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Design and development of a small-scale ceramic 3D printer

Final Report for Capstone Project

by

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Declaration

We hereby declare that this report entitled “Design and development of a small-scale ceramic 3D printer” is the result of our own project work except for quotations and citations that have been duly acknowledged. We also declare that it has not been previously or concurrently submitted for any other degree at Nazarbayev University.

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Abstract

A small-scale ceramic 3D printer received development under this project to improve traditional ceramic manufacturing through addressing three specific challenges: material waste, manufacturing precision difficulties and the limitation of creating complex shapes. A routine FDM printer became a Direct Ink Writing system through the implementation of a motor-driven screw for force delivery to create an affordable and adaptable ceramic printer solution. The system demonstrates effective material extrusion capabilities through increased control that enables ceramic components with precise structures to be produced. The approach received extensive literature review combined with 3D modeling and system building and parameter adjustment testing as well as mechanical tests to show its validity. The experiment produced devices that exhibited proper extrusion characteristics with satisfactory build potential as well as shape stability and workable compressive strength. The project succeeded in proving low-cost open-source hardware systems are suitable for ceramic additive manufacturing despite limitations in fully automating material flow control. The printing quality and reliability can be improved through future advancements that will merge real-time sensing systems with improved material compositions. The final project adds essential knowledge to the development of cost-effective and efficient ceramic 3D printing systems for research laboratories and industrial applications.

Key words: Ceramic 3D printer, Direct Ink Writing (DIW), extrusion system, small-scale printer, clay materials, additive manufacturing.

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List of Abbreviations and Symbols

AM: Additive manufacturing

FDM: Fused Deposition Modeling

CAD: Computer-aided design

DIW: Direct ink writing

R&D: Research and development

DIY: Do it yourself

FEA: Finite element analysis

G code: Geometric code

RPM: Rotations per minute

1.Introduction

1.1 Background

The manufacturing process of physical components through sequential stacking based on computer-aided digital models represents how modern additive manufacturing is functioning. Due to its contrasting approach from standard manufacturing which requires material removal from bulk items, additive manufacturing operates by stacking elements to develop complex and customized products without waste. The combination of capabilities in additive manufacturing attracts manufacturers across several sectors including aerospace and biomedical devices as well as automotive and energy generation fields. These attributes make additive manufacturing an attractive production method in diverse fields, such as aerospace, biomedical, automotive, and energy applications.

Amongst the wide array of additive manufacturing (AM) methods, Fused Deposition Modeling (FDM) stands apart as a cost-efficient and accessible technology. FDM involves the extrusion of thermoplastic filaments through a hot nozzle to build components sequentially in a layer-by-layer mode. FDM has initially been confined to polymer materials and has rapidly been extended to various composite and functional materials such as metals and ceramics due to feedstock and hybrid print methodology advancements [1].

The field of ceramic additive manufacturing has received much interest, mainly based on the excellent mechanical strength, chemical stability, and thermal resistance of ceramics. Such traits are especially relevant to applications of high-temperature structures, biomedical implants, and electronic substrates. However, the production of ceramics presents unique challenges, since high brittleness and high sintering temperatures make conventional processes complicated and often result in high production cost, limited design freedom, and long lead times [2].

Ceramic fabrication and FDM offer convenient manufacturing possibilities. The direct extrusion of dense ceramic pastes or the incorporation of ceramic particles within thermoplastic or polymeric matrices allows to create complex shapes with less limitations compared to traditional mold-based shaping methods. The manufacturing process needs additional steps which include binder burnout or sintering for reaching necessary manufacturing specifications. The process of ceramic printing represents a superior manufacturing approach for low-volume

applications when high product value matters because it reduces tooling requirements while offering customization capabilities [3].

Modern research shows that extrusion methods as part of additive manufacturing produce effective ceramic components. The use of clay materials being extruded through different nozzle shapes indicated tool configuration has an effect on the final part quality since square nozzles produced better compressive strength results. Prints produced by circular nozzles presented improved surface quality combined with reduced porosity[1]. The ceramic printing is still being optimized to offer less porous printed objects with better mechanical properties that can be printed in less time. Ceramic materials that include Al_2O_3 , ZrO_2 , and SiC are now possible to use for printing dense materials [2].

By utilizing ceramic AM processes, this project aims to contribute toward the ongoing industrial transition to agile, low-waste manufacturing, offering a customizable and sustainable alternative to legacy ceramic production routes.

1.2 Research Motivation

The ceramic materials are now much acknowledged to be fundamental components in contemporary engineering with their superior characteristics. Their unmatched shock resistance against heat, better chemical corrosion and erosion resistance, and outstanding mechanical stability make them a necessity in a vast array of applications with high demands. Some of them are structural parts in aerospace applications where the materials undergo severe temperature and mechanical stresses, biomedical devices like prosthetics and implants where there is a need for biocompatibility and structural integrity, and some components in energy systems that demand stability under severe chemical and heat conditions.

In spite of these benefits, conventional ceramic manufacturing processes like molding, slip casting, and sintering have considerable limitations. The time and cost involved, especially when manufacturing complex shapes or customized components, make the conventional processes tedious. Multistep processes, specialized tooling, and the requirement of high-temperature furnaces contribute to increased cost and complexity of production. Consequently, industries that require both precision and performance commonly encounter limitations in the adoption of ceramics at scale, especially of complex or lightweight components.

In order to overcome some of these limitations, ceramic additive manufacturing otherwise known as ceramic 3D printing has become a revolutionary solution. By achieving the build of parts by depositing them in a layer-by-layer fashion directly from digital files, ceramic 3D printing permits the production of intricate, lightweight, and customized structures that are challenging or impossible to manufacture with conventional methods. Among the many ceramic 3D printing techniques, FDM with a motorized extrusion system is a cost-effective and accessible method. This technology utilizes highly precise motorized pump systems to extrude ceramic-polymer composite pastes in a narrow nozzle, enabling full control over deposition and geometry.

This approach minimizes material waste by only placing material where the part requires it, and maximizes design freedom to fabricate hollow structures, internal passages, and small details. Additionally, the development cycle is shortened by making the prototyping process more streamlined, and allowing designers and engineers to rapidly iterate and optimize ceramic parts without the time loss involved with tooling or mold build.

With continuous demand increases in aerospace, biomedicine, and renewable energy, there exists a corresponding demand for more compact, efficient, and multi-functional ceramic 3D printing systems. This capstone addresses this demand by concentrating on the development and design of a compact ceramic 3D printer with the capability to fabricate detailed, structurally sound ceramic components. The project seeks to overcome the gap between the potential of ceramic materials and the limitations of standard processing methods. By integrating a highly accurate, motor-driven extrusion system with a programmable print platform, this research opens the potential applications of ceramic additive manufacturing to be more versatile, accessible, and influential to next-generation manufacturing and engineering applications.

1.3 Problem Statement

Conventional ceramic production processes like molding, casting, and manual shaping are frequently inefficient, not very accurate, and not very effective at producing sophisticated or tailored components. They are dependent upon manual labor, which diminishes design versatility and results in increased materials waste and variable quality. In applications within industries with demanding requirements like aerospace, medicine, and energy, such limitations hinder wider use of ceramic components.

There is a demand that is increasing for a cost-saving, efficient, and automated solution to overcome this issue. This project meets this demand by creating a compact ceramic 3D printer that can fabricate detailed, precise ceramic structures with less wastage of materials and a higher degree of operating flexibility. The new system is designed to revolutionize ceramic manufacture and enable new design freedoms for novel applications.

1.4 Aim and Objectives

Aims: To design small-scale 3D ceramic printer and develop the printing process to enhance the quality of printed ceramic material

Objectives:

- Design and assemble the printer parts to deliver a working extrusion system
- Optimize the printing parameters of the material (viscosity, extrudability, and buildability) through rheology analysis and find the best composition for printing
- Investigate the printability of the material through printing samples of complex forms and evaluating its physical properties (compressive strength, temperature resistance and durability)

1.5 Research Structure

The report exists in nine major parts which examine different key developments in making and developing small-scale ceramic 3D printer technology. The text progresses in a systematic manner which leads readers from project background information to the development process and subsequent results alongside the final project impact.

Chapter 1 presents an introduction that describes the project background, research motivation, goals, alongside an outline of report content to follow.

Chapter 2: Literature Review: This chapter presents an in-depth analysis of 3D printing technologies which transform contemporary industrial manufacturing operations. The chapter introduces fundamental properties of ceramic materials while demonstrating their rising importance in additive manufacturing processes to later explain future opportunities and limitations.

Chapter 3: Methodology: Here, the chapter to explain how the project progressed beginning with fundamental research and conceptual creation followed by construction and evaluation of the printer. This section uses a structured guide that resulted in the actualization of the project concept into the final product. This chapter investigates the specific engineering of the ceramic 3D printer. The chapter explains printer design choices alongside scientific foundations alongside component-level operation framework for enabling printer functionality.

Chapter 4: Results and Discussions: Here's where the project outcomes receive their presentation. The review section describes successful approaches as well as failed attempts along with acquired knowledge. The chapter provides recommendations regarding future development strategies for system enhancement.

Chapter 5: Conclusion: This chapter wraps everything up. It revisits the original goals, summarizes what the project achieved, and emphasizes why the results matter.

Chapter 6: References & Appendix: Finally, this section includes all sources cited throughout the report, as well as extra materials like technical drawings, code, and other supporting documents for anyone who wants to dig deeper.

The practical and organized examination of ceramic 3D printing technology demonstrates that project implementation led to the development of a functioning prototype. The report functions to both record the development path and encourage more research and development within this engaging field.

2. Literature Review

2.1 Introduction

Additive manufacturing (AM) has grown far beyond its origins in rapid prototyping to become a full-fledged production method, reshaping how goods are designed and produced globally. By combining digital design with shape fabrication, AM allows for a level of geometric complexity and flexibility that traditional methods simply can't match [1]. Within this broader shift, ceramic additive manufacturing (ceramic AM) stands out for its ability to produce components that perform reliably under extreme conditions such as temperatures above 1500 °C, exposure to corrosive chemicals, and intense mechanical wear.

Traditional ceramic shaping methods, like slip-casting, tape-casting, and injection molding still rely heavily on expensive tooling, slow drying stages, and energy-intensive firing cycles. These limitations hinder complexity and slow down design iteration. In contrast, ceramic 3D printing enables parts to be created directly from CAD files, cutting down development time and minimizing material waste [2].

However, ceramic AM still lags behind polymer and metal AM in maturity due to challenges such as controlling material flow (rheology), the fragility of “green” printed parts, binder removal, and shrinkage during sintering. As interest rises in small, cost-effective ceramic 3D printers especially for use in labs, startups, and educational settings there's a pressing need to better understand the materials, technologies, and process optimization strategies involved.

This chapter explores the current state of ceramic AM, beginning with the fundamentals of 3D printing, followed by a closer look at ceramic-specific materials and processes. It also includes reviews of experimental and numerical studies and concludes with an analysis of the key gaps still facing researchers and developers in this space [5].

2.1.1 3D Printing and Its' Significance in Modern Manufacturing

3D printing or additive manufacture entails a process of creating physical products from digital models by building layers. It provides significant advantages over alternative manufacturing methods by cutting on material wastage, facilitating fast prototyping, and the production of complex structures that cannot be done otherwise.

The technology gained growing significance in a wide range of industries such as aerospace, automotive, biomedical, and consumer products. Its capacity for accommodating individualized small-batch production makes the technology particularly useful within contemporary, adaptable manufacturing settings.

Of the numerous 3D printer methods, one of the most popular is FDM due to its ease of use and availability. Yet as the need for practical materials such as ceramics continues to expand, methods like DIW are becoming increasingly popular. These methods bring new avenues in material science and production, especially where precision, heat stability, and chemical resistance are needed. 3D printing continues to bring about new opportunities for advancement and is changing the way products are designed and produced in the modern world.

