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Developing A Multi-Material 3D Printing Platform: I- Developing A Clay 3D Printing System

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Abstract **–** In this work a new 3D printing platform was proposed. The 3D printing scenario is planned in a way that 3D printing of metal parts could be realized. Metal parts are supposed to be printed by planting metal balls next to each other. At the same time extruding a clay wall around the metal balls would hold the metal balls in their place. Every 3D printing platform consists of three main elements; which are a 3D slicing software, robotics of the printer and the microcontroller firmware. The first two elements are developed in this project from scratch; but for the later the Marlin firmware was used to read, interpreted and execute the generated Gcode file. The proposed 3D printing platform is equipped with two extruders; one is a clay extruder and another is a metal ball planter. The idea behind implanting metal balls is addressed. The design and fabrication of the clay extruder is presented. Clay preparation and loading into the extruder chamber is explained. The 3D printed models out of the clay is illustrated.

Keywords – 3D Printing Platform, Metal 3D printing, Ball 3D Printing, Paste 3D Printing.

I. INTRODUCTION

3D printing is a process for making a 3D object of any shape from a 3D model through additive processes in which successive layers of material are laid down under computer controls. Its advantages are optimal usage of material, increasing flexibility in design, precise manufacturing of parts and quicker production of the prototypes.

The first 3D printing was invented by a reasearch team at MIT late 1980s [1]. In their invention a layer of powder was spred and next a liquid adhesive material was spayed at selected areas to solidify the powder layer. This technique is like inkjet printers function; except in the 3D printing spreading of powder on the lower layers is continued until 3D parts is achieved. With 3D printing, parts with any geometric complexity can be created. Nowadays 3D printing has even entered into live tissue fabrication [2]. Though 3D printing is widely used to print toys, statues, metal parts and bioimplants [3]; It could be used to print micro and nano sturctures as well [4]. Such a micro and nano structures could be made with no other manufacturing method.

Materials of different sort like polymers, ceramics, wood and metals has been adapted for the 3D printing. The materials used in the 3D printing could be of different forms including filaments, powders, resins and pastes. The 3D printers for metal parts has very high economics value and these 3D printers retail for over US$500,000 [5].

Nowadays, rapid prototyping has a wide range of applications in various fields of human activity: research, engineering, medical industry, military, construction, architecture, fashion, education, the computer industry and many others.

Though the term "3D printing" is most widely asscociated with plastic extrusion, many 3D printing technologies have been introduced such that over thirty additive manufacturing technologies have already appeared [6]. To avoid confusion, they can be classified in seven classes. They can be named as Binder jetting, Directed energy deposition, Material extrusion, Material Jetting, Powder bed fusion, Sheet laminating [7-8].

To conclude, 3-D printing has progressively matured technically and witnessed a rapid growth. It has proven useful for both design, small batch production, and potentially distributed manufacturing [5]. The *Economist* speculated that these technical advances could result in a `third industrial revolution' governed by mass-customization and digital manufacturing following traditional business paradigms [9]. In short 3D printing can be considered the technology of future.

In this work a new 3D printing scenario is proposed. This report elaborates on the 3D printing concept first; and presents the details of 3D printing with clay next. 3D printing with clay was the first step taken to realize the scenario in practice. The work is a continuation to the multi-color dot printer project reported earlier [10].

II. MATERIAL AND METHOD

A. The 3D printing Scenario

This work is built on proposing a new 3D printing scenario. The scenario implemented in this project is planned in a way that 3D printing of metal parts could be realized. Metal parts are planned to be printed by planting metal balls next to each other. At the same time an auxiliary clay extruding system would be deployed to hold the metal balls in their place. This way working with two different material forms – metal balls and clay paste- would be practiced. It means that the proposed 3D printing platform will have the following potential for its future development plan. First it can print materials in different forms like solid and paste; second as solid balls are planted one by one in the printing process, it can be expanded to print metal balls of different materials and to create multi-material metallic prototypes.

Figure 1 ilustrates how the metal ball can be planted in the odd and even layers next to each other. This means that after planting metal balls next to each other on a odd layer, it is necessary for shifting metal balls center in the X and Y direction in even layers. This results for achieving maximum packing factor for the metal balls per unit volume.

