (α) can be calculated as

$$\omega = \frac{v}{L} \times 2\pi \qquad (2)$$

$$\alpha = \frac{a}{L} \times 2\pi \qquad (3)$$

Then, the angular velocity can be converted from radian per second to revolution per minute (RPM) using

$$N = \frac{60\omega}{2\pi} \qquad (4)$$

TABLE IV. SYSTEM VARIABLES

Symbol	Variable	unit	Symbol	Variable	unit
a	Linear acceleration	m/s^2	N	Rotational speed	r.p.m
F_{Ext}	External force	N	r	Lead screw shaft radius	M
F_{fr}	Friction force	N	T_a	Acceleration torque	N.m
F_g	Gravity force	N	T_L	Load torque reflected to the motor	N.m
F_{net}	Total force	N	T_{motor}	Maximum torque	N.m
F_p	Preload force	N	t	time	s
g	Gravitational acceleration	m/s^2	v	Linear velocity	m/s
I_{load}	Load inertia	Kg/m^2	ω	Angular velocity	Rad/s
I_{screw}	Screw inertia	Kg/m^2	θ	Step angle	Degree
$\sum I$	System total inertia	Kg. m^2	α	Angular acceleration	rad/s^2
L	Lead	m/revolution	η	Efficiency of mechanism	-
L_t	Total length of lead screw	M	μ	Friction coefficient	-
m_{load}	Mass of load	Kg	ρ	density	Kg/m^3
γ	Tilt angle	Degree			

The required step angle that satisfy resolution 0.03mm/step can be calculated using

$$\theta = \frac{360\times resolution}{L} \quad (5)$$

The inertia of the screw or other components that have rotational motion (e.g. gears), is

$$I_{screw} = \frac{1}{2}\pi\rho L_t r^4 \quad (6)$$

The inertia of components that have linear motion reflected to the motor (e.g. plate and extruder and table) is

$$I_{load} = \frac{m_{load}}{\eta} \times (\frac{L}{2\pi})^2 \quad (7)$$

The system total inertia includes the motor inertia in addition to the mentioned ones. In force calculation, friction force and gravity force are involved and the external force and the preload force are zero:

$$F_{net} = F_{Ext} + F_{fr} + F_g + F_p$$

$$= 0 + \mu g m_{load}\cos\gamma + g m_{load}\sin\gamma + 0 \quad (8)$$

Where γ is 0 or 90 degrees depending on the movement axis. Torque calculations:

$$T_L = \frac{(F_p+F_{fr}+F_g)}{\eta}\left(\frac{L}{2\pi}\right) \quad (9)$$

$$\mathrm{T_a} = \alpha \sum \mathrm{I} \quad (10)$$

Then, the maximum torque including safety required for each motor is

$$T_{motor} = 2(T_a + T_L) \quad (11)$$

The following motor specification were calculated using equations (4), (5) and (11)

- Speed = 449.9 rpm
- Step angle = 5.4°
- Maximum torque = 0.012 N.m

These specifications were used in selecting the appropriate motors and drivers

C. Components Selection

Motors in 3D printers are used to provide motion within the 3-axes (i.e. X, Y and Z). Also, an additional motor is required to feed filament to the hot end.

Stepper motors were selected because they are easy-to-use and can provide positioning accuracy. According to the mechanical calculations, the appropriate motors size was determined and stepper motor NEMA 17 with these specifications:

- Speed = 1800 rpm
- Step angle= 1.8°
- Maximum detent torque= 0.016 N.m

Positioning sensors in 3D printers are used to initialize the three axes to their home position. Also, they are used to protect the mechanism from damage by maintaining the motion within the allowed distance (i.e. safety interlocks). To achieve these purposes, end-stops sensors are used.

Hall effect sensor were selected due to its reliability and fast response. The distance between the hot end and the plate is very crucial and therefore hall effect sensor provide more practical solution than moving mechanical or optical end stops up and down by allowing tuning for this distance using potentiometer

Additional optical sensor was used to detect the presence of filament, to achieve this purpose Photo Interrupter (Type GP1A57HRJ00F) was selected.