2.1.2 Ceramic 3D Printing Applications

Ceramics are renowned to have superior mechanical characteristics, such as good compressive strength, excellent thermal stability, corrosion resistance, and biocompatibility. Such characteristics make ceramics suitable to fulfill the requirements of a broad range of industries, ranging from advanced engineering to mechanical and creative applications. The implementation of ceramic 3D printing permits the quick prototyping of intricate components and the direct production of functional parts, leading to material efficiency, less time spent on production, and increased product personalization [2].

In the aerospace field, ceramic 3D printing has vast potential because of the extreme conditions aerospace parts must survive. Aircraft engines, turbine blades, and thermal protection systems need materials resistant to heat and mechanical stress without degradation. Ceramic 3D printing allows the creation of such heat-resistant parts with intricate internal geometries impossible to make with conventional methods [6]. The ability to fabricate lightweight structural components like brackets, housings, and shields while minimizing material waste is particularly useful, as every bit of weight reduction leads to better fuel efficiency and performance. The capability to make iterative design innovations also quickens innovation cycles in aerospace technology.

In the semiconductor and electronics fields, insulation and heat control are essential. Alumina and silicon carbide are excellent materials for components such as heat sinks, circuit board substrates, insulating casings, and transmission parts at high frequencies. The accuracy of

3D printing makes it easier to manufacture components with precise details and narrow tolerances, integral to compact electronics. The dielectric and thermal conductivity characteristics of ceramics help dissipate power electronic heat, improving reliability and lifespan. As devices are made more compact and powerful, customized thermal and electrical components become essential applications ceramic 3D printing can provide.

For industrial applications, the ceramic 3D printer offers a dependable means of manufacturing parts placed under demanding conditions, such as abrasive materials, corrosive chemicals, or heavy mechanical stresses. Ceramic parts like seals, guides, bushings, pump impellers, and nozzles are printed with increased wear resistance, prolonging equipment lifespan and minimizing maintenance [6]. The printer is also useful in tooling and mold manufacture. Ceramic molds, with their hardness and heat resistance, are suited to metal casting, glass shaping, and hot-forming processes. Additive manufacturing in this area facilitates on-demand production and intricate molds with incorporated features that decrease assembly steps.

In sum, the small ceramic 3D printer built in this project marries the resilience of ceramic material with the versatility of additive manufacturing. Its applications across cutting-edge industries and the arts highlight its promise as a revolutionary technology that enhances innovation, personalization, and eco-friendly production. As industries increasingly demand compact, versatile, and sustainable manufacturing technologies, ceramic 3D printing emerges as a dynamic next-generation technology.

2.1.3 The Importance of Designing Small-Sized Ceramic 3D Printer

Typical commercial ceramic printers have $\geq 1 \text{ m}^2$ footprints and a price of $> \text{USD } 150 \text{ k}$ and use compressed air extrusion, excluding small businesses and universities from access [4]. A benchtop ($\leq 0.05 \text{ m}^2$) motor-driven extrusion device makes research accessible to more people, trims formulation tests by half, and permits class demonstrations. Small build volume ($\approx 150 \text{ mm}$ cube) minimizes lost material costs important when experiment inks cost $> \text{USD } 200$ per kilogram. The use of open-source electronics (e.g., 32-bit controllers) and modularity of the small-scale systems enable swift iteration: rheological adjustments may be tested within hours instead of delivering slurries to external facilities. Small-scale systems enable decentralized manufacturing by permitting remote clinics or lab sites in the field to print bioceramic implants or spare parts as needed. By publishing permissive-licensed design files, the academic

community enables community-driven improvement through shared collaboration, reflecting the open-source FDM revolution that fueled polymer AM's expansion.

These goals require careful trade-offs: the small frames have to be stiff within extrusion forces; thermal management has to prevent paste drying out at the nozzle while enhancing layer solidification; and such features as fume extraction during firing have to be housed within cramped spaces. The following theoretical, experimental, and numerical overviews enable these goals.

2.2 Theoretical Background

2.2.1 3D Printing Technologies and Parameters

3D printing or additive manufacturing involves the deposition of materials by layers to fabricate complex structures from digital blueprints. Direct Ink Writing (DIW) among the numerous 3D print methods finds specific applicability for ceramics like clay. DIW involves extruding a highly viscous ink or paste from a fine nozzle under precise control of the patterning of the material[2]. For the clay-based systems, the ink typically gets prepared by the mixing of the clay powder with water or additives such that the required rheological state is attained. The flow state or the viscosity needs to be finely tuned: the ink should have enough flowability for extrusion under pressure but thick enough for retention of shape upon deposition.

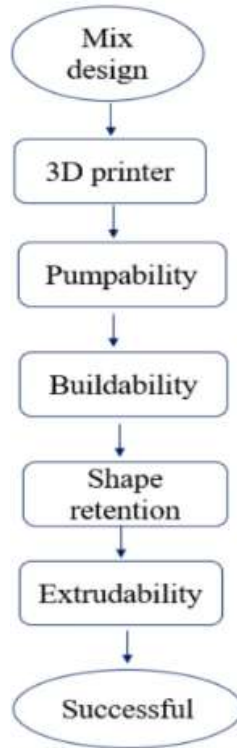


Figure 1. Printing parameters [13]

Key DIW parameters are nozzle diameter, extrusion pressure, print speed, and ink formulation[4]. Nozzle diameter determines the resolution and structural details directly, while extrusion pressure determines the flow rate. The print speed needs to be optimized such that smooth deposition occurs without introducing defects such as sagging or under-extrusion. For clay, the continuity of the water content within the clay plays a crucial role since the evaporation during print immediately would lead to clogs or unsatisfactory adhesion between the layers. Also influencing the clay's dry times between and during the print are environmental conditions like humidity and temperature. Tuning these parameters makes it possible to achieve stable complex clay structures that find applications in art, construction, as well as utility. DIW provides freedom of design as well as material usage and makes the technology very appealing for small-scale clay-based 3D print systems.

2.2.2 Existing 3D Printer Designs

Currently available 3D printer designs for materials based on clay are diverse based on the scale of the application and the purpose[6]. The vast majority of 3D printers for clay take a

gantry-based method where three mutually perpendicular linear axes (X, Y, and Z) enable accurate head movement. The extrusion of the clay generally involves the use of a syringe, auger-based, or piston-driven system for flow management. For small detailed print jobs, syringe-based methods are popular due to the simplicity of the mechanism as well as the finer level of control. For larger loads of clay and structures of larger dimensions, piston-driven setups are appropriate.

Direct mechanical extrusion designs incorporate the use of stepper motors applying pressure on clay through tubes. Others make use of pneumatic mechanisms involving compressed gas. Mechanical piston-driven systems are also popular due to reliability and less equipment complexity, particularly where compressed air supply is restricted. The mechanical structure of the frame could range from light aluminum profiles for a desktop printer to heavy steels for production-scale machines dealing with larger volumes of clay.

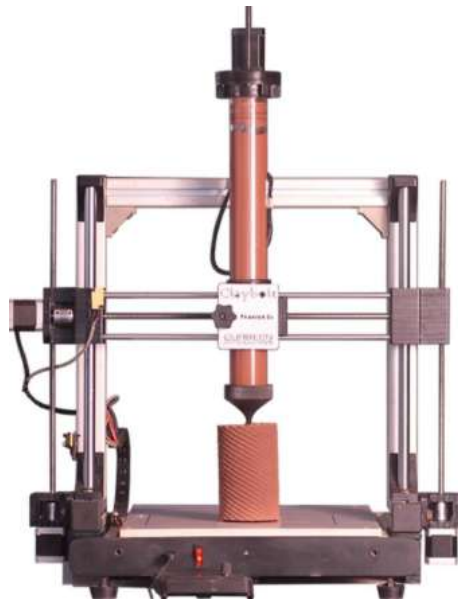


Figure 2. Claybot design [7]



Figure 3. GAIA MAXX design [7]

A lot of DIY and consumer-grade printers have interchangeable nozzles for accommodating variable clay particle sizes and target print resolution. Layer height, print bed travel, and bed heating modes are usually adjustable to fit the needs of varying clay mixes. Additionally, advanced models have features such as automatic bed leveling as well as moisture management subsystems for enhanced print consistency. Generally speaking, clay 3D printers emphasize the use of strong build materials, extrusion control adjustability, and the ability to accommodate the variability inherent in the use of clay as a print medium

2.2.3 Ceramic Materials Characterization

Clay is one of the oldest and most widely used ceramics materials and continues to be a top pick for contemporary ceramic 3D printing because of its abundance in nature, affordability, workability, and good mechanical characteristics[10]. Clay is chemically dominated by hydrated

alumino-silicate minerals consisting mainly of kaolinite ($\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$), together with small proportions of illite, montmorillonite, and trace phases of different minerals. The presence of water molecules within the crystalline form gives clay the plasticity and malleability required by extrusion-based 3D print methods such as Direct Ink Writing (DIW).

The approximate basic chemical composition of common pottery or industrial clay is as follows:

- 45–50% SiO_2 (silicon dioxide)
- 30–40% Al_2O_3 (aluminum oxide),
- 10–15% water (bound water), including minute traces of iron oxides (Fe_2O_3), potassium oxide (K_2O), magnesium oxide (MgO), and sodium oxide (Na_2O).

These oxides have the ability to color the clay and also affect its firing characteristics.

Economically, clay is a very cost-efficient material. Refined clays (e.g., kaolin or ball clay) suitable for 3D printing purposes cost between \$0.30 and \$2.00 per kilogram based on purity and treatment. Therefore, clay is a very cost-efficient solution for prototyping purposes, functional components, or artwork purposes compared to ceramics like alumina or zirconia.

Unfired (green) clay pieces have the following mechanical characteristics:

- Compressive strength: $\approx 1\text{--}5$ MPa (variable by water content),
- Flexural strength: $\sim 0.5\text{--}2$ MPa.

Upon firing (usually between 1000°C and 1250°C), the mechanical strength significantly improves:

- Compressive strength: $\sim 30\text{--}150$ MPa,
- Flexural strength: $\sim 10\text{--}50$ MPa,
- Density: approximately $1.9\text{--}2.5$ g/cm^3 (varies with the type of clay),
- Hardness: equal to typical structural ceramics.

The firing process drives away water and chemically bonded hydroxyl groups, facilitates sintering, and results in vitrification, imparting the resulting ceramic strength, stiffness, and water resistance. However, clay remains somewhat brittle compared to metals and polymers.

Due to its plasticity under moist conditions, ease of formability, and good potential for post-processing (through glazing and firing), clay possesses a unique ability to thrive as a small-scale 3D printer material for ceramics. It provides a cost-effective, environmentally friendly route for creating intricate geometries of high aesthetic and utilitarian value.

2.3 Experimental Studies on DIW 3D Printer Designs

Experimental studies done in recent times has brought major developments to Direct Ink Writing (DIW) 3D printers designed for clay-based materials. Scientists systematically researched nozzle diameter along with layer height and printing speed and extrusion pressure to improve both print quality and structure integrity.

The researchers studied Cone 5 porcelain clay to determine best print settings using a 1.5 mm nozzle diameter along with a 0.8 mm layer height and a printing speed of 25 mm/s[11]. The printing conditions enabled controlled material movement along with necessary layer bonding which led to printable results without structural defects.

