Extruder Design for 3D Printing of Ceramic Materials

Karel Slobodník
Department of Electrical and Computational Engineering
University of West Bohemia
Pilsen, Czech Republic
karelsl@fel.zcu.cz

Lenka Šroubová
Department of Electrical and Computational Engineering
University of West Bohemia
Pilsen, Czech Republic
lsroubov@fel.zcu.cz

Radek Spurný
Department of Electrical and Computational Engineering
University of West Bohemia
Pilsen, Czech Republic
spurnyr@students.zcu.cz

Martin Heimrath
Department of Electrical and Computational Engineering
University of West Bohemia
Pilsen, Czech Republic
heimrath@students.zcu.cz

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***Abstract*—This paper deals with the design and development of an extruder for printing ceramic materials including its control. The paper describes the experimental development of the extruder, divided into a mechanically extruded stack and the method of feeding the material into a print head equipped with a screw conveyor. The paper includes a computer model of the designed extruder. The aim of the paper is to demonstrate the proposed extruder and verify its functionality.**

***Keywords*—3D printing, ceramics, extrusion, extruder, construction, force analysis, stress simulation.**

I. Introduction

The paper focuses on the issue of 3D printing of ceramic materials. Ceramics, which is one of the early ancient materials, is combined with modern 3D printing technology. A custom 3D ceramic printer has several advantages. One of the main advantages is the speed from design to the final product. Another advantage of 3D printing is the saving of material because the exact amount of material can be calculated. There is also the advantage of creating decorations while printing. Traditional ceramics could be reproduced using screw type extrusion technology [1]. Not only for decorative and utility ceramics [2], but also for ceramics used in medical applications [3], [4], accurate and stable 3D printing is important. The aim of this work is the development of an extruder for printing dimensionally accurate and mechanically stable complex specific structures.

Options of printing materials for 3D printers are presented and analyzed [5]. Many works deal with the testing of ceramic materials, the extrusion of ceramic slurries and the testing of mixtures [6]. In some papers, the construction of a custom 3D ceramic printer is described [7]. These custom 3D ceramic printers mostly serve one purpose. A 3D printer for ceramic materials is being developed in the Department of Electrical and Computational Engineering. Our goal is to design a replaceable extruder for a 3D ceramic printer that would allow printing from different materials and would also be mountable in commercial printers.

II. Extruder for printing ceramic materials

For the purpose of printing ceramic materials, an appropriate extruder was needed. The decision for a divided extruder was made because of the layout of the printer base and also to be able to mount the extruder at any commercially available printer users. Extruder is split into two parts. The first is a clay tank, which carries the material and delivers it to the second part, the printhead, which extrudes the material onto the print bed.

A. Clay tank

Fig. 1 shows the clay tank. The basic principle of the material stack is to continuously dispense material into the printhead. The dispensing method is similar to the silicone cartridge system. It is very important to keep constant feeding of material from the stack to the printhead to minimize defects in the final product.

The stack carrying clay is fixed to the printer base with 3D printed plastic holders (2, 4, 10). One side of the stack is ended by transition into a tube leading to the printhead (11). The other side of the stack is the entrance for the piston (8).

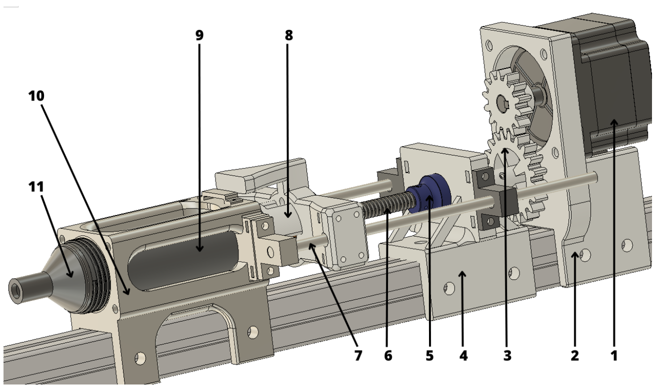

Fig. 1. Clay tank.
(1 - stepper motor; 2 - motor holder; 3 - gears; 4 - axial holder; 5 - bearing house; 6 - trapezoidal screw; 7 - guide rods; 8 - piston with trapezoidal nut; 9 - clay tank; 10 - clay tank holder; 11 - tube transition)

This piston is also constructed using 3D printed plastic parts in combination with mechanical elements for transition of rotational movement to translational movement with additional parts to limit the rotation of the piston itself (7). Piston is translationing on a trapezoidal screw which is rotated by a stepper motor (1). This motor was selected according to the required mechanical properties in particular especially with respect to required torque and stepping accuracy.

