Direct Ink Writing Additive Manufacturing: Process Optimization, Analysis and Sample Fabrication

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***Abstract*—Additive Manufacturing is a sophisticated manufacturing process that creates 3D items layer-by-layer from digital models. Direct Ink Writing (DIW) is one of the extrusions based additive manufacturing techniques that can print high viscosity materials such as ceramic pastes, polymer composites, hydrogels and conductive inks. Due to the increasing need for cheap and flexible additive manufacturing systems, researchers have studied the possibility of modifying traditional manufacturing machines to be used for additive manufacturing processes. This work modifies a standard 3-axis CNC engraving and milling machine to build a Direct Ink Writing Additive Manufacturing Machine. This time, the CNC machine has a syringe extrusion system instead of the spindle, which will be used to deposit the materials precisely, rather than performing the subtractive machining processes. The accurate layer-by-layer fabrication by a G-code controlled motion system is done by the current X-Y-Z motion system, an Arduino-based open-source controller and GRBL architecture. The main aims of this study are to: Development of an in-house Direct Ink Writing Additive Manufacturing System, parametric optimization of several materials and sample creation and characterization. Different process parameters like nozzle diameter, printing speed, layer height, extrusion rate and material viscosity are studied and optimized for stable extrusion, better surface finish, dimensional accuracy and structural integrity. Shear thinning, yield stress and thixotropic recovery are rheological properties of printable materials that have a strong impact on the printability and the quality of the deposited material in direct ink writing (DIW) techniques. Moreover, several samples are fabricated using the developed setup and characterized to evaluate the effect of processing parameters on print quality and performance. The results show that a typical CNC machine can be effectively converted into a cost-effective Direct Ink Writing additive manufacturing machine by the use of open-source control architecture. The developed system offers a simple, flexible and inexpensive solution which is suitable for educational, research and rapid prototyping applications.**

***Index Terms*—Direct Ink Writing (DIW), Additive Manufacturing, CNC Machine Conversion, Open-Source CNC Controller, GRBL Architecture, Material Extrusion, Rheology, Process Parameter Optimization, Syringe-Based Extrusion, Rapid Prototyping.**

I. INTRODUCTION

The manufacturing technologies are of great importance in industrial progress and modern engineering applications. Conventional manufacturing methods such as turning, milling, drilling, grinding and engraving are commonly used to produce mechanical parts with the desired dimensions and geometrical features. These techniques are usually categorized as subtractive manufacturing processes, as the extra material is eliminated from the workpiece to get the final product configuration. Conventional machining processes, although having good dimensional accuracy and surface quality, suffer from major disadvantages such as high tool cost, long machining time, large material wastage and difficulty in machining complex geometries. In recent years, the development of advanced manufacturing techniques named Additive Manufacturing (AM), driven by the increasing demand for lightweight constructions, bespoke goods, rapid prototyping and complex geometrical fabrication, has become a matter of great interest.

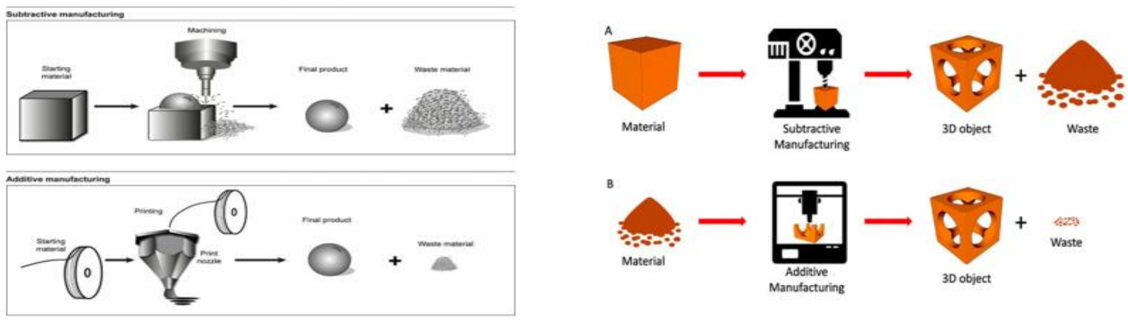


Figure 1. Conventional Manufacturing vs Additive Manufacturing

Additive Manufacturing (AM), commonly known as 3D printing, is a modern production method that builds objects layer by layer directly from digital designs. This process eliminates the need for traditional tooling and machining, offering greater flexibility and efficiency.