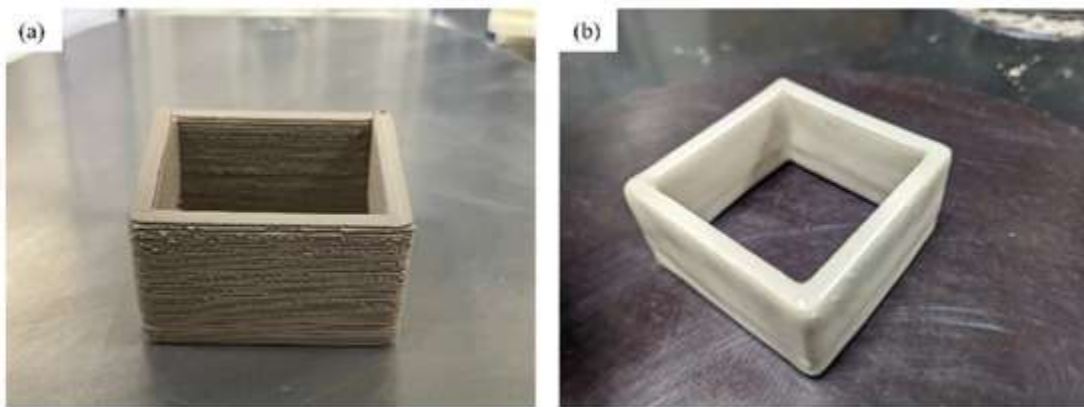


Figure 4. Cone 5 porcelain print through DIW: non-fired (a) and fired (b) samples [11].

An investigation studied porcelain clay paste rheology and printability by analyzing the relationship between extrusion pressure changes and solid content composition. The combination of 0.5 MPa extrusion pressure led to samples that achieved bending strength measurements up to 57.44 MPa while demonstrating a volume density level of 2.2943 g/cm³ [12]. The mechanical properties improved when solid content reached 0.075 wt% additive content at a pressure of 0.3 MPa to obtain a bending strength of 58.9 MPa and reduced dimensional shrinkage.

Produced parts get their optimal mechanical requisite properties from proper DIW 3D printing parameter regulations. Three crucial parameters involving nozzle diameter alongside layer height and printing speed need optimization to produce high-quality 3D prints with appropriate mechanical properties. Research advancement in the field will improve existing capabilities and potential applications of clay-based additive manufacturing.

2.4 Numerical Studies on Optimization for 3D Printing Parameters

Numerical modeling stands essential to optimize 3D printing parameters through its applications in extrusion-based additive manufacturing methods especially Direct Ink Writing (DIW). The proper execution of buildability performance indicators lays the foundation for achieving printing success.

A printed object's buildability indicates its capacity to preserve its structure during additional layer additions along with shape maintenance against collapse and dimensional distortion. The three determining factors for buildability include layer height (h) and printing speed (v) and the time interval between depositions (Δt). A basic method to analyze buildability consists of the following formula:

$$B = \frac{H_{actual}}{H_{designed}} [11]$$

Where:

B is the buildability ratio,

H_{actual} is the maximum height achieved without failure,

$H_{designed}$ is the intended design height.

A buildability ratio equal to 1 demonstrates that a structure aligns flawlessly with its intended design which means excellent buildability.

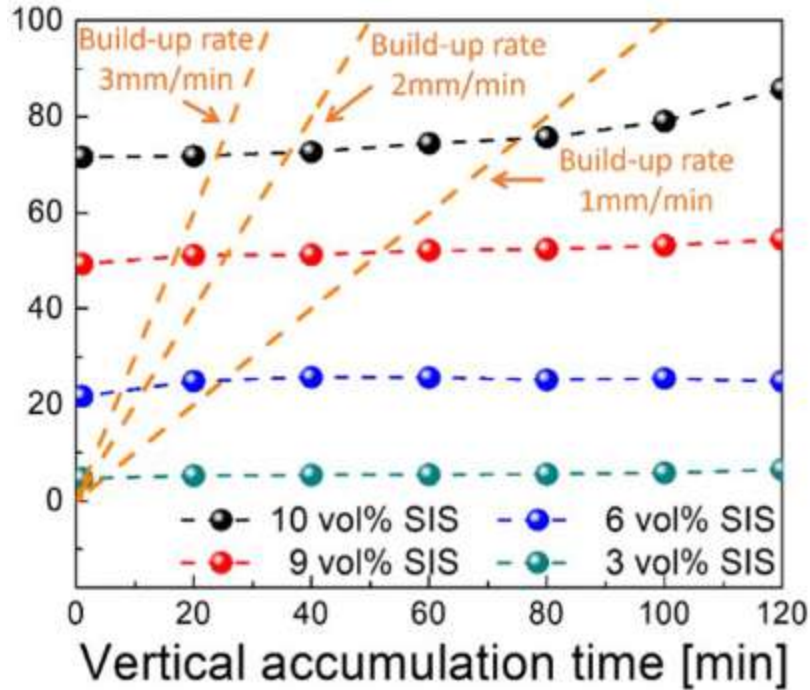


Figure 5. Expected height(in mm) against accumulation time [12].

FEA serves in numerical predictions of deformations and stability dynamics under varied conditions which enables the optimization of printing variables to enhance buildability.

The optimization of extrudability together with buildability results from research conducted through numerical modeling of print processes throughout various parameter ranges. Results analysis helps to identify perfect parameter partnerships that lead to enhanced print quality and structural strength. The combination of layer height and printing speed parameters determines the buildability of a structure directly.

2.5 Research Gap Analysis

Despite the significant advancements in ceramic 3D printing technologies, several critical research gaps remain, especially concerning the use of clay-based materials and the design of small-scale, low-cost 3D printers optimized for such materials.

Firstly, most of the existing R&D on ceramic 3D printing has centered on high-performance engineering ceramics such as alumina, zirconia, or silicon carbide. Relatively less attention has been provided to clay, although it benefits from cost-effectiveness,

environmental benignity, and ease of manufacture. The rheological characteristics of clay during extrusion-based 3D printing (e.g., DIW) have not been optimally investigated, particularly in ensuring flowability while avoiding sagging and collapse of intricate structures. More research needs to be performed to adjust water content, particle size distribution, and additive use toward optimizing a balance between printability and green part mechanical integrity.

Secondly, the majority of currently available 3D printer designs for ceramics are oversized industrial machines or complex laboratory prototypes. There exists a definite scarcity of compact, cost-conscious, and easy-to-use 3D printers specifically designed for clay extrusion. Current small-scale designs typically adopt components and control strategies optimized for polymer printing (such as FDM), which are not suitable for the higher viscosity and flow properties of clay slurries. Therefore, there is a significant need for specialized clay 3D printer designs complete with suitable pumping mechanisms, nozzle geometries, regulated drying systems, and platform heating.

Thirdly, there are scarce numerical and experimental investigations on the optimization of printing parameters for clay-based materials. Parameters such as extrusion pressure, nozzle diameter, print speed, layer height, environmental humidity, and drying time between layers have a significant effect on the dimensional accuracy, surface quality, and strength of printed parts. Few systematic studies establish procedural guidelines for these parameters, resulting in unpredictable print results and preventing repeatable, high-quality production.

Furthermore, the firing process also presents challenges. Although established firing procedures exist for traditional clay ceramics, applying them to 3D-printed structures often featuring thinner walls, internal voids, and complex geometries remains underdeveloped. Cracking, warping, and uneven shrinkage during firing are serious issues that require more experimental research to solve.

Moreover, sustainability aspects of clay-based 3D printing such as water utilization, recycling of print failures, and minimizing energy consumption during firing and drying have not been systematically addressed in the literature. With increasing calls for sustainable manufacturing practices, this area represents an important avenue for future research.

Overall, while ceramic 3D printing with clay offers huge potential for artistic, architectural, biomedical, and industrial applications, there are significant opportunities for research in material characteristics, printer development, process improvement, post-processing

methods, and sustainability modeling. Bridging these gaps will be key to developing dependable, scalable, and cost-efficient clay-based additive manufacturing systems.

3. Methodology

3.1 Overview

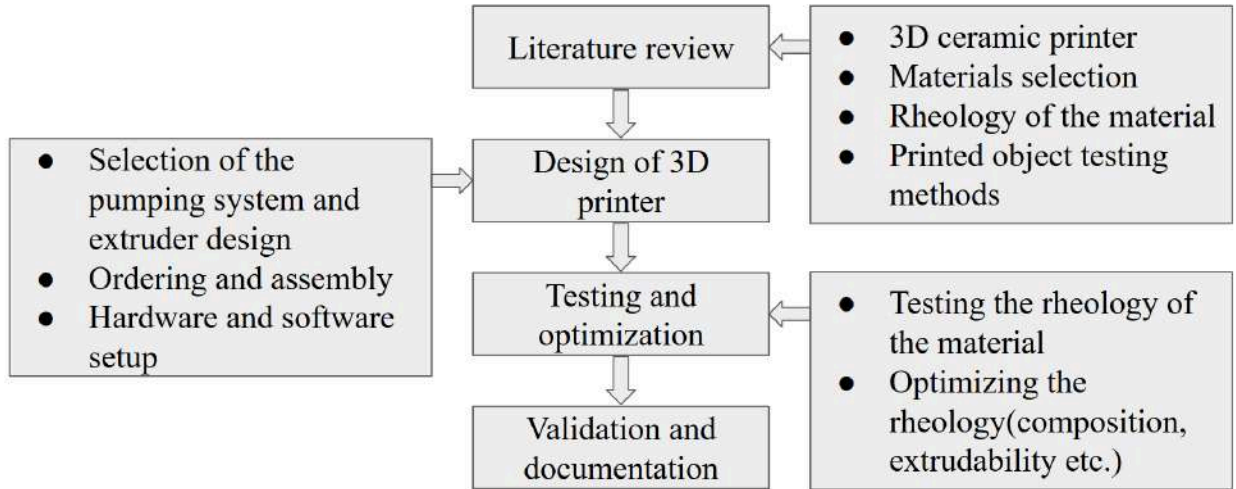


Figure 6. Methodology diagram

The methodology was planned as a closed-loop cycle through the stages of construction, design, testing, and validation (Figure 1), to ensure that development of the hardware or materials within each successive iteration provided insights of value to be applied for improvement. The process started with a thorough review of current advances within ceramic direct-ink-writing technology as well as motorized pump technology to understand the key functional requirements and constraints of the prototype printer. Based on these specifications, a modified design was developed in which a stepper-screw cartridge pump transports a chosen material through a durable steel nozzle that substitutes for the original hot-end of the Creality Ender-3 Max frame.

All mechanical components were modelled, fabricated and assembled before initial testing. A mixed statistical approach (Taguchi L9 design) was then adopted to monitor key process variables such as nozzle diameter, layer height, pump RPM, carriage speed, and bed temperature in three response metrics: flow stability, dimensional accuracy, and body density. Information derived from rheometry, inline pressure measurement, and structured-light metrology was integrated into both the material preparation (solid content 55–65 wt %) and the printer software.

The final validation phase involved mechanical testing, namely three-point bending tests, characterization of resistance to heat, and measurement of dimensional accuracy of the sintered parts. Moreover, a thorough reproducibility test was performed for CAD models, slicing parameters, and G-code. The success criteria were established beforehand as a layer-height variation of less than 10%, a flexural strength of at least 60% of solid SiC, and process consistency within $\pm 5\%$ for all tracked variables.



Figure 7. Creality Ender-3 Max 3D printer

Figure 7 illustrates the donor platform chosen for this project, the Creality Ender-3 Max. The machine offers a 300x300x340 mm build volume on an open-frame XYZ gantry built from aluminium extrusions. The firmware gives repeatable positioning to within ± 0.05 mm, while a single-board power supply, heated glass bed and stock hot-end extruder keep the bill of materials low. Crucially for a DIW, the motion system and control electronics are entirely open-source: unused stepper and thermistor channels can be reassigned to a syringe-pump and inline pressure sensor without complex modification, and the carriage provides rigid mounting points for the custom nozzle bracket described in Section 3.2.3.

3.2 Designing DIW 3D Printer for Ceramic Material

3.2.1 Design Concept of a DIW 3D Printer

The direct-ink-writing (DIW) platform is realised by converting a stock Creality Ender-3 Max FDM machine into a viscous material extrusion system while leaving its proven XYZ gantry, stepper drives and motherboard intact. The process focuses on replacing the polymer filament pathway with a positive-displacement material pathway that can handle the high-viscosity SiC–phenolic feedstock selected in Chapter 2.