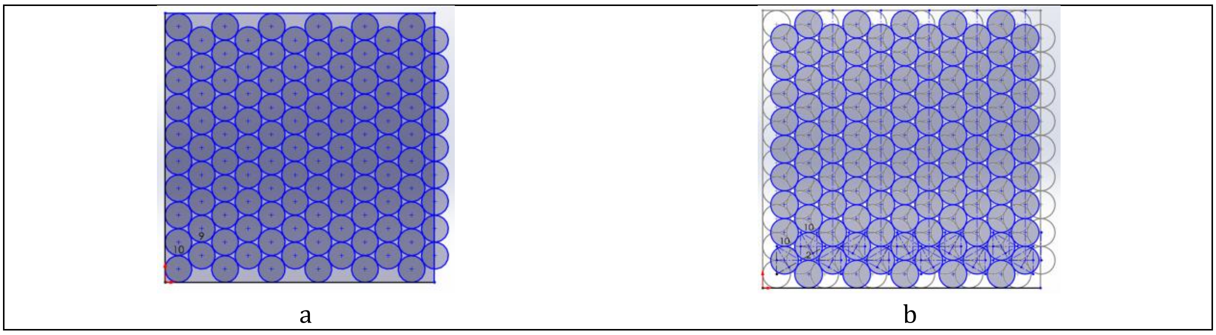


Figure 1. The planting pattern of the balls: a) in the odd layer, b) in the even layers.

As in this printing scenario, metal balls are planted next to each other to create a layer, the layer thickness in slicing a STL file will be a function of metal balls. Considering Figure 2, the first layer thickness is 0.5*D and for the second and higher layers is D*sqrt(2.0/3.0). In case of D= 2 mm, the first layer height will be 1.0 mm and the higher layers' height will be some 1.63 mm. This can be seen in Figure 2.

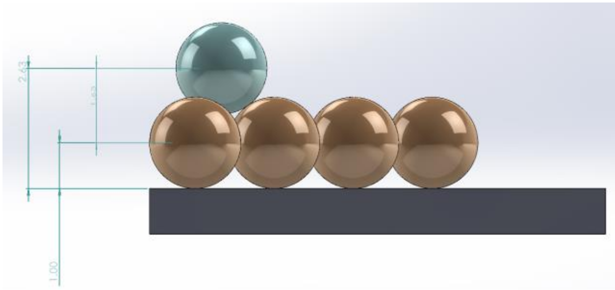


Figure 2. The layer thickness representation for a ball diameter D = 2 mm.

The ball planting adopted in this work is very much like the faced-centered cubic (FCC) particular packing in the material science. The atomic packing factor (APF) is defined as the volume of the atoms per volume of the unit cell. For a FCC particular packing, it is found that $APF = \frac{\pi}{3\sqrt{2}} = 0.74$. This means that 74% of the 3D printed model volume will be filled with metal balls and there will be 26% of empty space inside the 3D printed model. Definitely it is desirable to increase the material filling percentage up to 100. Theoritically, this matter can be achieved by planting cubic metal balls instead of spheric metal balls; but it is out of the scope of this work and needs to be adressed seperately.

As metal parts are planned to be printed by planting metal balls next to each other layer after layer, an auxiliary clay extruding system is planned to be deployed to hold the metal balls in their place. The clay extruding system could create a shell around the metal balls. Further there should be a clay layer both beneath the metal balls and on top of them. This way the realized metal part would be encapsulated inside a clay shell from all sides. Indeed final 3D printed part would consists of a clay shell filled by metal balls planted next to each other. Ofcource such a 3D printed model needs to be sintered in an oven to bond the metal ball together creating a solid 3D model.

The development of the 3D printing systems consists of four main steps. The four steps are mechanical design and fabrication of 3D printer robotic setup, design and fabrication of 3D printer nozzle and extruder system, slicing and user interface software development and developing the firmware for the microcontroller board of the 3D printer. Ofcourse not necessarily the four steps should be taken in subsequent manner.

The design of a 3D printer robotic system is a routine job hence it is not the focal point of the project and is addressed shortly. The 3D printing robot is a cartesian three axes robot. Figure 3 illustrates the robot. It can be seen that, the robot can move in X, Y and Z directions. The movement in X and Y axes is conducted by a pulley-belt system; but the movement in Z axis benefits from a leadscrew and nut system. The movement on all axes is produced by a stepper motor. The table plate is moved in Y direction. The Z axis itself is carried by the X axis to the left and right. The Extruders are mounted on the Z axis plate and can be moved upward and downward. The structure of the robot consists of 20x40 mm sigma profiles.