B. *Printing head*

The printhead is developed to withstand the operating pressure of the material. The essence of this head lays in a screw conveyor, which by rotating the screw transports in standart circumstances usually loose materials. The rotation of the auger covers the stepper motor. The initial designs were made of plastic parts. These did not meet requirements in strength which led to destruction of these early attempts. However, they helped specify the influence of the auger shape and its cover.

Through continuous testing we came to the final shape of the auger. The optimal version for our purposes has a pitch 30 mm with length of 133.5 mm. The position of the auger end is preferred to be as close as possible to the nozzle to prevent its clogging.

Furthermore it is very important to set the correct ratio of stepper motors speed, which were set from observing the volume ratio of the extruded material from the stack and the printhead. For correct functionality these two volumes should have the same value. To accomplish this we had to change the speed of the stepper motors. Keeping the velocities the same value for both motors would lead to an overpressure in the system and after some time into the destruction. Based on knowledge of the stack and the printhead dimensions, a ratio was derived which would cover up the differences in volumes of the individual parts. Basically, we want to extrude the same amount of material volume from the stack as from printhead per one revolution. For the current design version this ratio was calculated 5:1 in favor of the printhead.

The volumetric flow rate of the printhead, which is the volume of fluid which passes through the printhead in a given unit of time, has to be the same as the volumetric flow rate of the stack. Using this continuity equation, we work with the assumption that the flow of the material from the stack will equal the flow out of the printhead. It is also important to note that the use of this equation applies to any incompressible fluid, which clay can be defined because it cannot be compressed.

The material extruded from the stack per revolution is shown in equation 1.

$$V_{STACK} = \pi r_{STACK}^{2} l \tag{1}$$

where r_{STACK} is the stack radius and l is trapezoidal screw pitch.

The volume of the material part of the auger of one revolution is determined in equation 2.

$$V_{AUGER} = S_{AUGER} l_{AUGER} = \left(\frac{\pi r_1^2}{2} + \frac{\pi r_2^2}{2}\right) l_{AUGER} \tag{2}$$

where S_{AUGER} is the area of the screw with the central shaft support element, r_1 is the shaft radius of the auger and r_2 is the radius of the screw conveyor, and l_{AUGER} is the pitch of the auger conveyor.

The volume of auger cover V_{COVER} is shown in equation 3.

$$V_{COVER} = S_{COVER} l_{AUGER} \tag{3}$$

where S_{COVER} is the circular auger cover area and l_{AUGER} is the pitch of a modeled auger conveyor.

The volume of material which is inside of the auger cover is calculated according to equation 4.

$$V_{MATERIAL} = V_{COVER} - V_{AUGER} \tag{4}$$

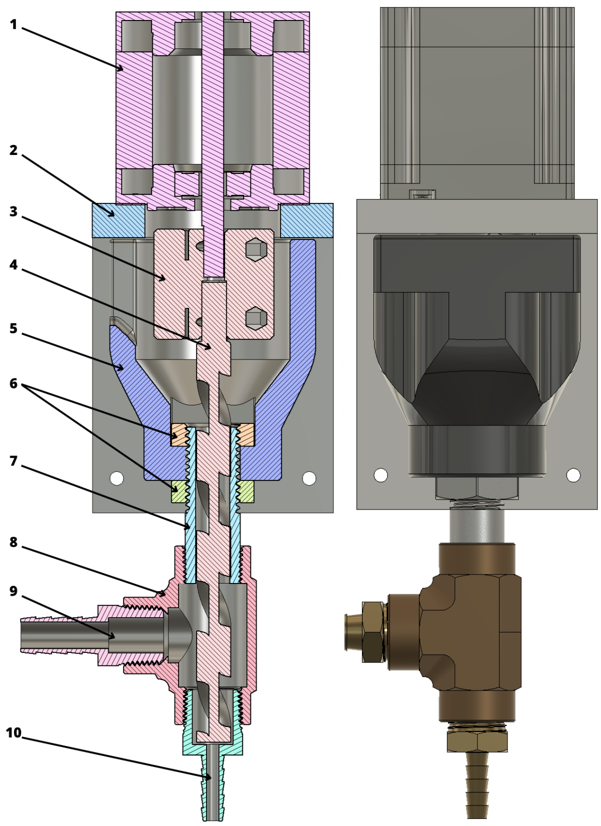

Fig. 2. Printhead.
(1 - stepper motor; 2 - printhead holder; 3 - motor coupling; 4 - the auger; 5 - flange; 6 - counter nuts; 7 - connecting rod; 8 - T connector; 9 - material inlet, 10 - nozzle)