The main conversion equipment is a stepper-screw cartridge pump. A 60 mL stainless-steel syringe is mounted vertically on the carriage with an 8 mm-pitch lead-screw, driven by a NEMA-17 stepper, advances the extrusion and delivers steady flow. Since flow is generated mechanically rather than pneumatically, deposition rate depends only on motor speed, not on compressibility or air-line fluctuations, giving higher flow stability across the expected viscosity range of the desired material

A polyurethane tube (4 mm I.D., 300 mm long) couples the syringe to a hardened-steel nozzle that replaces the printer’s original hot-end extruder. The nozzle allows the paste to be centered before exit. Steel is chosen for abrasion resistance since ceramic particles would rapidly erode brass or aluminium. No heating element is retained and the material is deposited at ambient temperature and relies on shear-thinning for flow.

A custom PETG bracket bolts the syringe–nozzle assembly to the carriage in place of the former extruder, keeping the centre of mass within the X-rail dimensions so that the gantry’s dynamics and positional repeatability are preserved. Small firmware edits are needed, which include re-mapping the new motor to the new stepper driver, enabling required pressure, and disabling the hot-end temperature interlock to complete the electrical integration.

Because deposition pressure is now decoupled from carriage speed, volumetric flow can be tuned independently. The closed, all-metal material path also compresses the paste slightly and expresses trapped air bubbles, preventing porosity during the sintering cycle.

This design combines low-cost, open-hardware components with three custom printed or machined parts: cartridge mount, nozzle carrier and interface bracket showing that a DIW printer is serviceable with standard FDM equipment yet capable of precise, repeatable extrusion of high-performance ceramic material.

3.2.2 Determination of Optimal Pumping System Type

The printing of ceramic material requires a pumping assembly that can offer reproducible volumetric flow at lower shear rates, as well as the ability to rapidly respond to start and stop commands embedded on G-code. The comparison between two commercially available options was done between a stepper motor-driven device and a pneumatic pump assembly. The selection criteria included five factors based on literature available as well as initial tests where flow-rate accuracy, compatibility with very abrasive materials, compatibility with the electronics of the Ender-3 Max printer, maintenance needs, and cost factors were evaluated.

Pneumatic systems are controlled by the throttling of a regulator. However, the compressibility of the air introduces a time delay leading to unevenness of print. On the other hand, a stepper screw offers lower latency of material supply since motor displacement relates to micro-steps. Stable flow ensures good layer and height control, and a stepper motor pump will meet these needs.



Figure 8. Pneumatic Pumping system example [8].

Processing viscous materials requires a consideration of the possibility of clogging. The pneumatic system can supply enough pressure to resist clogging [9]. However, any transient air pulse-induced pressure may negatively impact the quality of the final printed product. In contrast, the screw device can provide steady pressure without pressure overshoot, thus ensuring that clogging does not impact the rate of material extrusion.

A pneumatic system would need an external electro-pneumatic regulator and a closed-loop pressure sensor, complicating wiring and G-code synchronisation. On the other hand, stepper motors can offer simple connection to available motherboard pins.

The screw device is limited to routine syringe maintenance and nozzle replacement. In contrast, a compressor system requires filters, hose, and a regulator, which collectively cost at least twice as much as the latter and demand regular leak checks [9]. Given the improved stability of the flow, lower integration needs, and lower lifetime costs, the initiative classifies a stepper-driven pump mechanism as the most efficient solution for the DIW process of ceramics. For the purposes of the present small-scale prototype, the motor-driven approach offers the most beneficial balance of accuracy, durability, and simplicity.



Figure 9. Example of screw-driven pumping system [8].

3.2.3 Extrusion and Pumping System Integration

A NEMA-17 motor is rigidly coupled to an 8 mm-pitch stainless lead-screw while four brass rods keep the plunger perfectly axial as it drives a PTFE cartridge. Every motor micro-step displaces approximately 0.2 μL of slurry, giving moderate volumetric flow control. The plastic manifold that supports the cartridge was printed to hold the internal pressure and to provide threaded inserts for quick-connect fittings.

A push-fit connector on the manifold outlets to a 4 mm PTFE tube shown in Figure 10. The tube's low compliance and inert bore prevent back-flow or resin adsorption and due to its room-temperature throughout no heat insulation is required. At the carriage the tube terminates in a second push-fit that seats directly in the nozzle holder, allowing the entire tube end to be detached and cleaned in under a minute.



Figure 10. Connecting PTFE tube

The factory Ender-3 Max board already has a spare stepper driver and heater/thermistor ports. To assemble it, the unused E-motor port to the syringe stepper should be plugged in. Stock hot-end extruder should be disconnected and reassigned the “heater” to drive the build-plate fan. Thermistor header should be left free for a future inline pressure sensor or connected in a loop to set the temperature of the extruder to a constant value. This keeps the firmware open-source and preserves all stock safety interlocks.

Since material rheology and particle size may change during optimisation, we use swappable nozzles. Plastic tips in 0.8 mm and 1.0 mm sizes offer cheap, non-abrasive, ideal for low-solids test pastes. Their low thermal conductivity prevents premature drying of a material. Hardened-steel tips come in 0.6 mm, 0.8 mm and 1.2 mm sizes. Steel nozzles tolerate bigger particles but limit minimum feature size to 2 mm. The 0.8 mm steel tip is therefore set as the baseline for Taguchi method trials.

This extrusion assembly, once mounted to the Ender-3 Max carriage via a PETG bracket, becomes the fully-functional DIW print head.

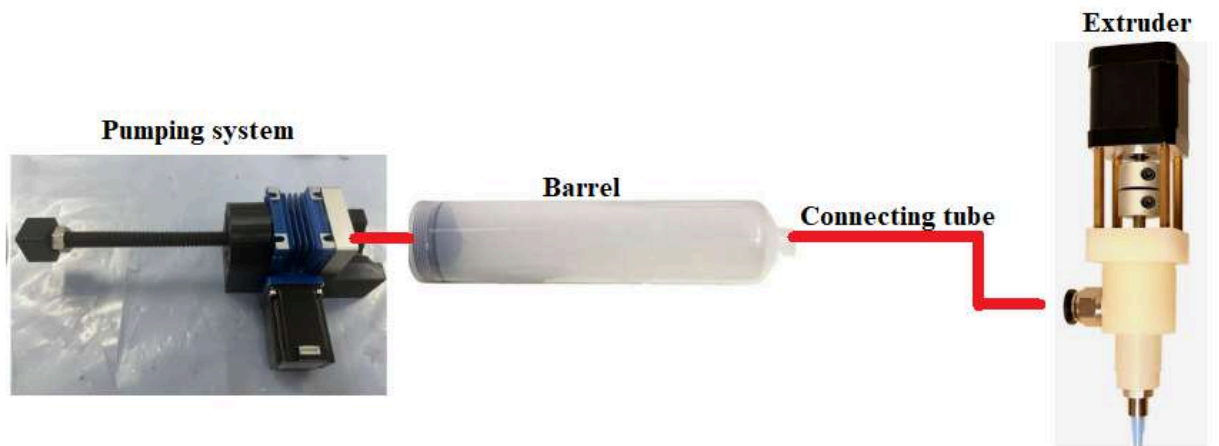


Figure 11. Extrusion and Pumping System Integration scheme

3.3 Upgrading FDM Printer to DIW Printer and Assembly Plan



Figure 12. FDM 3D printer upgrade plan

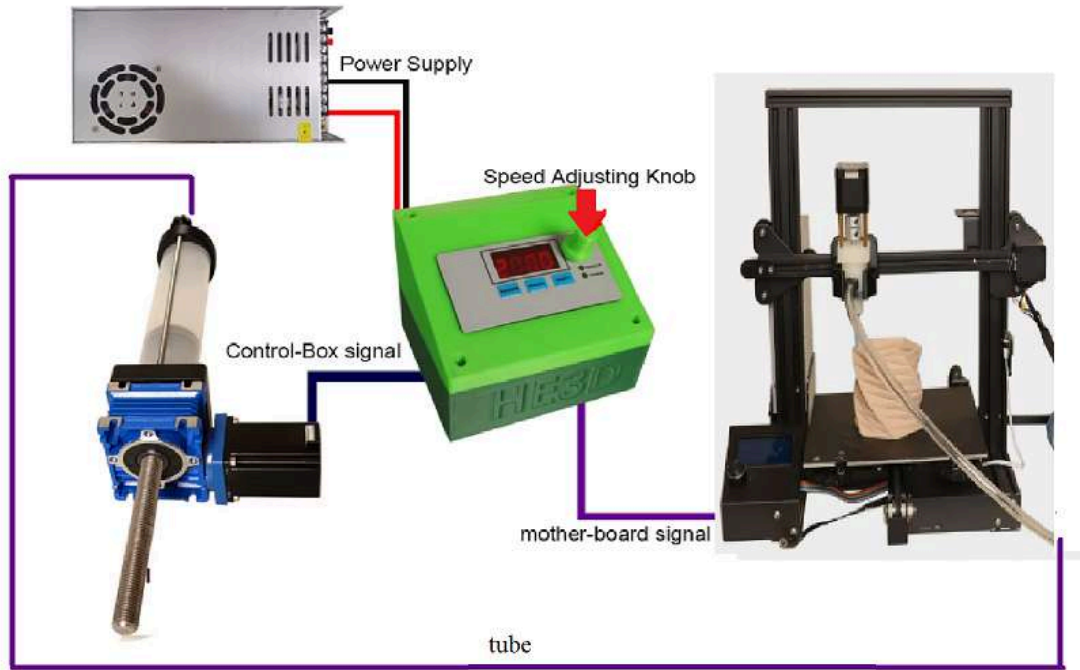


Figure 13. Hardware connection scheme

Figure 13 shows the signal and material flow after the printer assembly. A lead-screw syringe pump is mounted beside the Ender-3 frame and linked to the ceramic extruder by a 4 mm PTFE feed tube (purple line). The pump's NEMA-23 motor is driven by an external speed-control box which receives a step/dir signal (black line) from the printer motherboard, so extrusion begins and stops in sync with G-code commands. Both the controller and the printer share the existing 24 V power-supply (red lines), eliminating the need for extra power supplies. In short, the motherboard commands the green control box to turn on according to the printing parameters, the box powers the pump, so that the pump pushes material through the tube, and the Ender-3's gantry deposits the material layer-by-layer.

The assembly process began by creating all of the required parts including the nozzle carrier and carriage bracket were produced by 3D printing using the PETG material while the hardened-steel nozzles and brass guide rods were sourced externally. Having obtained these

parts, the syringe pump was assembled by press-locking the PTFE-lipped cartridge into the nylon manifold and mounting the NEMA-17 motor-lead-screw assembly on the guide rods before a quick manual inspection was conducted to verify free plunger movement. The assembled pump was then mounted on the Ender-3 Max next. The original extruder is removed, the PETG bracket is mounted on the carriage using the provided hardware and the nozzle is set at a height such that its tip is at the same level with the surface of the bed.

Once the hardware is acquired, a 4 mm inner-diameter PTFE tube is pushed between the nozzle inlet and the manifold outlet with both sides hand-tightened, and the line is flushed using water to verify the freedom from leakage. Electrical integration is then done by routing the syringe motor lead through the mount and wiring into the spare E-motor pin on the mainboard of the printer, with the cable tied away from the lead screw to avoid wear. The firmware should be next reprogrammed to allow the use of the extruder, set the steps-per-millimeter for the pitch screw, and optimize the whole system.