Arduino Mega microcontroller was selected as the main controller because of its good performance, interface capability, ease-of-use and availability. The microcontroller was responsible for processing G code instructions, controlling stepper motors, controlling the temperature

A special shield (signal conditioning circuits) for Arduino Mega microcontrollers is required to fit the entire electronic needed for FDM printers. A RAMP shield 1.4 version was selected because it provides good features when developments are needed. Also, it offers SD card reader which allows the using of printer without a computer.

Extruder is the mechanism responsible for feeding the printing filament to the hot end . The hot end melts the filament and thus allowing the filament to flow according to the supplied 3-Dimensional data . An *all metal* hot end extruder was selected because it works with different type of materials and provides a detachable filament guide.

PLA and ABS are the most common materials for 3D printing because of their relatively low melting temperature and cost compared to other materials. In this project, PLA filament was selected.

D. Electrical Circuit Wiring

The circuit wiring is shown in Fig. 4. This circuit includes four stepper motors (one for each axis and additional one for the extruder) connected to Polo stepper motor driver. The thermistor for the hot end was connected to the signal conditioning circuit on the shield [10].

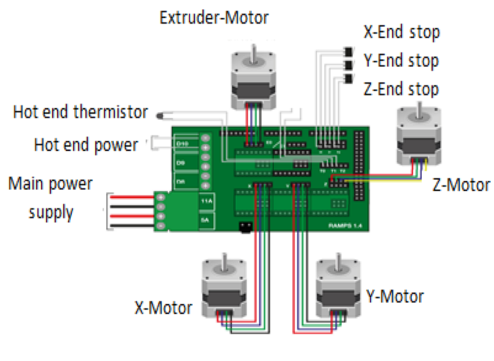

Fig. 4. CIRCUIT WIRING

IV. IMPLEMENTATION

Implementation is a critical step in the design process because it is used to test the products' functionality and performance.

The built prototype is shown in Fig. 5 where the frame, extruder, and plate are displayed and the three axis motors are shown. The extruder moves along X- axis while the printing plate moves along Y and Z axes the mechanical structure was supported by two stands (i.e. legs).

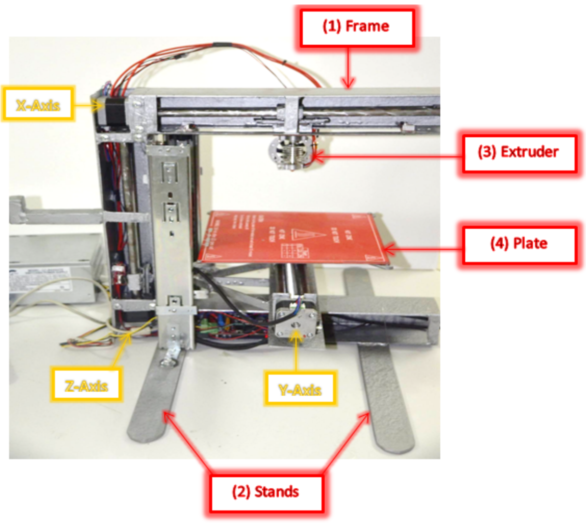

Fig. 5. PROTOTYPE BUILT

V. CONCLUSION

The experience gained in designing and implementing a 3D print prototype was presented. The developed prototype is a fully functional engineering system that included electronic components, electrical motors, mechanical structure, embedded program, and software interface.

Different design options were studied and an *Eventorbot Rep Rap* mechanism was chosen. Ardunio MEGA 2560 was used as the microcontroller and three stepper motors (with their associated drivers) were selected to position the 3-axes. As for the sensors, six hall effect sensors was chosen to detect the limits of each axis. *Ponterface* was used as the main host interface software and *all metal* rostock delta combo: extruder & Bowden hot end was chosen to print the objects.

The developed 3D prototype is a good step in building local knowledge in this new and fast-growing technology. The presented work followed a step-by-step design which can be used as a case study for a mechatronics design education. The paper also summarized and highlighted available 3D printer information and therefore can be used as a reference to readers interested in developing such printers

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