The ratio of extruded material from stack and extruded material from printhead per one revolution is determined in equation 5.This ratio is determined for the following values: the stack radius is 0.0238 m, trapezoidal screw pitch is 0.003 m, S_{AUGER} is 42.8 m^2, the pitch of the auger conveyor l_{AUGER} is 30 mm, and the radius of the circular auger cover is 5 mm (Fig. 3).

$$k = \frac{V_{STACK}}{V_{MATERIAL}} = 4,97 \tag{5}$$

Using the equations above we came to the previously mentioned conclusion that the volume of stack extruded per one revolution is approximately five times bigger than the volume of material extruded from printhead per one revolution. Therefore, it is necessary to make the velocity of printhead 5 times greater than stack velocity.

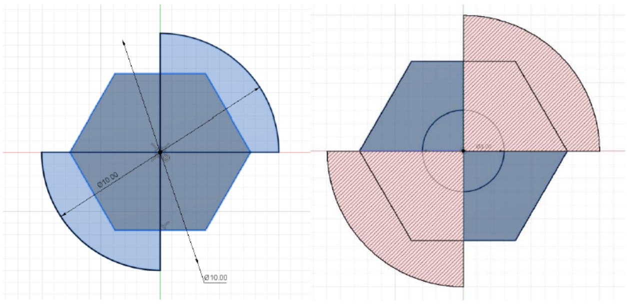

Fig. 3. Designed auger

III. Simulations

The design process led to a prototype of the extruder and consisted of several steps. Some of the steps were repeated a couple of times depending on the necessity for improvements and adjustments in the extruder design. The design process was started by preliminary investigations of the mechanical behavior of the current used silicone cartridge system. The mechanical design of the extruder was always influenced by the results of the analyses of the feeding of material from stack to the printhead at any point of the design process.

Component testing was performed after completing the simulations. Subsequently, if any insufficient qualities were discovered in any component, the process of design and simulations were repeated until the successful design was obtained.

Static simulations under loading forces, shape optimization and clay mass flow simulations were performed.

The simulation of the static loading of the extruder components corresponding to the force acting on these components was performed in Autodesk Fusion 360 [9].

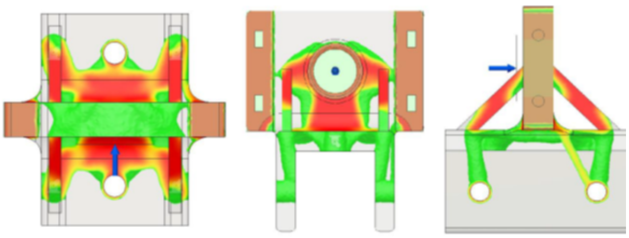

Fig. 4. Shape optimization of the radial bearing holder.

In the design of the plastic printed parts of the extruder, topological optimization was performed to save material with respect to its load and manufacturability. The topological optimization resulted in optimized shape of parts that are lighter while maintaining strength assumptions. Fig. 4 shows the shape optimization of the radial bearing holder and the thrust bearing support. The optimized shape corresponds to a mass of 30 % of the total predicted mass of the original unoptimized design. The final shape was modified to an easier printable form, and optimizations were taken into account, so the use of optimizations resulted in material savings.

Clay mass flow simulations were performed in Solidworks software [10]. For the correct flow simulation, it is necessary to set the boundary conditions and input parameters so that the simulation is close to the real environment.

The mass method of measuring the consistency of the mixture was used to determine the ratio of dry clay to water. Fig. 5. depicts the clay mass flow velocity in the screw conveyor.