The main advantages of additive manufacturing are:

- Reduced material wastage
- Minimal tool requirements
- High design adaptability
- Ability to quickly prototype
- Ability to create complex geometries
- Less time to produce

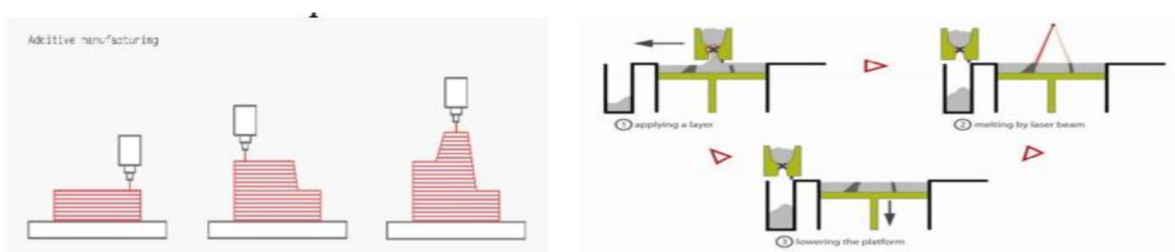


Figure 2. Layer-by-Layer Additive Manufacturing Process

The DIW (Direct Ink Writing) is an extrusion-based additive manufacturing process, where highly viscous materials are systematically deposited through a nozzle, to build 3D structures layer-by-layer. In the DIW technology, the printable material is typically contained in a syringe or cartridge and extruded by mechanical or pneumatic force through a narrow nozzle. The nozzle trajectory is controlled by pre-defined G-code trajectories generated from the CAD model. The deposited layers are gradually merged to form the final 3D structure. Direct Ink Writing technology can print many materials including Ceramic mix, Polymer Composites, Conductive ink, Hydrogel (1), Biomaterial, Cementitious Materials, Multi-phase composite materials The successful application of DIW technology depends highly on the rheological properties of the printed material.

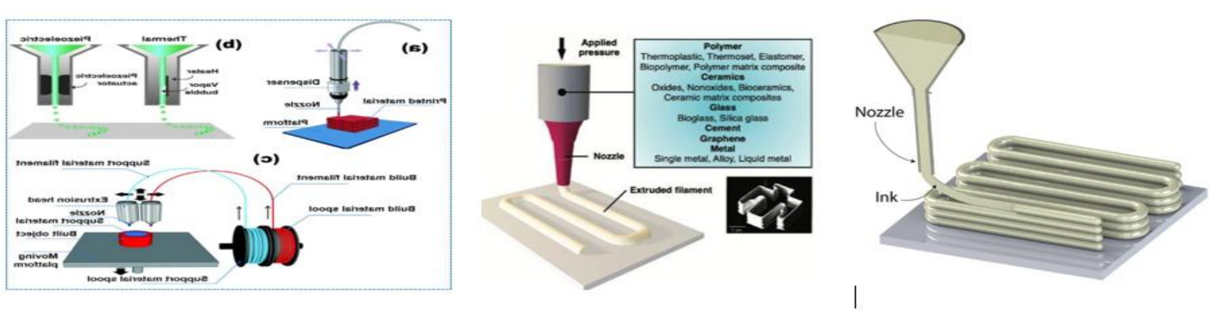


Figure 3. Working Principle of Direct Ink Writing

PRO CNC Machine: A Mini 3018-PRO CNC GRBL machine was used and modified to develop a Direct Ink Writing (DIW) system. It provides X-Y-Z motion, USB communication, and open-source GRBL control with G-code compatibility. The machine uses NEMA17 stepper motors, a T8 lead screw system, and A4988 drivers for precise motion. The original 775 DC spindle motor was replaced with a syringe-based extrusion mechanism for material deposition. Built from aluminum and Bakelite, the machine is lightweight yet rigid, with a repeatability of 0.05–0.1 mm, making it suitable for low-cost additive manufacturing.