3.4 Printing Trials and Optimization of the Printing Parameters

Each trial round begins with a simple test geometry, starting with single-wall lines, proceeding to cubes, hollow cylinders and finally an open-top box. After slicing is done with the Cura software, the part is printed while layer width, corner accuracy and layer collapse are observed in real time. When the print finishes, dimensional error, layer profile and overhang quality are recorded.

Results are checked for certain criteria such as flow uniformity, shape retention and wall thickness. A failure in one of these criteria requires a single change to a printer parameter (nozzle size, pump rpm, travel speed) and the geometry is reprinted after adjusting the printer parameter. This iterative loop continues until the cube, cylinder and box all print within set dimensions and layers remain intact for at least 50 mm of vertical build, after which more complex demonstration parts are attempted.

Once the printer can repeatedly deliver defect-free cubes and cylinders, the study shifts from simple “go/no-go” checks to a quantitative optimization loop. The Taguchi L9 design of experiments is deployed to screen several controllable factors including pump rpm, carriage speed, layer height, nozzle diameter and material delivery. For every run the software collects data about extrusion pressure, actual layer width and surface waviness, while specimens are weighed, measured and then sintered to record linear shrinkage and flexural strength.

With the favourable parameter values achieved, the experiment narrows to a fine-tuning around that point. Pump rpm and carriage speed are adjusted in 5% increments while the remaining factors are held constant. The resulting data are then fitted to other parameters, which allows the prediction of the exact motor-speed and travel-speed pair that stabilizes layer width with proper spacing and keeps layer height consistent across all further printing trials

3.5 Mechanical and Rheological Testing

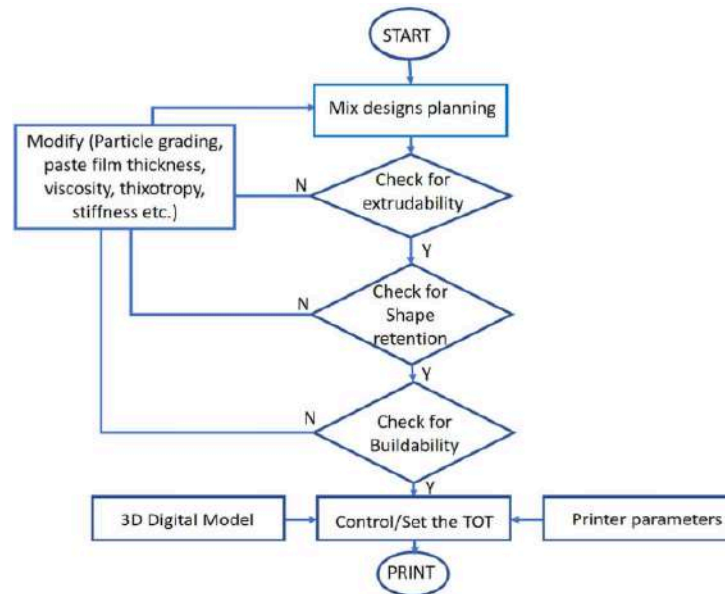


Figure 14. Printing parameters checking plan [13]

The three performance indicators shown in Figure 14 are extrudability, shape-retention and buildability. They are checked at every optimization step because each controls a different failure during ceramic printing[12].

Extrudability defines whether the paste can even leave the nozzle. During a trial the operator watches the first layer of a single-wall line. A stable layer with little to no width variation and no pressure spikes is recorded as a pass. Any pulsing, gaps or sudden pressure rises indicate nozzle clogging or a paste that is too viscous. In that case, the run is stopped and either material delivery or pump-rpm is tweaked before reprinting.

Shape retention defines whether a freshly-laid filament keeps its intended geometry. After the base layer sits for one minute, layer thickness and width are measured at three random

locations. If the filament has sagged or spread from its designed dimension then the paste or printing parameters should be modified[14]. Successful shape retention is confirmed when successive prints show no change between the immediate and one-minute mark.

Buildability defines if many layers can be stacked without the wall deforming. A complex shaped wall vase is printed, then vertical shrinkage and lean of the walls is recorded while the part is still freshly printed. The print passes when the wall remains within 1 mm of plumb over the full height, no inter-layer cracks appear under a fingertip push, and final height deviates 5 % from the G-code targeted height after drying. If any criteria fails, related parameters must be modified

By cycling through these tests, the extrudability, shape retention and buildability can show if changes in rheology or a slicer parameter improves the whole print. Successful trials then proceed to mechanical strength tests and can be validated after.

3.6 Calendar Plan for the Project

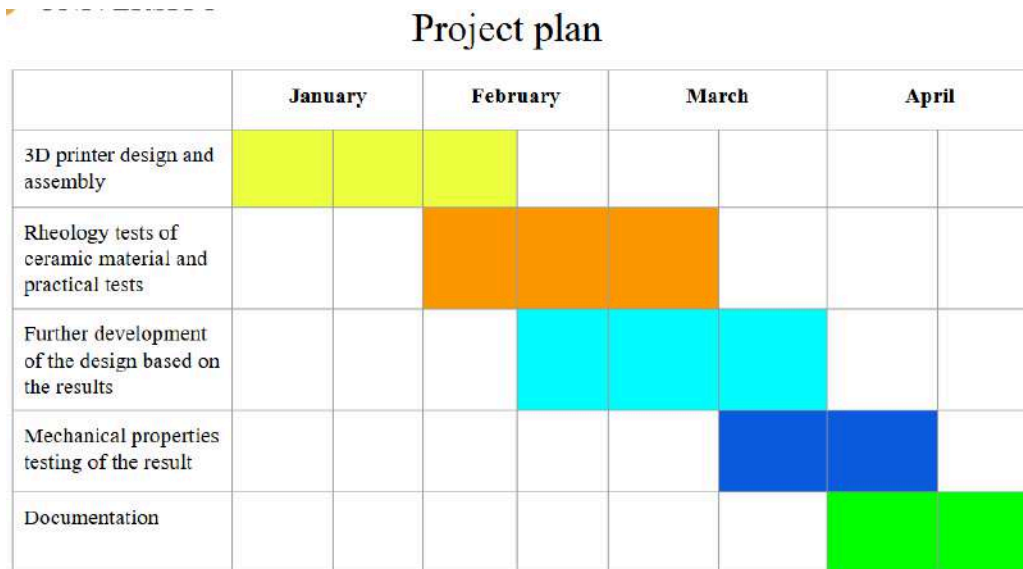


Figure 15. Project Plan

The project timeline specifies a formal time schedule for research and development of a ceramic 3D printer. In January and early February, the assembly and design of the 3D printer are done. Concurrently, rheology tests of the ceramic material and hands-on printing tests are performed between February and March. Depending on the outcome of these tests, the design is

further refined in February and March. Late March and early April are when the mechanical properties of the printed parts are evaluated. The final stage, spanning April, is to compile records of the entire process and results. This organization allows for sequential movement from development to testing and final reporting.

4. Results And Discussions

This chapter introduces the results of the design, development, and tests phases of the small-sized ceramic 3D printer. The chapter begins with a detailed description of the process of assembly with special focus on converting an ordinary FDM 3D printer to a Direct Ink Writing (DIW) system through the addition of a motor-driven screw-type pump mechanism. The modifications and the problems encountered during the mechanical and electrical installation are stated.

Following the assembly, the chapter reports experimental trials conducted to tune the printing parameters including pumping power, printing speed, and extrusion factor. The effect of these parameters on the quality and uniformity of printed ceramic structures is examined, observing the iterative process of tuning needed in order to achieve stable printing conditions.

Furthermore, the chapter includes rheological characterization of the ceramic composite material to establish whether it is viable for extrusion-based additive manufacturing. Mechanical characterization of printed specimens is also included to establish their strength and integrity. Together, the findings provide insights on the relationship between material behavior, process conditions, and resulting part quality and form a foundation for further development of ceramic 3D printing.

4.1 Assembly

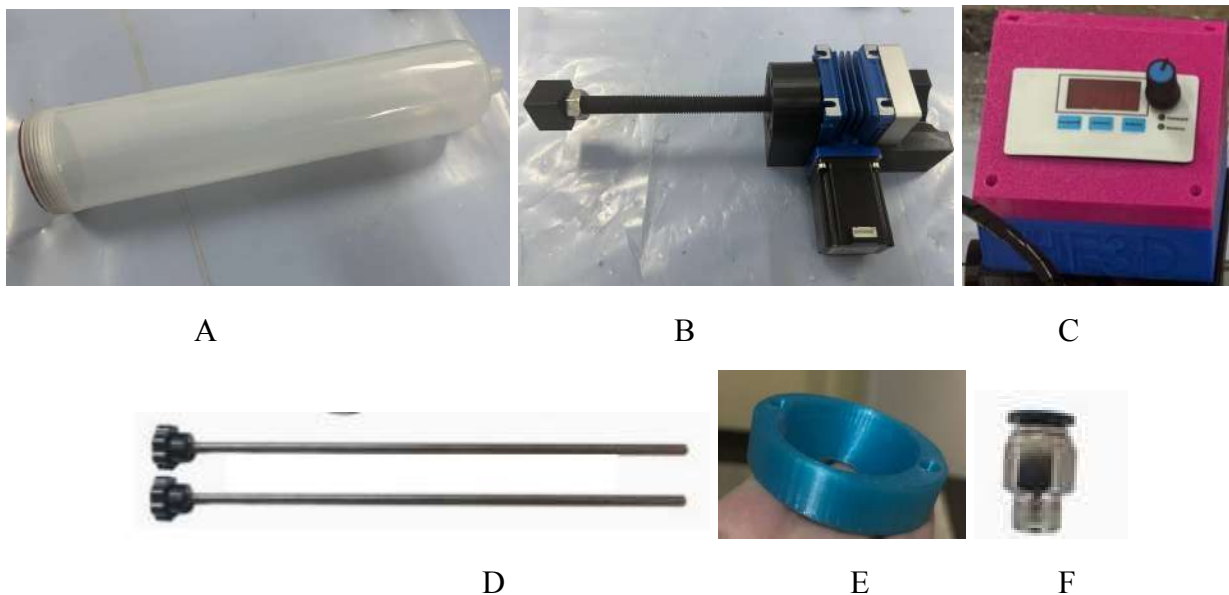


Figure 16. A - Barrel (500 ml), B - Screw type motor driven system, C - Control Box (Potentiometer), D - Barrel tightening screws, E - Barrel holder, F - Barrel outer plug

Figures above represent the details of the Pumping system to be assembled. We have a barrel (A) that is going to be connected to the screw-type motor-driven system (B). Barrel will be tightened with screws (D) and barrel holder (E). The tip of the barrel will have an outer plug (F) to connect a tube in a further assembly. Control box (potentiometer) will be connected with wires directly to the motor of the extruder and to the 24V power source that the Ender 3 Max printer has on its own. Control box is controlled manually, because no signal can be given to the FDM printer as it was not initially designed for the pumping system to be integrated.



Figure 17. Assembly result of pumping system

Figure 17 shows assembly results of the pumping system with all the details from Figure 14.



Figure 18. Extruder with a holder

Extruder has a designed plastic holder to replace an old extrusion system for an Ender 3 Max printer, as it is shown in the figure above. Holder has holes for the screws to secure the static placement.

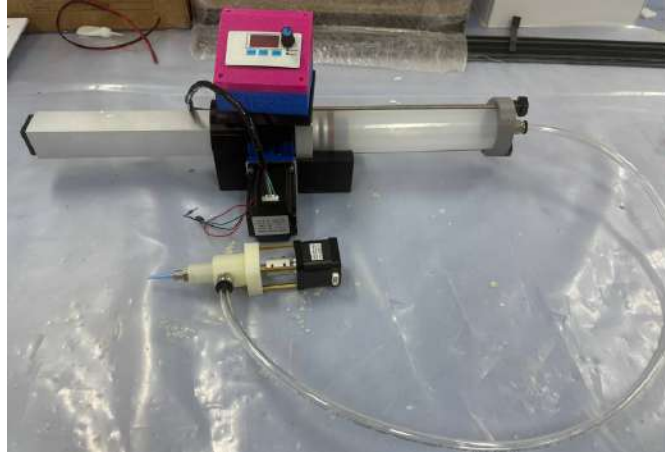


Figure 19. Extrusion and Pumping System Integration

Figure 19 represents how an extruder is connected to the pumping system. Connecting tube connects the extruder and barrel through outer plugs, shown in Figure 16 (F).