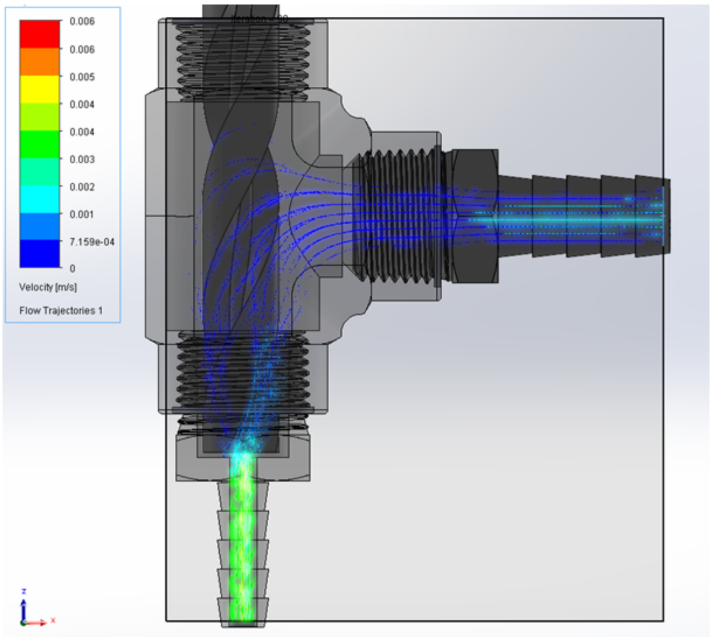

Fig. 5. Clay mass flow in the screw conveyor

IV. Firmware

For the purpose of controlling the extruder setup the modified Marlin firmware was used [8]. Marlin is open source firmware originally designed for RepRap project FDM (fused deposition modeling) 3D printers using the Arduino board and RAMPS shield. It runs on the 3D printer's main board, managing all the real-time activities of the machine. It coordinates the heaters, steppers, sensors, lights, LCD display, buttons, and everything else involved in the 3D printing process. Known for its versatility and compatibility with various 3D printer hardware, Marlin provides an extensive set of features, including support for multiple extruders, automatic bed leveling, thermal protection, and advanced motion control algorithms. For the presented 3D printer automatic bed leveling and thermal control were disabled, since there is no heating involved.

Marlin firmware was set up in a mixing configuration. This configuration is usually used for color mixing in FDM 3D printers. It allows control of multiple extruder stepper motors to feed material into a single nozzle synchronously. It also allows setting a mix factor to define a speed ratio of individual motors.

In our example the two extruder stepper motors were configured, one for a clay tank piston, second for a printing head. They were set up as one virtual extruder in a mixing mode. In the mixing mode of the extruder, it is possible to separately define the speeds of both motors and thereby set the extrusion ratio to ensure a smooth extrusion of the material without pressure build-up. The pair of extruders set in this way was then saved and the virtual extruder T2 was created. Printer was controlled by a PC with a Pronterface software that is used to send g-code directly to Marlin firmware.

V. Illustrative Example

The developed extruder was tested on several samples of materials intended for ceramic production. The extruder described in this work was practically verified on a 3D printer developed at the Department of Electrical and Computational Engineering. The printer has dimensions of 0.8 m x 0.8 m x 1 m, with an internal print area of 0.45 m x 0.45 m x 0.7 m. Stepper motors fitted with trapezoidal screws are used for movement in the Cartesian coordinate system of *x,y* and *z* axes. For the *z* axis, four motors are used to distribute the load and provide a stable feed in this axis. The control of the motors in the *x,y* and *z* axes is handled by an Arduino MEGA2560, equipped with a RAMPS shield, which was designed to control three-axis devices. Fig. 6. depicts the verification of prototype functionality.

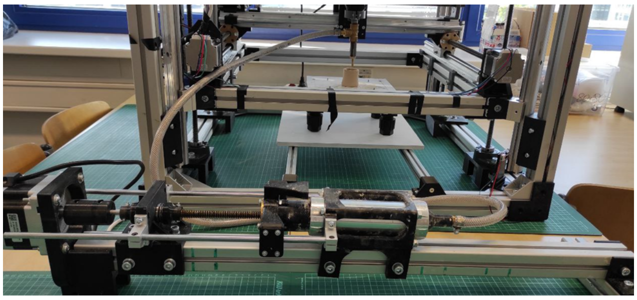

Fig. 6. Verification of prototype functionality

The first material for the print test was a self-hardening material. After testing the printing of the self-hardening material, we proceeded to print ceramic clay. Validation of the computer model was performed on data obtained from individual experiments when printing from ceramic clay mixed with water. Fig. 7 shows the extruder testing during 3D printing from the ceramic clay.

Fig. 7. Extruder testing during printing

VI. Conclusion

The main objective of this paper was to design, construct and verify the functionality of a prototype extruder for printing ceramic materials. The final prototype version of the extruder is divided into two parts, a clay tank part and a print head part.

The tank part is designed and constructed with a view to saving material together with sufficient ability to withstand mechanical stress. The print head is designed according to the principle of a screw feeder, which delivers the material through a nozzle to the print pad. The use of a mechanical extruder design capable of continuous printing has been experimentally verified, the need for more robust print head parts has been demonstrated, and the negative effect of a wide auger design on material extrusion has been revealed. The position of the auger should be as close as possible to the nozzle and should be within the dimensions of the guide tube diameter.

A wide range of models with different dimensions were created in the simulation program, followed by functional verification. Both shape and flow computer simulations were performed. The prototype was fabricated according to the optimal design of the model. The extruder was tested by printing from self-hardening materials and ceramic clay.

Further developments will be directed towards 3D printing products from several different materials using multiple extruders.

Acknowledgment

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