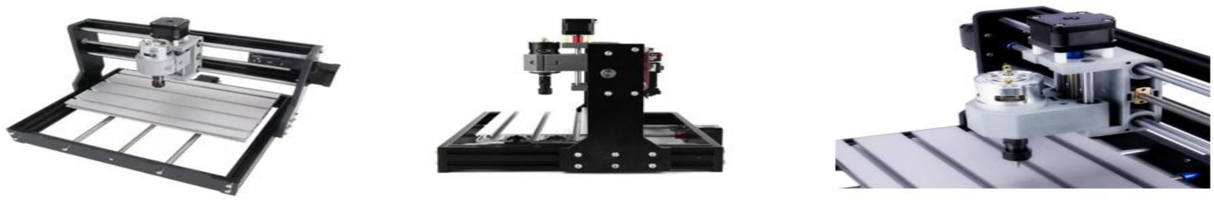


Figure 4. CNC Machine 3018-PRO For Research Work.

Research Work Outcome

The objective of this project is to create an economical Direct Ink Writing Additive Manufacturing Machine by utilizing a standard 3018-PRO 3-axis CNC engraving and milling machine, together with an open-source GRBL-based control system.

Research Objective

The main aim of this project is to create a low-cost Direct Ink Writing (DIW) Additive Manufacturing system which is built around a standard 3018-PRO 3-axis CNC engraving and milling machine and an open-source, GRBL-based control framework. The specific objectives of the research are:

1. In-house DIW AM setup development:
2. Parametric Optimization of Different Materials
3. Fabrication and characterization of samples

Scope of the Study

The scope of current research is:

- Modification of a conventional CNC engraving machine
- Design and development of a syringe-driven extrusion system
- Open-source control systems integration
- An analysis of the behavior of printed materials
- Procedural parameter optimization
- Preparation of test samples

The primary objective of the study is to develop an economical additive manufacturing platform for educational and research purposes

Parameter	Specification
Machine Model	3018-PRO CNC
Working Area	300 × 180 × 45 mm
Motion Axes	X-Y-Z Axis
Controller	GRBL 1.1
Stepper Motor	NEMA17
Stepper Driver	A4988
Screw Mechanism	T8 Lead Screw
Spindle Motor	775 DC Spindle
Spindle Speed	10000 RPM
Power Supply	24V / 5A
Positioning Accuracy	0.05–0.1 mm
Machine Structure	Aluminum & Bakelite
Interface	USB
Supported Files	txt, tap, nc, ncc, cnc

Table 1. Specifications of 3018-PRO CNC Machine

II. LITERATURE REVIEW

Direct Ink Writing (DIW) has emerged as a key additive manufacturing technique, due to its capability of fabricating intricate three-dimensional structures with highly viscous materials such as ceramic paste, hydrogels, conductive inks and polymer composites. Researches are concentrating on the development of low-cost additive manufacturing systems, extrusion processes, rheological optimization of printable materials and adaptation of traditional manufacturing equipment for additive manufacturing applications. This chapter reviews the literature on:

- Direct Ink Writing process
- Extrusion-based additive manufacturing
- Rheological properties of printing inks

- CNC machinery modification
- Open-Source CNC Control Systems
- Toolpath Generation
- Hybrid manufacturing systems
- Development of low-cost additive manufacturing

The literature review is helpful in understanding the existing research landscape, identify research gaps and justify the rationale for the current study.