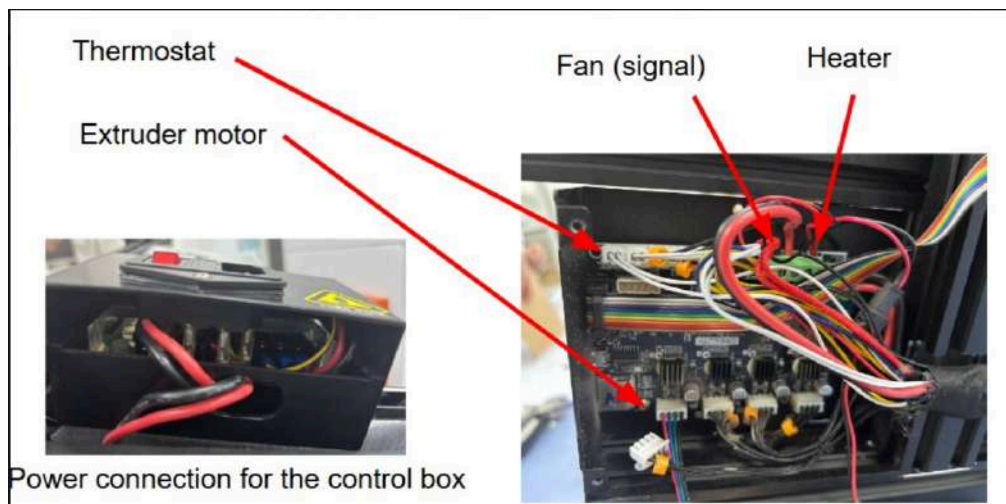


Figure 20. Wire Connection to an Ender 3 Max printer motherboard

After assembling the pumping and extrusion system, the next step is to connect the wires of the extruder motor to the motherboard of the printer and control box to the 24 V power supply, as shown in Figure 20. Wires of an old extruder, thermostat, fan and heater are removed completely and replaced with new wires of our DIW system.

Old extrusion system to be removed

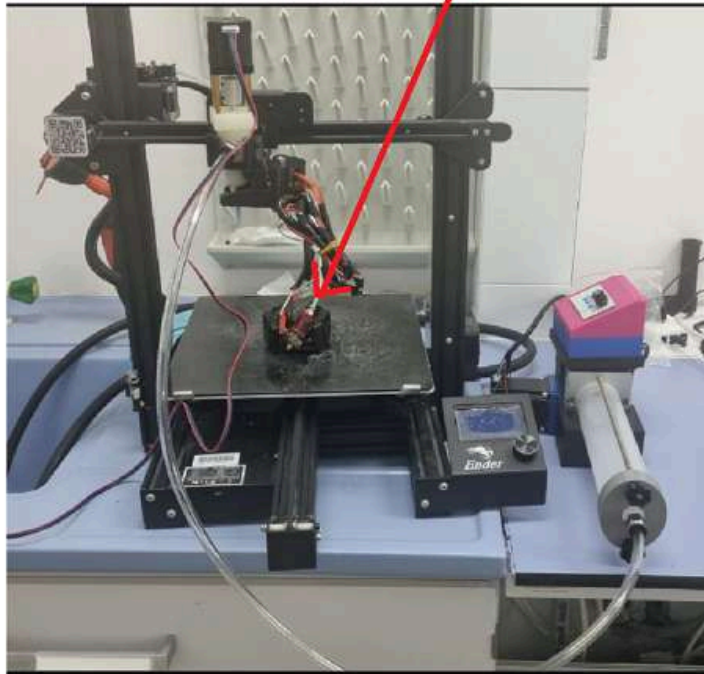


Figure 21. DIW 3D printer assembled design

After connecting all the wires, the work of the whole system was checked by turning on the printer and visually inspecting the work of the extruder and pumping motors. As they were successfully working, we assembled the system to our Ender 3 Max printer (Figure 21). After successful assembly, our next step is to set up the software and adjust it to our new DIW printer.

4.2 Software Setup

Software installation was central to making the ceramic 3D printer easy to use and maintain. MainSailOS, a web-based, cutting-edge control system for direct control of the 3D printing process, was used to control the printer. MainSailOS provided an easy-to-use interface for real-time monitoring, manual adjustment of printing parameters, and remote control of the printer through an attached Raspberry Pi. Major print parameters such as pumping motor speed, extrusion flow rate, and movement instructions were accessed directly from the MainSailOS dashboard with easy and precise control during experimentation.

Cura slicing software was utilized for printing. Cura translated 3D models into G-code directives suitable for the printer, and print path control, layer thickness, print speed, infill density, and other printing parameters were in control. Cura slicing parameters were optimally set to the material characteristics and extrusion dynamics of the ceramic paste. Integration of Cura for slicing and MainSailOS for printer management resulted in a strong and flexible software environment needed to develop and improve the ceramic 3D printing process.

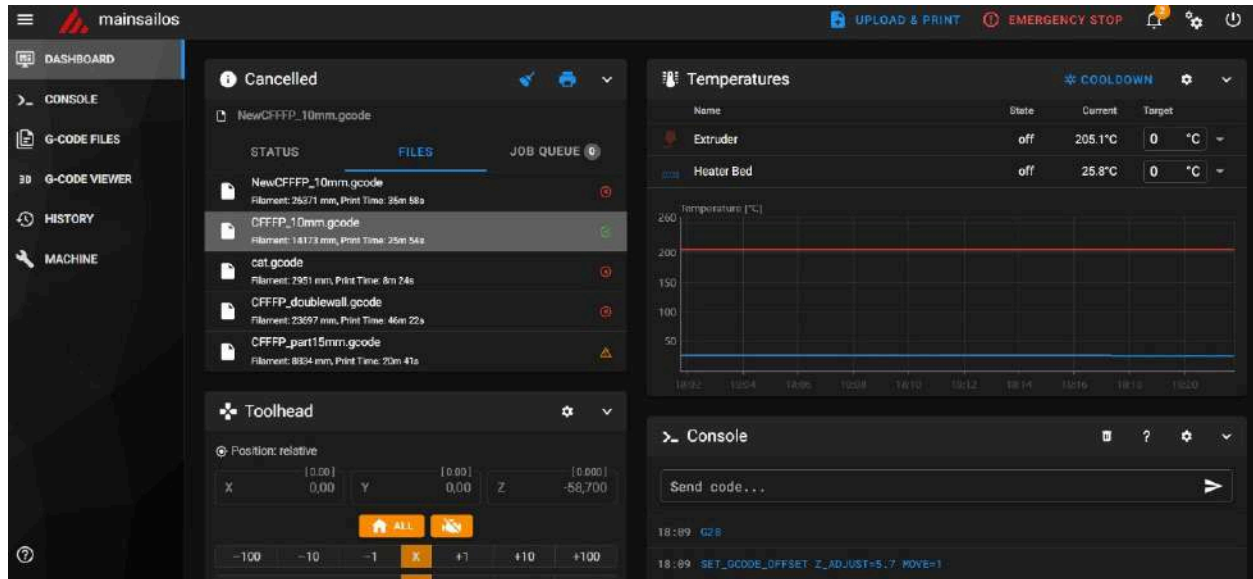


Figure 22. MainsailOS Control Panel

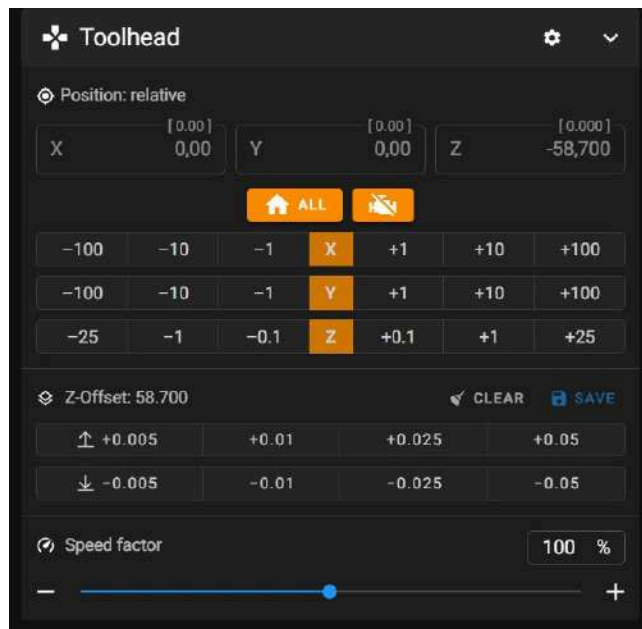


Figure 23. Z-Offset setup

The first thing to set up in MainSailOS was the Z-Offset parameter, because the old extruder had different height dimensions in comparison with the extruder designed for DIW purposes. After testing the movement of the extruder in the MainSailOS control panel, the optimal Z-Offset value was calculated to be 58.7 mm.

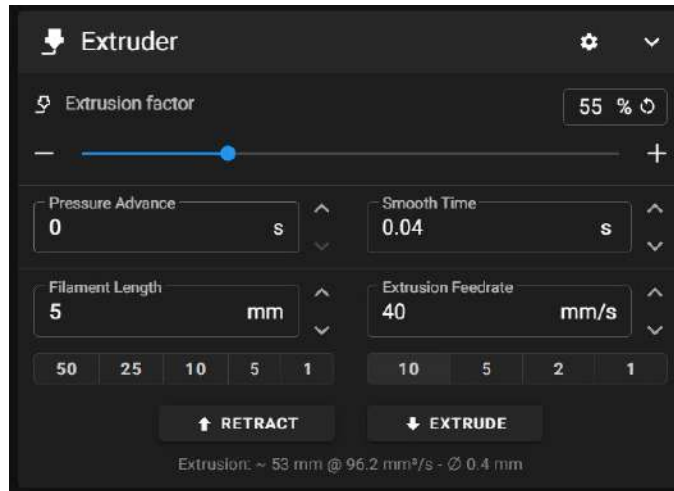


Figure 24. Extruder setup.

Figure 24 shows what values extruder parameters were optimized to ensure a smooth extrusion process. As we are working with ceramic material, which is different from melted plastic, the extrusion factor must be lower. In addition to that, material is being pushed with a pumping system, meaning that the extrusion factor should be less than 100%. After some tests with the motor being manually tested, the optimal value for an extrusion value was calculated to be 55%.

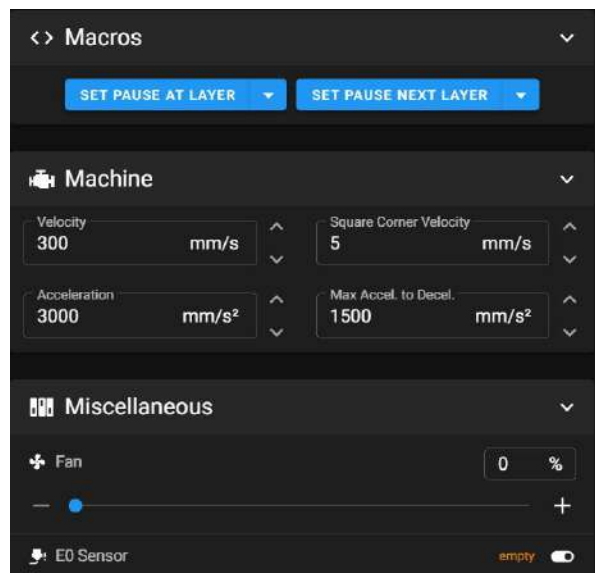


Figure 25. Machine setup

Machine setup was left with its initial optimal values, as it was not affected with our upgraded DIW system.

