Design and Control of Ceramic 3D Printer

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***Abstract*—This article deals with the design and control of a ceramic 3D printer. The paper describes the design of the ceramic printer, the development of the extruder and the control of the 3D printer. The paper includes a computer model, analysis and simulation. The aim of the paper is to demonstrate the designed 3D printer and verify its functionality.**

Keywords—design, control, 3D ceramic printing, material extrusion, ceramic clay, mechanical properties, stress analysis.

I. INTRODUCTION

The aim of this paper is to present the design and control of a custom ceramic 3D printer that will be used to print dimensionally accurate and mechanically stable complex geometric shapes with customizable material properties. The advantage of the ceramic 3D printer is also the possibility of printing various details and decorations. Modern 3D printing technology is combined with one of the first ancient materials. The admixture-free material can be reused after soaking up water, which is beneficial for the environment. The products can be further worked with, cured, glazed and accessories can be added.

An interchangeable extruder for such a ceramic 3D printer has been proposed, which allows printing complex specific structures from different materials and which can be mounted into different printers. [1]

Ceramics exhibit excellent properties such as high strength and hardness, oxidation resistance, high melting point, and in some cases wear resistance. These properties make ceramic materials ideal for use in a variety of applications. 3D printing of ceramics has so far been used mainly for the production of consumer products, artwork, decorative and utility ceramics [2], and sculptures, prototyping, but is currently seeing growing interest from industries that use ceramic tools and small-volume parts, such as electronics [3], chemical engineering, aerospace and automotive industry [4, 5], dentistry, healthcare and medical applications [6, 7]. Another important factor is the growing demand for products to enhance the aesthetic value of homes, hotels, restaurants and businesses.

The basic concept of 3D printing brings advantages that differentiate it from conventional ceramic manufacturing, speeding up prototyping, accelerating production through computer-aided design, minimizing waste and being economical. [8]

Many works deal with the design of ceramic 3D printers [9], the use of screw type extrusion technology [10], extrusion of suspensions, testing of ceramic materials and mixtures [11]. These custom ceramic 3D printers are mostly single-purpose. The 3D printer for ceramics developed at the Department of Department of Electrical and Computational Engineering prints precise shapes with accurate dimensions from various materials or a combination of materials.

Fig. 1. Ceramic 3D printer

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II. DESIGN OF CUSTOM CERAMIC 3D PRINTER

Fig. 1 depicts the ceramic 3D printer whose outer dimension was chosen to be 0.8 x 0.8 x 1 m. The control of the 3D printer is performed in the Cartesian coordinate system. Stepper motors equipped with trapezoidal screws are used for movement in x, y, z axes. Four motors distribute the load and ensure stable feed in the z-axis. The outer support profiles have been fitted with linear support rods at the corners to stabilize the extruder's internal support structure. The counter bars are attached to the inner square gantry. The inner square gantry carries the motion in the x and y axes. The structure that supports the printhead section is fixed on two support rods in both x and y axes. The internal print area is 0.45 x 0.5 x 0.7 m. The ceramic printer is equipped with a display that shows data from the sensors.

The construction of the ceramic 3D printer consists of aluminium parts and plastic parts printed on a 3D printer. The plastic printed parts were optimized for load, manufacturability and material savings. While maintaining strength, the topologically optimized parts had a reduced mass density of up to 30 %.

III. CONTROL

The presented 3D printer is controlled using an Arduino Mega as a mainboard and a RAMPS 1.4 shield. The firmware used was a customized version of Marlin firmware. Marlin is an open-source firmware originally created for RepRap project FDM 3D printers. It runs on the mainboard and handles all the tasks of the machine in real time. This includes coordinating activities such as controlling stepper motors, sensors, buttons, lights, displaying information on LCD, and everything else that is part of the 3D printing process. Due to the current requirements of NEMA 23 stepper motors, external stepper motor drivers EM542S were used.

Extruder control in a Marlin firmware was set up in a mixing configuration. The primary purpose of this configuration is to enable colour mixing in FDM 3D printers. It allows precise control of multiple extruder stepper motors. These motors feed materials into a single nozzle simultaneously. Additionally, it also allows setting a mix factor to define the speed ratio of individual motors.