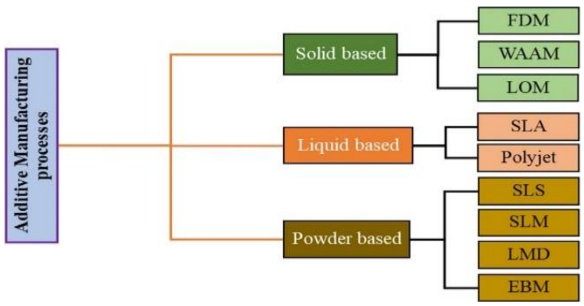


Figure 5. Literature Review Classification for Present Research

III. METHODOLOGY

The present research is based on the development and implementation of a low-cost Direct Ink Writing (DIW) Additive Manufacturing system using a modified 3018-PRO GRBL-based 3-axis CNC engraving and milling machine. The existing approach employs mechanical modification, open-source motion control architecture, CAD/CAM-based creation of toolpath and syringe-based material deposition to facilitate controlled layer-by-layer manufacturing. Here is the full methodology.

- Choosing the right CNC platform
- Mechanical modification of the CNC machine
- Development of a syringe-driven extrusion device
- Integration of a CAD design and GRBL-based motion control system with slicing workflow
- Procedure for G-code production and upload
- Running machines with candle software
- Direct Ink Writing Implementation
- Optimization of the experimental conditions
- Characterization and preparation of samples

The methodological approach implemented aims at exploiting the existing X-Y-Z motion capabilities of the CNC machine and transforming the subtractive manufacturing system into an extrusion based additive manufacturing system

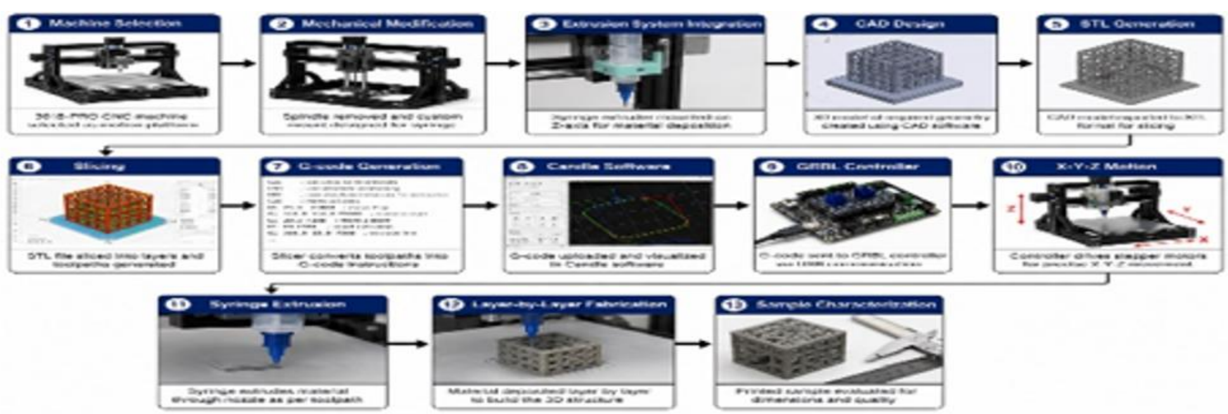


Figure 6. Overall workflow adopted in the present research work

Principle of Developed DIW System: The Direct Ink Writing system is based on the premise of controlled layer-by-layer deposition of material through coordinated translation along the X, Y, and Z axes using a syringe-based extrusion nozzle. The first step of the workflow is the creation of a CAD-model of the required geometry. The generated model is converted to STL format and processed by slicing software to generate toolpaths for printing and G-code instructions. The generated G-code is uploaded into Candle program and transferred to the GRBL controller through USB communication. The GRBL controller reads the G-code commands and produces synchronized motion signals to drive the CNC machine's X, Y and Z axis movements. The syringe extrusion mechanism extrudes the printed material through the nozzle simultaneously according to the generated toolpath trajectory. This deposited material creates layers, gradually forming the 3D structure that is required. The entire printing process goes in the sequence:

- Developing CAD models
- STL conversion
- Segmentation procedure
- G-code generation and later upload using Candle software
- Motion execution based on GRBL Coordinated X-Y-Z nozzle maneuvering
- Syringe based material deposition
- Layered structure formation

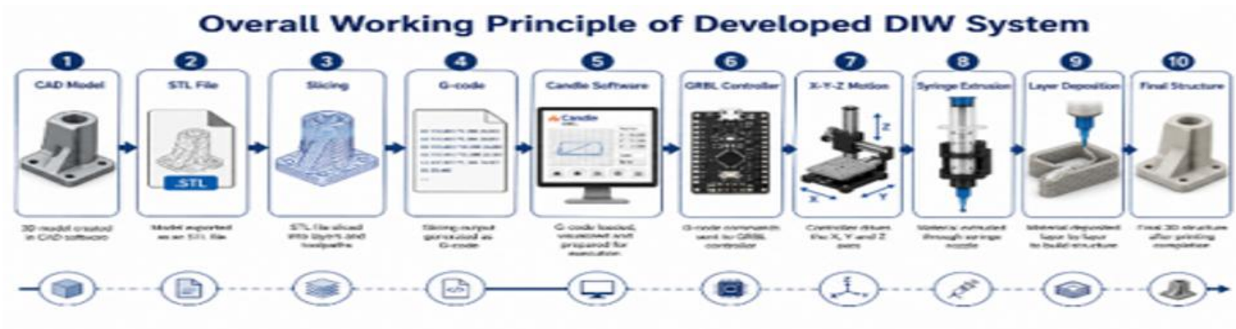
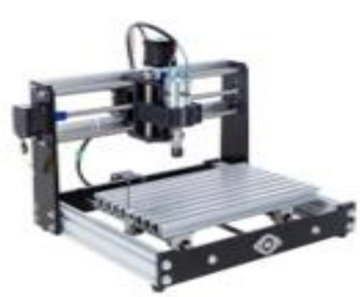


Figure 7. Working Principle of Developed DIW System

Experimental Configuration-In this work, a low-cost Direct Ink Writing (DIW) Additive Manufacturing system is developed by converting a commercially available 3018-PRO GRBL 3-axis CNC engraving and milling machine into an extrusion-based additive manufacturing system. The experimental setup for this study utilizes the CNC machine's inherent X-Y-Z motion features along with a custom-designed syringe-based extrusion system for the layer-by-layer deposition of material with precision. In recent years, additive manufacturing technologies have received much attention because they can produce customized and geometrically complex structures directly from digital models. Among the diverse additive manufacturing methods, Direct Ink Writing is a versatile extrusion-based technology that is capable of printing highly viscous substances such as ceramic pastes, hydrogels, conductive inks, cementitious materials and polymer composites. However, present commercial DIW systems are typically expensive and require complex infrastructure, making them unsuitable for low-cost educational and laboratory applications. In this paper, the use of a low-cost desktop CNC engraving machine as a motion platform for additive manufacturing applications is suggested. The main goal of the experimental setup is to convert a current subtractive manufacturing system to an applicable additive manufacturing platform by means of mechanical modifications and the adoption of an open-source controller. The entire experimental setup is constructed to benefit from the existing motion control capabilities of the CNC machine. The current CNC platform already delivers: Accurate movement along X, Y and Z axes, Positioning with stepper motors, G-code support, Open-source controller support, Linear motion guidance system, Compact mechanical design, Universal Serial Bus (USB) communication interface, Capability to execute automated motion.