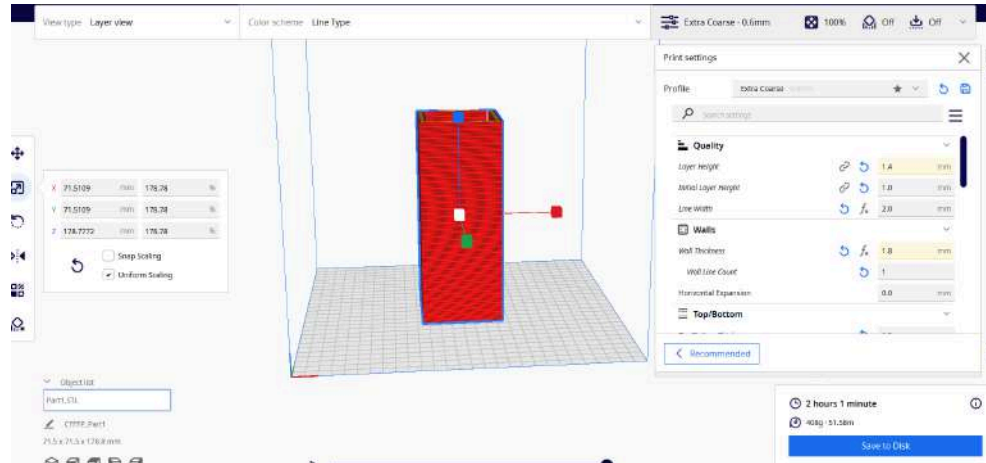


Figure 26. 3D model slicing with Cura

After setting up the MainSailOS panel with optimal parameters, our next step was to prepare g-code with the sliced object. Figure 26 represents an example of Cura software slicing a simple object to start our first printing trials.

4.3 First Printing Trials

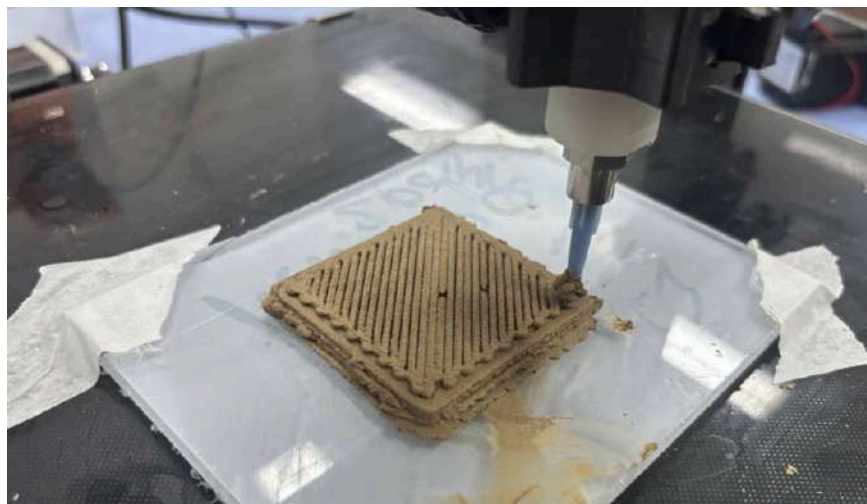


Figure 27. First printing trial

The initial cube was printed without tuning the default parameters of the Creality printer. Figure 27 shows over-extrusion and since the layer height was set too low, the extra material piled up on the nozzle and produced wavy, uneven layers instead of flat, parallel lines. Material drag at the corners confirms the nozzle was continuously extruding extra material through the excess. Additionally, the layer width is also not suitable for this material as there are gaps appearing between layers. This trial shows that the DIW printer does not support default FDM printing parameters and further adjustments are needed.



Figure 28. Second printing trial

Second printed trial shown in Figure 28 also lacks tuning of the printing parameters, yet the layer height was slightly adjusted to eliminate over extrusion of the material that was recorded during the first trial. At this step, the problem with material building up on the nozzle was partially solved, and the second print had better shape than the first one. However, it was noticed that the material extrusion rate is still excessive which can be seen from low layer uniformity and uneven lines. This trial suggests that despite adjusted layer height, the material extrusion rate is still in need of proper tuning.

4.4 Printer Parameters and Software Optimization Based on the Printed Results

After first printing trials, the optimization of printing parameters was started.

- The layer height value - 0.7 mm;
- Line width - 1 mm;
- Wall thickness - 2.5 mm;
- Printing speed - 60 mm/s;
- Printing temperature - 0 degrees for all the prints, as our system does not include heater

- Pumping system value - 130 (stdev: P-04)



not ideal

Figure 29. First successful printing result

Figure 29 shows the result of already adjusted parameters and the printed vase as a result. The material has good extrudability, shape retention and buildability. However, the layer uniformity was slightly off the required value which can be seen from uneven layers and random gaps in the object. The material extrusion rate is still high for such a complex shape and at some points of printing, the layers are too thick.



Figure 30. Adjusted printing result

Figure 30 presents that after tuning the wall thickness up to 3 mm and reducing the pumping up to 100, satisfactory layer uniformity was achieved. Figure 30 demonstrates that the printed object has better layer quality than the previous try, but random interlayer defects are still present, meaning that the amount of material sometimes was insufficient.



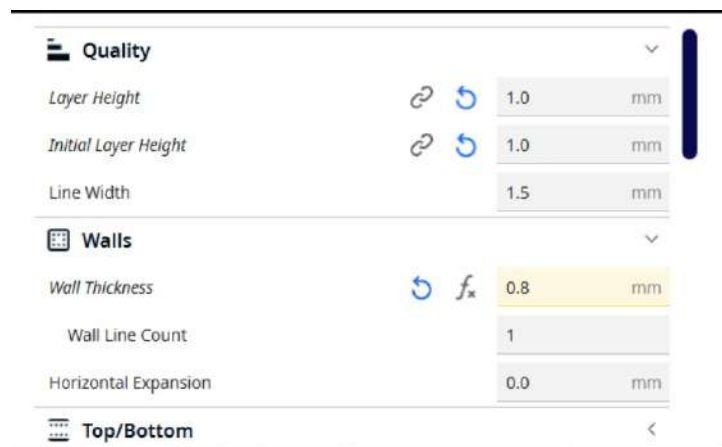
Figure 31. Successful print with slight drawbacks

By tuning the printing parameters from the previous try, a solid quality of printing was achieved. Figure 31 shows successful print of an open top box with equal layer spacing, uniform material extrusion and good buildability. The potentiometer value was 80 and the optimal printing speed was found to be 40 mm/s. Layer height was set to 1 mm. Despite slight wall lean, the print was recorded as successful and the printing parameters were saved for further improvement. The wall leaning was noticed to appear due to an additional cardboard bed, which was put on the original printer bed to quickly remove the printed objects. Eliminating the uneven cardboard bed would noticeably increase buildability. Moreover, the wall thickness was too thin (1.5 mm), meaning that the power of the pumping system was too low and not enough material was supplied at a time, even though the layer height value was found to be optimal.



Figure 32. Best printed result

The adjusted parameters allowed the production of a tall curved vase with unbroken layers. The Figure 32 depicts a consistent wall thickness, which suggests that print quality is good throughout the entire length of the model. The only small defect at the top layer shows that Z offset, extrusion rate and motor RPM were tuned correctly. The values of the optimized printing parameters in Cura software are shown in figure below.



A

Infill Density	↻	0.0	%
Material			▼
Printing Temperature	↻ f_x	0.0	°C
Speed			▼
Print Speed	↻	40.0	mm/s
Wall Speed	↻ f_x	20.0	mm/s
Top/Bottom Speed		20.0	mm/s
Travel Speed	↻ f_x	40.0	mm/s
Initial Layer Speed		20.0	mm/s

B

Figure 33. A, B - Cura Software optimized parameters



Figure 34. Complex printed example

After successful optimization of Cura printing parameters, the complex shapes had to be tested to ensure that the system works perfectly with any objects. The cat model (Figure 34) demonstrates that the geometry can be followed, but the extruder dripped while traversing gaps, which means that even though the extruder stopped rotating while traversing between different

positions, the pumping system still supplied the material. This resulted in extra material being extruded in blank spaces. Control box can not be directly connected to the motherboard, as the Ender 3 Max printer was not designed for DIW printing technology. That is why right now it is a limitation of this research and cannot be solved without additional funds to change the whole printer system. The only thing that can be done is to reduce all parameters by relatively an equal amount, hence slowing down the printing process.

4.5 Printing Performance and Evaluation

The efficiency of the ceramic 3D printer was evaluated through testing of key printing characteristics such as extrudability, buildability, and shape retention. Extrudability is the ability of the ceramic material to be extruded smoothly and in an orderly manner continuously through the nozzle without jamming or sudden changes in pressure. The extrusion flow rate and pumping power were during experimental operations adjusted cautiously in a way that there would be a free material flow without degrading size.

Buildability was assessed by observing the ability of the printed layers to support subsequent layers without deformation or collapse. Test structures were printed in several layers, and the material's ability to hold the required geometry under its own weight was quantitatively measured at printing and after a given time interval. Shape retention was quantitatively measured by observing the change in printed part height with time. The initial height was taken as soon as it was printed, and afterwards the height was taken after a period of time to observe the amount of deformation or settling.

Also, the number of layers printed was checked against the total part height as expected for layer consistency. Any observed height discrepancy between actual and predicted indicated possible material rheology or print parameter errors, such as too high flow, under-drying between layers, or structural instability. The process facilitated careful investigation of the interaction between material composition, print parameters, and end-part quality and was an important step toward process optimization of ceramic 3D printing.

Shape retention factor - theoretical height/experimental height

Table 1. Shape retention factor calculation with layer height - 1 mm

Tests	Theoretical Height/mm	Experimental Height/mm	Shape retention factor/%
5 layers	5	4.99	99.8%
10 layers	10	9.91	99.1%
25 layers	25	24.68	98.72%
50 layers	50	48.95	97.9%
100 layers	100	97.8	97.8%

A shape retention factor study followed the parameter optimization because it examined how printed clay structures maintained their shape throughout the drying process. The printed objects reached an actual height of 100.5 mm(layer height is 1mm) after manufacturing due to material deposition effects which slightly expanded dimensions. The drying process required intermittent measurements which were obtained at day 1 and day 2 and day 3. On the third day the height measurement of printed objects dropped to 97.8 mm. The clay material undergoes natural moisture evaporation which results in decreasing dimensions. The total dimensional change amounted to 2.5% thus meeting the criteria for acceptable shrinkage in clay-based 3D printed parts. The printed structures successfully maintained their designed forms and operational printing conditions delivered satisfactory green strength and dimensional stability before drying.

Figure 32 illustrates smooth and uninterrupted extrusion with a flawless result because of excellent extrudability. The precise contour setting of the layer height creates an even finish on the entire printed object surface. Effective extrusion processes help create enhanced print quality which results in better mechanical strength and visual quality of the final product. The process runs optimally due to perfect material flow and process control which leads to both strength and attractive appearance in the printed outcome.

4.6 Mechanical Tests



Figure 35. Cube for compressive strength tests



Figure 36. Example of compressive strength results

Table 2. Compressive strength test results for 6 trials

Time of curing	Specimen 1 (MPa)	Specimen 2 (MPa)	Specimen 3 (MPa)	Average (MPa)
1 day	0.29	0.31	0.28	0.29
3 days	0.44	0.46	0.45	0.45

The table above shows 6 trials of tests for compressive strength. The average compressive strength of ceramic cube is equal to 0.29 MPa one day after curing. The 3rd day compressive strength increased by 0.16 MPa due to evaporated water in the material. The compressive strength of uncured clay after being 3D printed aligns with the compressive strength of uncured clay made manually (approximately 0.02 MPa) [14]. This suggests that 3D printed clay in uncured state is easy to manufacture with the ceramic printer and offers the same compressive strength. The difference in compressive strength values may refer to clay content that differs from manufacturer. This 55% strength increase in the first 72 hours supports the statement that the evaporation of moisture is the main mechanism for early strengthening. In addition, these findings place DIW-printed clay within or above the ranges for manually fabricated clay bodies that have been established, thus validating the extrusion and curing procedures followed in this study.