Developing the firmware for the 3D printers is a very fundamental step and needs an idependent work. Marlin being an open source firmware is reputable among 3D printer developers and it is used in a lot of commercial 3D printers todays. Hence, the Marlin firmware was used to read, interpret and send the Gcode commands to the printer's step motors. Further developing the slicing and user interface software was conducted as part of this project. But reporting on would be the subject of another paper.

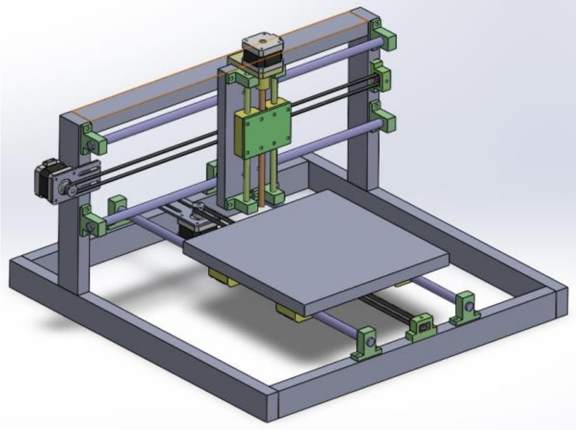


Figure 3. The 3D view of the designed cartesian robot.

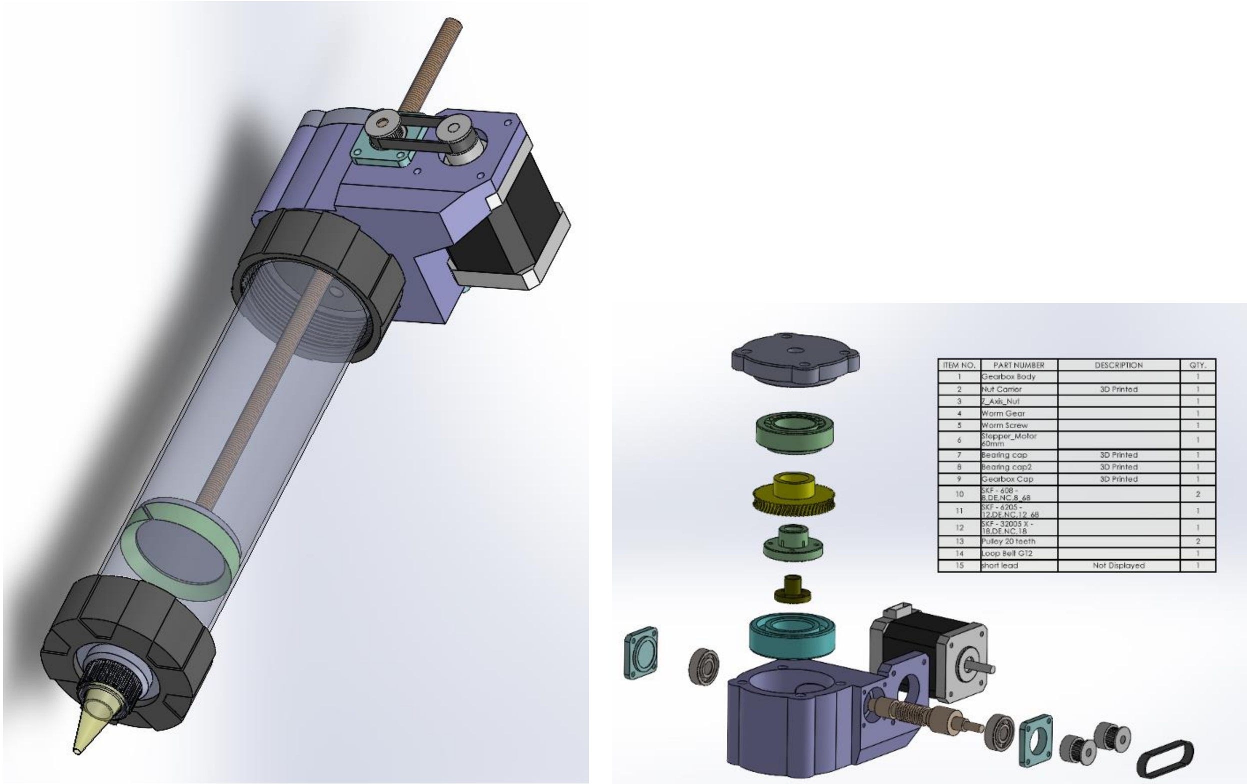
Design and fabrication of 3D printer nozzle and extruder is one of the key steps in realizing 3D printing task. In this project two different extruding system was developed which are a clay extruder and a metal ball planter. This paper reports the procedures and steps in designing and developing the clay extruding system.