Figure 8, Table 2



Component	Function
3018-PRO CNC Machine	X-Y-Z motion platform
Arduino Controller	Motion control
GRBL Firmware	G-code interpretation
A4988 Drivers	Stepper motor driving
NEMA17 Motors	Axis movement
T8 Lead Screw	Linear motion transmission
Syringe Extruder	Material deposition
Nozzle Assembly	Layer formation
CAM Software	Toolpath generation

Result- The experimental results, process observations, material deposition behavior, motion control performance, dimensional analysis, and overall printing capabilities of the developed Direct Ink Writing (DIW) Additive Manufacturing system, built on a modified 3018-PRO GRBL-based 3-axis CNC engraving and milling machine. The established configuration was experimentally tested to evaluate the conversion feasibility of a low-cost CNC engraving platform into an extrusion-based additive manufacturing system using open-source control architecture and syringe-based material deposition. The experimental inquiries were mainly directed to:

- Performance of motion along X-Y-Z axes
- Motion synchronization with GRBL
- G-code execution capability
- Running candle software
- Extrusion method by syringe driven
- Layered Deposition Performance
- printable material rheology
- Print quality
- Solid construction
- Exact geometrical
- Parameter tuning

The complete workflow of the set up DIW configuration included:

- CAD model creation
- 3D STL file conversion
- Operation segmentation.
- Toolpath creation
- G-code Creation
- Uploading G-code with Candle program
- GRBL motion run
- Syringe Extrusion
- layered construction

Print quality and structural integrity were examined under different operating parameters to determine the influence of printing speed, nozzle diameter, layer height, extrusion continuity and material viscosity. The system as it stood was able to create simple geometric shapes by synchronized CNC motion and controlled deposition of material through the nozzle.

Parameter	Observation
X-axis motion	Smooth
Y-axis motion	Stable
Z-axis positioning	Accurate
Motion synchronization	Proper
GRBL communication	Successful
Machine vibration	Minimal