5. Conclusion

This project centered around the design and engineering as well as the testing process of a miniature Direct Ink Writing (DIW) ceramic 3D printer which used clay as its printing material. Standard FDM printers received an upgrade that integrated a motor-driven extrusion system to show that inexpensive commercially-available hardware functions for building ceramic components. The built printer succeeded in producing clay components which displayed suitable dimensional precision along with adequate mechanical performance therefore proving the conceptual validity of this method. The project solved clay-related printing issues by properly adjusting material processing methods together with extruder settings and process parameter adjustments. This project progressed low-cost ceramic additive manufacturing and created fundamental knowledge needed for developing better small-scale ceramic printing systems in the future.

5.1 Major Contributions to Knowledge

The research made significant advancements to the domain of ceramic additive manufacturing technology. The research presented the successful conversion of an Ender-3 Max FDM 3D printer to DIW operation through the implementation of a screw-driven paste handling system. Researchers established an operational method for creating clay materials and controlled

their rheological properties to strike the right equilibrium between material mobility and constructible stability during printing. The system achieved stable printing processes combined with reliable part quality through multiple experimental tests that studied the optimization of printing parameters including extrusion flow rate and layer height and printing speed. The developed system manufactured useful clay components which maintained original shape throughout various stages of drying and firing while experiencing minimal physical alterations. The project established that a low-cost portable ceramic printer can work effectively in academic as well as research labs and basic manufacturing spaces. Our work contributes to enhanced understanding of polymer-based 3D printing technology application for ceramics while providing foundational knowledge for additional improvements in the printer design and automation procedures.

5.2 Future Research Directions

The future versions of this system should include a built-in potentiometer directly connected to the motherboard that will automate material extrusion termination after each print session. The addition of an automated mechanism control would stop material extrusion exactly at print completion thus reducing material waste and enhancing final print quality.

A merged approach with real-time sensor feedback components such as flow meters or pressure sensors would maximize both precision and reliability of extrusion operations. Such systems enable automatic extrusion parameter modifications when material properties or environmental elements change.

The development of clay formulations requiring additional research focuses on rheological property modifications that would enhance their print capabilities as well as their structural competence. The printer's functionality needs expansion to enable multiple materials printing capabilities and reinforcement material implementation for future functional ceramic component development.

Advanced research directions in DIW 3D printing for ceramics will focus on automation in extrusion control and sensor improvements as well as material research to optimize performance and applicability.

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Appendix

Figures that can help to understand some of the concepts of our project

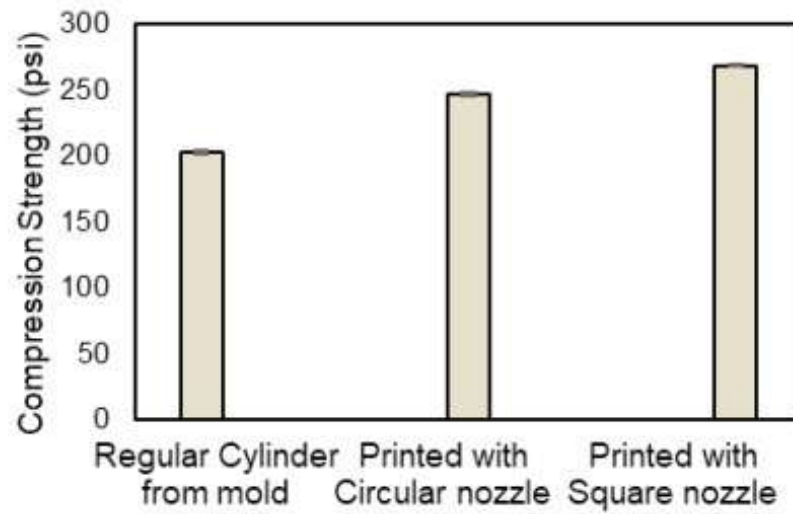
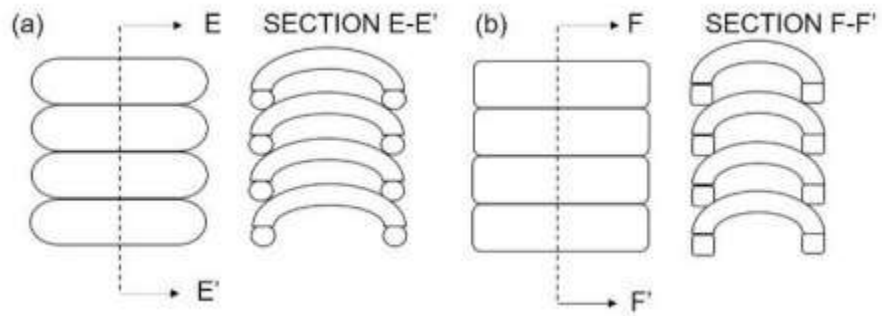


Figure 37. Nozzle parameters (explained in printer design)



Figure 38. Nozzle types used in the project.

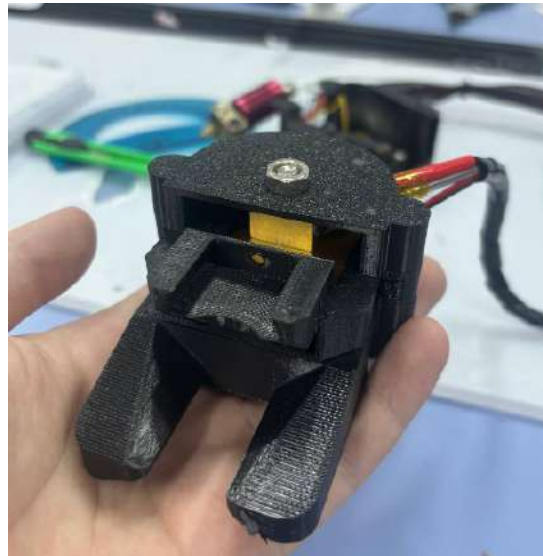


Figure 39. Fan for future research directions.

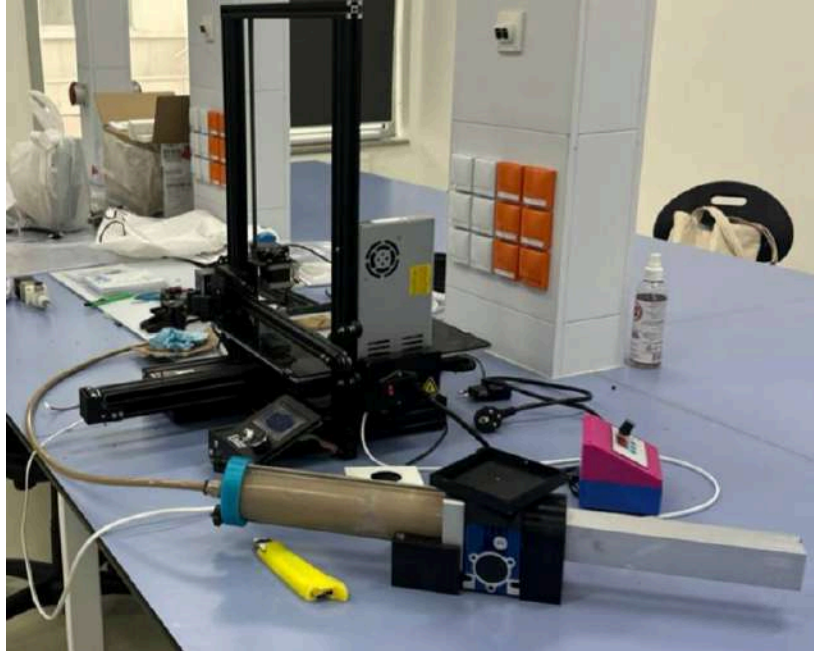


Figure 40. Complete printer setup

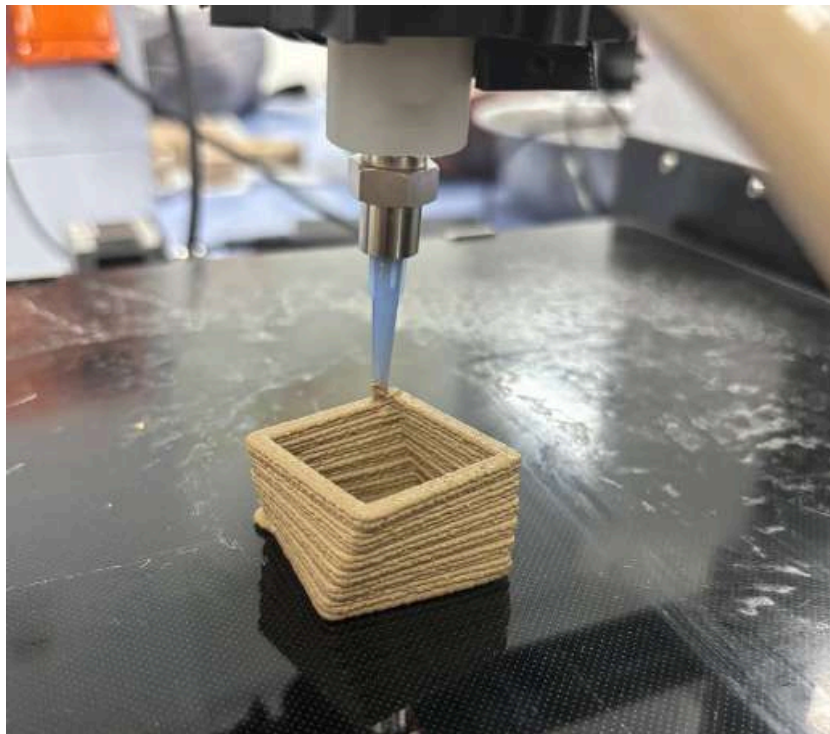


Figure 41. Printing Process

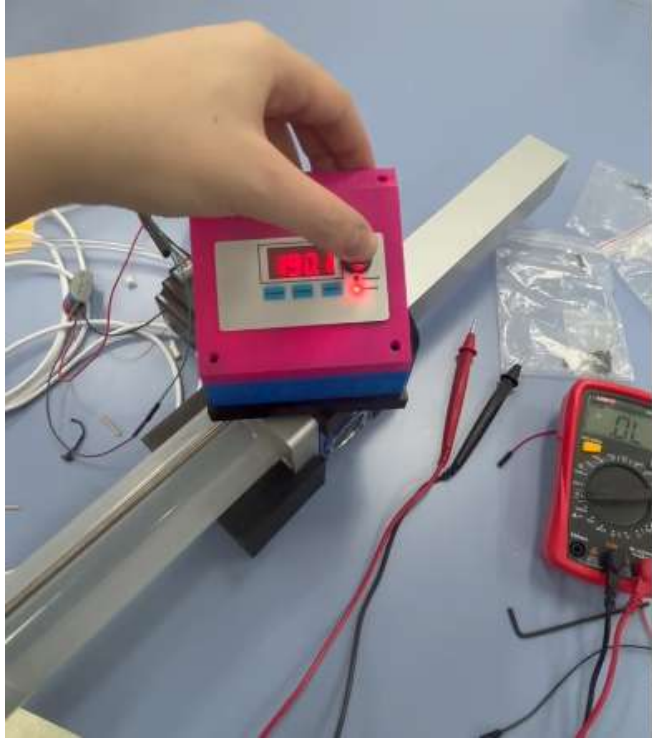


Figure 42. Control Box Switch Button