To properly extrude a paste clay material a system of two extruder stepper motors was controlled, one for a clay tank piston, and the second one for the printhead. In this extruder mode, it is possible to individually control the speed of each motor. This allows setting the extrusion ratio as needed. The result is a smooth material extrusion process without any pressure build-up. The pair of extruders set in this way was then saved and the virtual extruder T2 was created. The printer was managed using a PC with Pronterface software that is used to send g-code instructions directly to Marlin firmware.

The printer allows print speeds ranging from 5 mm/s to 15 mm/s. The speed is low enough to achieve an accurate shape and minimize errors.

IV. SIMULATIONS

Simulations of the individual extruder parts [1] and other components were performed in Autodesk Fusion 360 supplemented with a number of own procedures prepared for this purpose. [12, 13]. Special attention was paid to the extruder of the 3D printer. The customized extruder is adapted to fulfill the needs of extrusion of ceramic materials. Layout of the universal printing platform disabled use of the single extruder, therefore the use of an extruder divided into two parts was needed. Many cases of the internal arrangement of the material stack and printhead have been simulated and tested. The optimal variant is presented in Chapter V.

The simulations of clay mass flow are expressed by the continuity equation (1) that describes the conservation of mass.

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \mathbf{u}) = 0 \tag{1}$$

where ρ is the density of the clay mass, t is time, and $\nabla(\rho \mathbf{u})$ represents the divergence of the density times the velocity vector.

The simulations were performed in Solidworks software [14]. It is necessary to set the boundary conditions, input parameters and output parameters, i.e. initial and final ceramic clay levels, flow velocities, temperature, and material properties of the ceramic clay according to the measurements so that the simulation corresponds to the real environment. Fig. 2 shows the velocity of the mass flow of the clay in the screw conveyor. The speed depicted in Fig. 2 is the velocity of the clay relative to the rotating auger in the printhead.

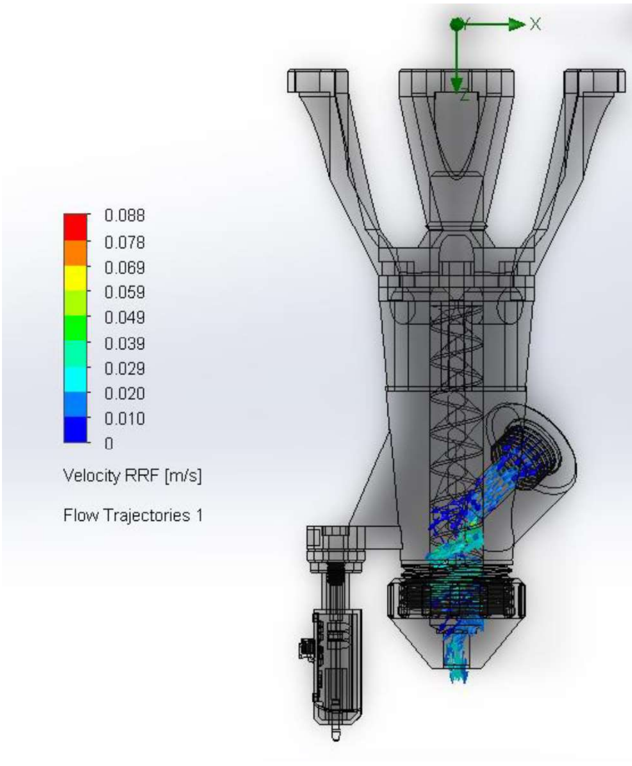

Fig. 2. Clay mass velocity

V. EXTRUDER FOR CERAMICS PRINTING

The presented printing device consists of two parts, the material stack containing the clay tank and the print head. The clay tank based outside of the printable space of the printer extrudes material through a braided hose into the printhead.

The principle of material stack is to dispense material into the printhead. Need of continuous material supply is required to minimize defects in the final product. Therefore, the dispensing method was based on a principle similar to silicone cartridges.