Table 3. Initial Calibration and Motion Testing

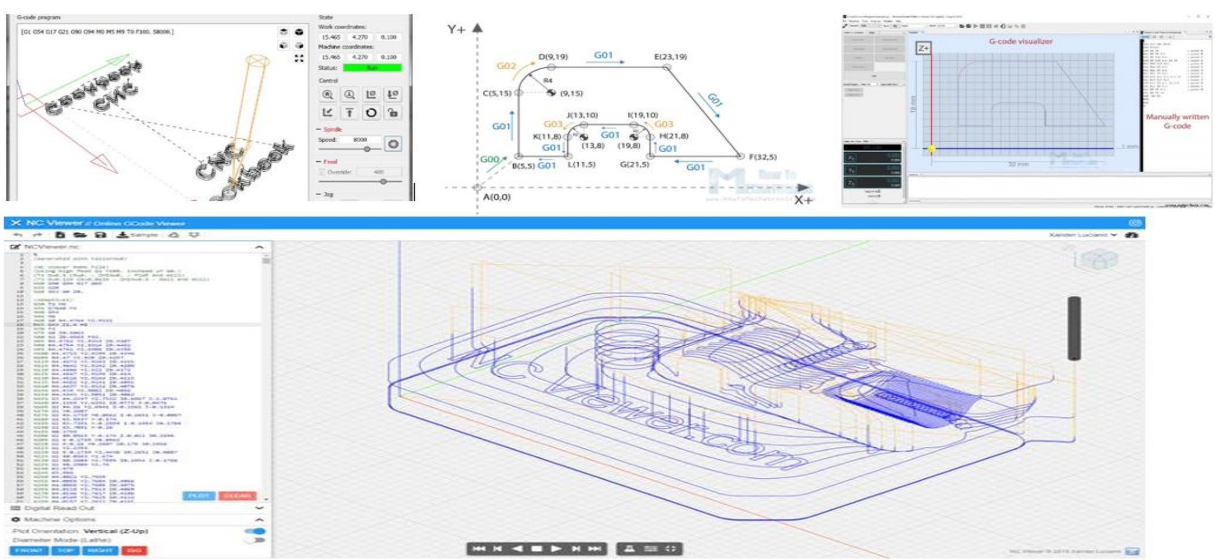


Figure 9. Example of Generated G-code File

IV. CONCLUSION

This research successfully demonstrated the development of an inexpensive Direct Ink Writing (DIW) Additive Manufacturing system with a modified 3018-PRO GRBL-based 3-axis CNC engraving and milling machine. The system utilized the natural x-y-z motion features of the CNC platform and a syringe-based extrusion method for accurate layer-by-layer material deposition. The research mainly focused on the conversion of a conventional subtractive manufacturing machine into an extrusion-based additive manufacturing system by using open-source hardware architecture and customized mechanical modification methods. The setup that was in place, integrated successfully:

- GRBL controller for Arduino
- A4988 Stepper Motor Driver
- NEMA 17 steppers
- Lead screw motion device T8
- Apparatus for extrusion by syringe
- Motion control process driven by G-code

The experimental study demonstrated that the commercially available 3018-PRO CNC engraving machine can be successfully used as a cost-effective additive manufacturing platform for Direct Ink Writing applications. The configuration was proven successful in the coordination of motion in the X-Y-Z axes, uniform movement coordination, and controlled nozzle's trajectory in the printing process. The resulting G-code instructions were parsed precisely by the GRBL-based control architecture and the nozzle movements were synchronized during the layer-by-layer manufacturing. During the experiment, the entire digital process from creation of the CAD model, conversion to STL, slicing, generation of G-code, upload via the Candle software and motion execution under the control of the GRBL software was successfully carried out. The workflow developed provides a simple and efficient way to perform automated additive manufacturing processes with open-source CNC architecture.

The test on the printing speed indicated that the speeds that were too high had the effect of discontinuous extrusion and poor adhesion between the layers whereas the speeds that were too low had the effect of excessive accumulation of material and layer spreading. It was observed that stable layer growth and increased dimensional consistency were achieved under moderate printing speed conditions. The nozzle diameter was an important factor for the printing resolution and the flow behaviors of the material. The smaller nozzles showed better geometric detail and printing precision, but had higher extrusion resistance. Larger nozzle diameters improved the continuity of material flow at the expense of the resolution of printing and surface quality.

Principal Results of the Study:

The main results obtained from the present investigation are given below:

- Successful conversion of 3018-PRO CNC engraving machine to additive manufacturing
- Design and implementation of a syringe extrusion system
- Successful integration of a motion control system based on GRBL
- Candle Software Reliable G-code printing procedure
- Successful layer by layer deposition of material.

Research Contributions:

The main contributions of the present research effort are:

- Development of a low-cost CNC Direct Ink Writing platform
- Integration of Additive Manufacturing with Open-Source CNC Frameworks
- Development of a syringe-based material deposition mechanism
- Experimental study of process variables influencing extrusion quality
- Exhibition of affordable and commercially available CNC machines for additive manufacturing
- Development of a versatile research platform for additive manufacturing applications at educational and lab scales

REFRENCES

[1] S. De Smedt, B. Attaianese, and R. Cardinaels, “Direct ink writing of particle-based multiphase materials: From rheology to functionality,” *Current Opinion in Colloid & Interface Science*, vol. 75, p. 101889, 2025.

[2] H. Baniasadi, R. Abidnejad, M. Fazeli, J. Lipponen, J. Niskanen, E. Kontturi, J. Seppälä,

and O. J. Rojas, “Innovations in hydrogel-based manufacturing: A comprehensive review of direct ink writing technique for biomedical applications,” *Advances in Colloid and Interface Science*, vol. 324, p. 103095, 2024.

[3] P. Rodríguez-Lagar *et al.*, “Effective, versatile and inexpensive extruder system for direct ink writing of high-viscosity pastes,” *The International Journal of Advanced Manufacturing Technology*, vol. 131, pp. 4739–4753, 2024.