B. Developing The Clay 3D Printing System

In this study, two differentmextrusion systems were designed, fabricated and tested for clay 3D printing. The first clay extruding system was a long-distance extrusion system; in which clay was loaded into a cylindrical chamber and pushed by pressurized air. As the air pressure is applied, the clay is feed from the clay chamber through the connecting hose into the extruder. The extruder stepper motor rotates a helical part forcing the clay out of nozzle and upon the movement of the printer axes the clay printing was conducted.

In this approach the clay chamber regardless of containing considerable amount of clay stays constant and does not move during printing. This will reduce need for using stronger and heavier robotic systems and make it possible to drive the printer end effector with smaller stepper motors. This is considered an important advantage. During printing with clays having different water contents, it was observed that, the thick clays cannot be pushed through hoses with relatively small diameter. In result to benefit this extrusion system the clay should be diluted enough with water. This is considered an important disadvantage. Because the printed clay might not preserve the printed form and could be distorted easily or even collapse totally. As another fact, this extrusion system adds considerable complexity to the printing process and it was decided to look for a simpler substitute.

The favorite substitute is a direct extrusion system. Figure 4(a) shows the Solidworks design for the extrusion system. In this system, the clay inside the chamber is extruded by a threaded rod. The threaded rod itself is driven by a worm-gearbox. The design of the worm-gearbox is shown at Fig 4(b). In this design, the extruding stepper motor rotates the worm. This is done via a toothed pully and belt movement mechanism. The worm rotates the gear which itself is integrated with a trapezoid nut and a leadscrew system. In result, the rotation of gear drives the central leadscrew forward which extrudes the clay through the nozzle.



(a) (b)

Figure 4. a) The design of direct clay extruding system; b) The clay extruder gearbox design in exploded view.

The realized direct extruder is shown in Figure 5. The clay chamber is made of a Aluminum tube that can be easily detached from the gearbox as well as from the nozzle and the throat part at its bottom. The internal diameter of tube was 51 mm. All this makes the cleaning and maintenance much easier and user friendly. Nozzle itself can be removed and cleaned easily as it is connected by a threaded fitting.

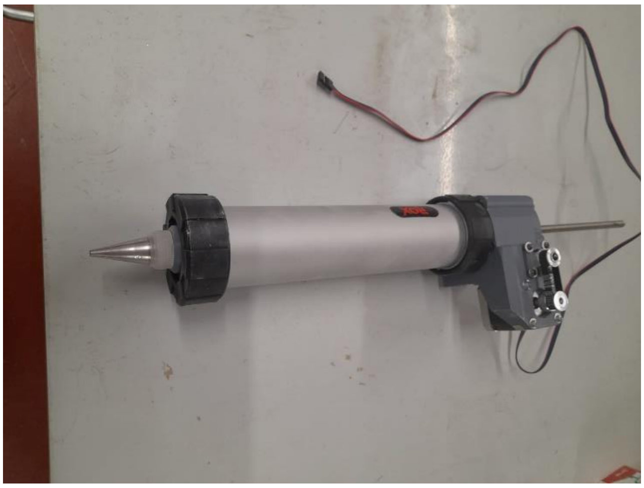


Figure 5. The realized direct clay extruding system.

III. RESULTS

In printing with clay, its water content plays an important role on the extruding motor power and size. In this project, it was planned to use a Nema17 stepper motor equipped with a worm gearbox mechanism. It was important to find out how-thick a clay can be extruded through a 3mm diameter nozzle effectively.