Material inside a tube or as we call clay tank (9 in Fig. 3), is held to an aluminium profile with help of 3D plastic printed holders (2, 3 in Fig. 3). Output of tube is 2 holes where first is for the hose connection with printhead and the second is for pressure measurement.

On the other side of the clay tank is the entrance for the piston, which is on a trapezoidal screw (4 in Fig. 3). Trapezoidal screw is routed through a trapezoidal nut fitted inside an axial housing assembly. By rotating the stepper motor a trapezoidal nut rotates, which is embedded inside gear connected to the motor shaft by gearing. Axial movement of screw is suppressed by axial housing which consists of two axial bearings.

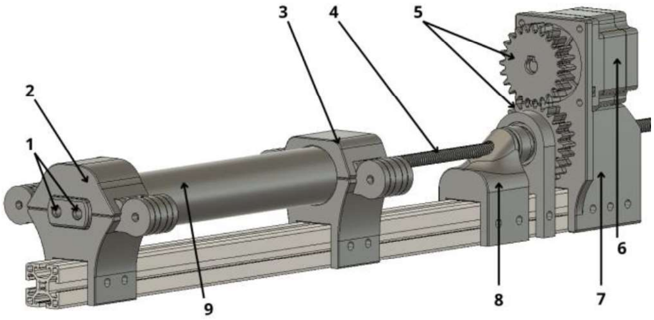

Fig. 3. Material stack
(1 - material outlet; 2, 3 - container holders; 4 - trapezoidal screw; 5 - motor gears; 6 - stepper motor; 7 - stepper motor holder; 8 - axial house; 9 - clay tank)

The principle of the printhead of a ceramic printer extruder lies in a screw conveyor. A screw conveyor was developed for moving loose materials. With correct additions and with use of 3D plastic printing, the conveyor was designed and manufactured to be able to move more like paste materials.

A necessary part of the development process was to take into consideration the correct ratio of each stepper motor. This ratio was determined by comparing the extruded volume of stack and printhead material per 1 rotation of stepper motors. By correcting individual speed, we can achieve fluent material extrude with no drawbacks.

The correction ratio of individual speeds was obtained with the use of the continuity equation as shown below. In other words, the volumetric flow of material extruded from the printhead was taken and divided by the volumetric flow of the material extruded from the clay tank, both per 1 revolution. [1]

The volume of material extruded from the stack per revolution is given in equation (2).

$$V_{STACK} = \pi r_{STACK}^2 l \qquad (2)$$

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

The volume of material inside the auger cover is determined by equation (3) and is given by the difference between the volume of the auger cover and the volume of the material part of the auger.

$$V_{MATERIAL} = (S_{COVER} - S_{AUGER}) l_{AUGER} \qquad (3)$$

where l_{AUGER} is the pitch of a modeled auger conveyor, S_{COVER} is the circular auger cover area, and S_{AUGER} is the area of the screw with the central shaft support element. The area of the screw is calculated according to equation (4).

$$S_{AUGER} = \left(\frac{\pi r_1^2}{2} + \frac{\pi r_2^2}{2}\right) \qquad (4)$$

where 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.