[4] J. Liao and Z. Huang, “Data model-based toolpath generation techniques for CNC milling machines,” *Frontiers in Mechanical Engineering*, vol. 10, p. 1358061, 2024.

[5] V. G. Ráczi and B. Mikó, “Laser Engraving on a CNC Milling Machine,” *Acta Materialia Transylvanica*, vol. 7, no. 2, pp. 100–108, 2024.

[6] R. Sonawane, A. B. Rane, and D. S. S. Sudhakar, “Development of a 3-Axis CNC Milling Machine with an Open-Source Controller,” *International Journal of Research in Engineering and Technology (IJRET)*, vol. 6, no. 8, pp. 9–15, 2017.

[7] P. Bhasin, P. Singh, and S. Singh, “Design and Fabrication of Low-Cost Wood Working Mini CNC Milling Machine for Students Skill Development,” *International Journal of Advance Research and Innovation*, vol. 8, no. 1, pp. 66–72, 2020.

[8] J. A. Lewis, “Direct Ink Writing of 3D Functional Materials,” *Advanced Functional Materials*, vol. 16, no. 17, pp. 2193–2204, 2006.

[9] J. E. Smay, G. M. Gratson, R. F. Shepherd, J. Cesarano, and J. A. Lewis, “Directed Colloidal Assembly of 3D Periodic Structures,” *Advanced Materials*, vol. 14, no. 18, pp. 1279–1283, 2002.

[10] B. Derby, “Inkjet Printing of Functional and Structural Materials: Fluid Property Requirements, Feature Stability, and Resolution,” *Annual Review of Materials Research*, vol. 40, pp. 395–414, 2010.

[11] B. G. Compton and J. A. Lewis, “3D-Printing of Lightweight Cellular Composites,” *Advanced Materials*, vol. 26, no. 34, pp. 5930–5935, 2014.

[12] Gibson, D. Rosen, and B. Stucker, *Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing*. New York, NY, USA: Springer, 2015.

[13] T. D. Ngo, A. Kashani, G. Imbalzano, K. T. Q. Nguyen, and D. Hui, “Additive Manufacturing (3D Printing): A Review of Materials, Methods, Applications and Challenges,” *Composites Part B: Engineering*, vol. 143, pp. 172–196, 2018.

[14] G. C. Anzalone *et al.*, “Open-Source 3D Printing for Low-Cost Scientific Equipment,” *PLOS ONE*, vol. 8, no. 3, 2013.

[15] D. S. Nguyen, J. Song, Y. Fu, and A. C. To, “An integrated hybrid wire-arc directed energy deposition, friction stir processing and milling system for multi-track, multi-layer part manufacturing,” *Additive Manufacturing Letters*, vol. 11, p. 100247, 2024.

[16] H. H. Aung *et al.*, “Towards a study protocol: A data-driven workflow to identify error sources in direct ink write mechatronics,” *MRS Advances*, vol. 9, pp. 837–843, 2024.

[17] Dangat, V. Zalte, P. Potdar, and V. Gaikwad, “Low-cost CNC Machine based on custom built Open-Source CNC Controller,” *International Journal of Engineering Research & Technology (IJERT)*, vol. 11, no. 6, pp. 256–260, 2022.

[18] R. S. Stubblefield, L. X. Guang, Z. Xiaodong, and S. B. Akoi, “Simulation and Optimization of 3 Axis CNC Milling Machine Structure,” *International Journal of Mechanical Engineering*, vol. 10, pp. 44–55, 2025.

[19] V. S., R. Kumar, N. N., C. P., S. S. K. S., K. B., L. Kumar, and N. A., “Design and Fabrication of CNC Milling and Laser Engraving Machine,” *International Journal of Research Publication and Reviews*, vol. 6, no. 3, pp. 9000–9008, 2025.