A sample of porcelain clay available on market was purchased. The clay is used in pottery makings. Initial handling of the clay made it clear that it is too thick (with low water content) for being extrudable though a nozzle of few millimeters. Clearly it showed impossible to extrude though a 3 mm diameter nozzle lately. As another attempt, a sample of the clay was dried to find out its water content. It was found that pottery clays on the market almost contain three portion of soil and one portion of water. In another words water consists 25% of the resulted clay.

Consequently, a series of experimental trials was conducted to find out how thick a clay can be extruded effectively through the clay extruder designed in this study. It was found out that, clay has to have minimum of 29% water content and a clay with water content of 30% would be extruded through a 3 mm nozzle easily.

In order to obtain a flawless clay printing, it is important to make sure that no air bubble is trapped inside the clay. But when the clay chamber is filled by manual procedures the chance of air trapped between consequent pushes of clay inside clay chamber is very high. To avoid this issue a simple but significantly successful procedure was adopted. Here is all the steps followed for the bobble free clay preparation until its loading into the extruder chamber: a) the required water amount is added to the dry soil and mixed until a humogen clay is obtained, b) two pieces of plastic PVC tube is used for clay loading. In the meantime a thin polyethylene plastic film is set as a sleeve on the inside surface of one of tubes, c) The clay is loaded by a wood stick into the tube with no plastic sleeve. The clay loaded in this stage will have considerable amount of air trapped inside. d) the loaded tube is set on the top of the unloaded tube by means of an adaptor part, e) and the clay is pushed by a piston from the top tube into the bottom one. At this stage most of the air trapped inside the clay will exit and almost an air-free clay will be resulted. f) the clay together with its thin plastic sleeve is brought out and is fed into the extruder chamber. g) finally, the nozzle head fixed at extruder chamber opening. By this process two important achievement is made. Firstly, an almost bubble-free clay is achieved and secondly the clay will not pollute the inside wall of the extruder chamber. Indeed, by these steps a clay sausage is created.

Figure 6. The printed models with the clay of 30% water content.

3D printing with clay starts with opening the STL model of object by the 3D printing software. In this study a single clay wall was considered; so, the Gcode file containing the peripheral of the model was generated. Later this file was copied into a SD card and was executed by the 3D printer controller. Figure 6 shows some of the printed models with the lately developed extruder. The clay had 30% of water content.

IV. DISCUSSION

The 3D printing platform is built to plants metal balls of 2 mm in diameter. The process is continued by 3D printing a clay shell around the metal balls in each layer. For conducting such scenario a custom slicing algorithm was developed which is not addresses here and is planned to report it separately.

The Marlin firmware, version bugfix-1.1.x, was used as the 3D printing controller and was downloaded on a Mks Gen L V2.1 3D printer motherboard. Since extruding the clay does not need any haeting, as it is the case in printing with the plastic filaments, the 3D printer had no temperature sensor and in the configuration file of the Marlin the temperature sensor was set as #define TEMP_SENSOR_0 998. Thanks to the setting a dummy table that always reads 25°C as the temperature will take effect by the temperature sensing algorithm of the Marlin. Further the DEFAULT_AXIS_STEPS_PER_UNIT parameter for the clay extruder was set to 691. As it is calculated as microstepping number * number of steps for a full turn of the stepper motor * number of worm gear teeth * (clay nozzle diameter / clay extruder internal diameter)^2. The relevant numbers are 16, 200, 60, 3 and 50 mm respectively in this study.

In the 3D printing with the clay, the peripheral shape of model could have arbitrary complexity. But the wall should not have large angles respect to the vertical axis. This could result in deformation of the 3D printed wall or even could result to its collapse totally. The practiced layer thickness was mainly 1 mm. This thickness is considered quite suitable considering the fact that the metal ball diameter is 2 mm.

V. CONCLUSION

In this work a new 3D printing scenario was proposed. The 3D printing scenario can be used for the 3D printing of multi-metal parts. The design of 3D printing robot was addressed and the design and fabrication of the clay 3D printing extruder was presented. The successful 3D printing of varius models with clay was reported. It was observed that the peripheral shape of model could have arbitrary complexity. But the wall should have not have large angles respect to the vertical axis of the model.

Considering the proposed 3D printing scenario, as the second step the design and development of the metal ball planting system is undertaken. As third step, the metal ball planting and the clay 3D printing will be integrated in a single scenario.

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