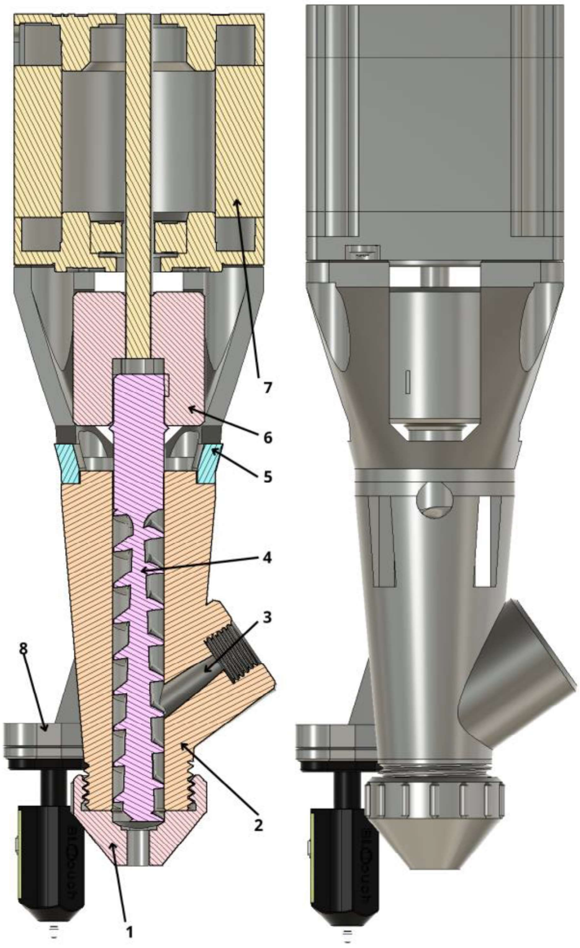

Fig. 4. Printhead.

Equation (5) determines the ratio of material extruded from the stack to material extruded from the printhead per revolution. This ratio is determined for the following values: the stack radius is 23.8 mm, trapezoidal screw pitch is 3 mm, $V_{MATERIAL}$ is 4426,351 mm^3.

$$k = \frac{V_{STACK}}{V_{MATERIAL}} \doteq 1{,}2\ (-) \qquad (5)$$

Several methods have been tested to remove bubbles from the clay that could lead to cracking of the products. The venting is done with a screw in the extruder during the extrusion of the clay.

VI. TESTING

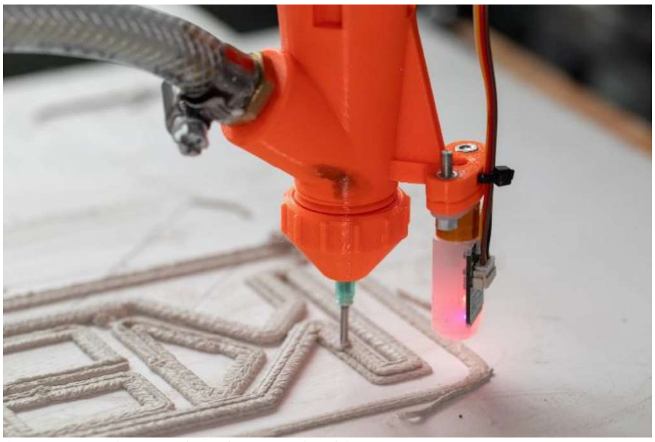

Fig. 5. Sample 3D print of a ceramic object

Many tests have been carried out. The printed parts were made of different types of ceramic clay and self-hardening materials. Tensile, compression and bending tests were carried out. It was verified that the printed parts were accurate and met the required specifications. The printed objects are of accurate dimensions according to the technical drawings and meet the given geometric tolerance.

In order to optimize the appropriate parameter settings for specific situations, several test prints were made with different fillings of the inner space of the object (Fig. 5, 6).

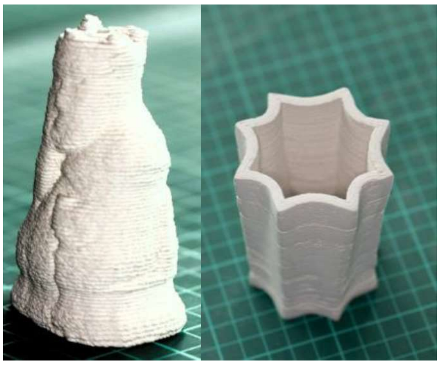

Fig. 6. Printed ceramic objects

VII. CONCLUSION

The main objective of this work was to design and control a 3D printer for ceramics, to construct and verify the functionality of the prototype of this printer. A wide range of models with different dimensions were created in the simulation program. Computer simulations of the shape of the printer itself, and also of the extruder were performed. The flow and extrusion of the ceramic mass was optimized so that the extruder is capable of continuous printing. Based on the simulations, a prototype was created and its function was verified by printing many samples of different materials.

The prototype of the ceramic 3D printer was manufactured according to the optimal design model. The control is carried out in the Cartesian coordinate system using stepper motors fitted with trapezoidal screws. The printer prints from a variety of self-hardening materials and ceramic clays.

A custom ceramic 3D printer has been developed that will be used to print dimensionally accurate and mechanically stable complex geometric shapes including added small details and decorations into the final printed products.

We are currently working on printing ceramics with an admixture of iron particles. Further developments will be directed towards 3D printing of products using multiple extruders with different materials.

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REFERENCES

[1] Slobodník, K., Šroubová, L., Spurný R., Heimrath, M. Extruder Design for 3D Printing of Ceramic Materials." 2023 *24th International Conference on Computational Problems of Electrical Engineering* (CPEE), Grybów, Poland, 2023, pp. 1-4, doi: 10.1109/CPEE59623.2023.10285143.

[2] Hua L., Bowen P. Application of Ceramic 3D Printing Technology in Modern Ceramic Manufacturing, *2021 7th International Symposium on Mechatronics and Industrial Informatics*, Zhuhai, China, 2021, pp. 160-163.

[3] Alhendi, M., Alshatnawi, F., Abbara, E. M., Sivasubramony, R., Khinda, G., Umar, A. I., Borgesen, P., Poliks, M. D., Shaddock, D., Hoel, C. Printed electronics for extreme high temperature environments. Additive Manufacturing, Volume 54, 2022. ISSN 2214-8604, https://doi.org/10.1016/j.addma.2022.102709.

[4] Feng, C., Zhang, K., He, R. et al. Additive manufacturing of hydroxyapatite bioceramic scaffolds: Dispersion, digital light processing, sintering, mechanical properties, and biocompatibility. *Journal of Advanced Ceramics*, Volume 9, pp. 360–373, 2020.. https://doi.org/10.1007/s40145-020-0375-8

[5] Varma, M. V., Kandasubramanian B, Ibrahim, S. M. 3D printed scaffolds for biomedical applications. *Materials Chemistry and Physics*, Volume 255, 2020. ISSN 0254-0584, https://doi.org/10.1016/j.matchemphys.2020.123642.

[6] Ly, M., Spinelli, S., Hays, S., Zhu, D. 3D Printing of Ceramic Biomaterials. *Engineered Regeneration*, Volume 3, Issue 1, 2022, pp. 41-52, ISSN 2666-1381.

[7] Jazayeri, H. E., Rodriguez-Romero, M., Razavi, M., Tahriri, M., Ganjawalla, K., Rasoulianboroujeni, M., Malekoshoaraie, M. H., Khoshroo, K., Tayebi, L. The cross-disciplinary emergence of 3D printed bioceramic scaffolds in orthopedic bioengineering. *Ceram. Int*., 44 (2018), pp. 1-9.

[8] Lakhdar, Y., Tuck, C., Binner, J., Terry, A., Goodridge, R. Additive manufacturing of advanced ceramic materials. *Progress in Materials Science*, Volume 116, 2021. ISSN 0079-6425. https://doi.org/10.1016/j.pmatsci.2020.100736.

[9] Owen, D., Hickey, J., Cusson, A. *et al.* 3D printing of ceramic components using a customized 3D ceramic printer. *Prog Addit Manuf* **3**, pp. 3–9 (2018).

[10] Kim, N. P., Cho, D., Zielewski, M. Optimization of 3D printing parameters of Screw Type Extrusion (STE) for ceramics using the Taguchi method. *Ceramics International*, Volume 45, Issue 2, Part A, 2019, pp. 2351-2360, ISSN 0272-8842.

[11] Chen, Z., Li, Z.,Li, J., Liu, C., Lao, C., Fu, Y., Liu, C., Li, Y., Wang, P., He, Y.. 3D printing of ceramics. *Journal of the European Ceramic Society*, Volume 39, Issue 4, 2019, pp. 661-687, ISSN 0955-2219.

[12] Spurný, R. Methodology of Testing Printed 3D Structures. Plzeň, 2021 Bachelor thesis. University of West Bohemia. Supervisor: Pavel Karban. (only in Czech)

[13] Autodesk Fusion 360. https://www.fusion360.cz/

[14] Solidworks. https://www.solidworks.com/

[15] MarlinFirmware. https://marlinfw.org/