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# Development of a small-scale 3D concrete printer

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**Abstract**

*This paper presents the development of a small-scale 3D concrete printer designed to address the high cost and impracticality of large-scale systems for research and study. The printer measuring 700 mm × 450 mm × 500 mm, consists of three key components: a control unit, an extrusion system, and a linear motion system. The control unit is for automation whereas the screw-driven extrusion system guarantees a constant flow of concrete, and the linear motion system helps movement along X and Z axes. The control unit (Microcontroller) synchronizes various systems for exact running. Through literature careful decisions were made to choose switches, motor drivers, DC motors, and controllers to maximize the performance. The calibration and testing of the developed system confirmed the printer's operation was effective. The system is capable of operating in X and Z plans with a maximum printing length of 600mm and height of 300mm, which was reasonably economical for research purpose to study the shrinkage and distortion in the printed concrete. Y axis motion was excluded to keep the system less complex and cheap, focusing instead on studying the shrinkage, distortion and layer stacking. Consequently, this study contributes to low-cost and readily available 3D concrete printing technology for educational and scientific study purposes.*

***Keywords***— 3D Concrete Printing, Lab-Scale Printer, Screw-Driven Extruder, Cost-Effective Fabrication, Arduino-Based Control System, Material Formulations

## 1 Introduction

By allowing the automated and exact building of intricate constructions, the development of 3D printing technology has transformed several industries, including building. Among these developments, 3D concrete printing has significantly grown due to its minimal time requirement, reduced human involvement, and minimal waste generation among many other merits. Commercial companies all around have effectively created and used large-scale 3D concrete printers to show the viability of additive manufacturing in the building sector. However, research and educational institutes, which usually need more flexible and reasonably priced solutions to run tests and develop novel materials, find difficulty with the high cost and complexity of these big systems.

Nevertheless, the aim was to solve this problem by developing a lab-scale 3D concrete printer. This small-scale printer provides a more affordable and sensible alternative to commercial systems, therefore enabling research and development in regulated laboratory environments. Providing a platform for quick prototyping and material testing, the printer lets researchers experiment with many concrete formulations, printing settings, and structural designs. The system consists of an Arduino-based control unit, a screw-driven extrusion mechanism, and a linear motion system. The developed 3D printer has its frame dimensions measuring 700mm x 450mm x 500mm. Therefore, the printer's small size qualifies for both research and instructional use.

This work presents the conceptual design, construction techniques, and production method of the lab-scale 3D concrete printer, emphasizing its potential as a reasonably affordable tool for academic and research facilities exploring advancements in 3D concrete printing technology.

# 2 Related Studies

Several commercial firms in India and across the world have achieved notable progress in the development of large-scale extrusion-based 3D concrete printing systems. However, the exorbitant cost of these large-scale 3D printers presents a significant barrier, rendering their acquisition impractical for numerous research institutes. On the other hand, the lab-scale printer is smaller, easy to fabricate, cheaper, and is more suitable for research work. Lab-scale printers allow researchers to control the conditions under which they conduct experiments with different material formulations, printing parameters, and structures [1][2]. The ability to test many variations in a controlled lab environment facilitates rapid iterations and innovations in materials, hardware, and processes [3][4][5].

While the studies carried out by the above researchers notably emphasize the merits of the system as proposed, they quite often miss out documentation on design, control strategies and standard practices. Moreover, there is a gap in scaling the lab-based and commercial based system. Therefore, we developed a system which is customizable, cost effective and suitable for research and study purposes.

[6] developed a compact linear concrete printing system. This system could print concrete layers with a width of 38.1 mm and a height of 24.4 mm at a linear speed of 60 mm/s. There are many companies that specialize in the manufacture of 3D printers for concrete applications. COBOD (Denmark-based company) is popular for producing BOD2 Gantry 14 printers (World Leader in 3D Construction Printing). Figure 2 presents the printer developed by COBOD. WASP (Italy-based company) popular for producing Crane Wasp Crane/Gantry printers. Figure 1 presents the printer developed by WASP. Vertico (Netherlands- based company) makes the EVA Robotic Arm printer. Figure 2-8 presents the printer developed by Vertico (Everything about robotics and AI).

Despite their capabilities, commercial 3D concrete printers are primarily designed for industrial and large-scale production incurring huge capital investment as well as providing limited options for users or researchers to study, making it extremely unsuitable for research setting. Also, we can't make any changes or test new materials which as a result necessitate to develop lab-scale based 3D concrete printing, overcoming all constraints.

CyBe (Netherlands-based company) makes the CyBe G Gantry printer (3D Concrete Printers CyBe Construction). In India, there is no concrete printer manufacturer to date, yet Micob and Tvasta, a company specializing in manufacturing 3D-printed buildings, has become known throughout India because of its many accomplished projects for high-profile clients (Popular Construction 3D Printing Companies in India).

Despite the impressive effectiveness of these concrete printers that produce complex structures in a short timescale, it is necessary to take into consideration the significant cost implications related to their acquisition. For example, the Vulcan II concrete printer has a price tag of just under Rs.2.2 crores. Another example is a fixed 3D concrete printer installed by CyBe Construction with a starting price of 2.54 crores (3D Concrete Printers CyBe Construction). The exorbitant costs associated with concrete printers have the potential to obstruct accessibility and prevent the pace of innovation, thereby posing a challenge to research and development.

*Printing facility developed by COBOD (adopted from COBOD)*

*Printing facility developed by Wasp (adopted from RoboticsBiz)*

Figure 1: Printing facilities developed by COBOD (left, adopted from COBOD) and WASP (right, adopted from RoboticsBiz).

Exorbitant price tag for such large 3D concrete printer and its technology quite often halts the academic progress and restricts pace of research and innovation especially in the developing country.

A paper by Zhang et al., (2019)[12] mentions that 3D printing has various advantages as it is efficient, cost saving, and fewer construction wastes are generated as compared to the conventional construction mechanics. In their (Ayesha Siddika Md. Abdullah Al Mamun and Alyousef, 2020) study they have similar conclusions about the 3d printer advantages, highlights on the growing demands and applications and its performance.

# 3 Methods

## 3.1 Concept Design

Three major components of a 3D concrete printer are typically the linear motion system, extrusion system, and control unit. The linear motion system of a printer is responsible for moving the printing head and building structure. The extrusion system facilitates a consistent and uniform flow of concrete mortar during printing, whereas a control unit is responsible for integrating and synchronizing the linear motion system and extrusion system. The frame of the printer is built using mild steel for sturdy, reliability and durability, hopper of the system is constructed using high-density polyethylene for its resistance to chemical reaction, smooth surface and hard structure.

We created the conceptual design of the printer using Fusion 360 [9] a commonly used 3D modeling software. The process began with an initial sketch, followed by the utilization of parametric modeling tools in Fusion 360 to create three-dimensional models for linear motion system and extrusion system.

The initial phase of developing the printer involved creating a conceptual design that focused on the frame structure. Along the X, Y, and Z axes, the frame structure has dimensions of 700 mm, 450 mm, and 500 mm. Figure 3 shows the concept design and dimensions of the frame structure of the concrete printer.

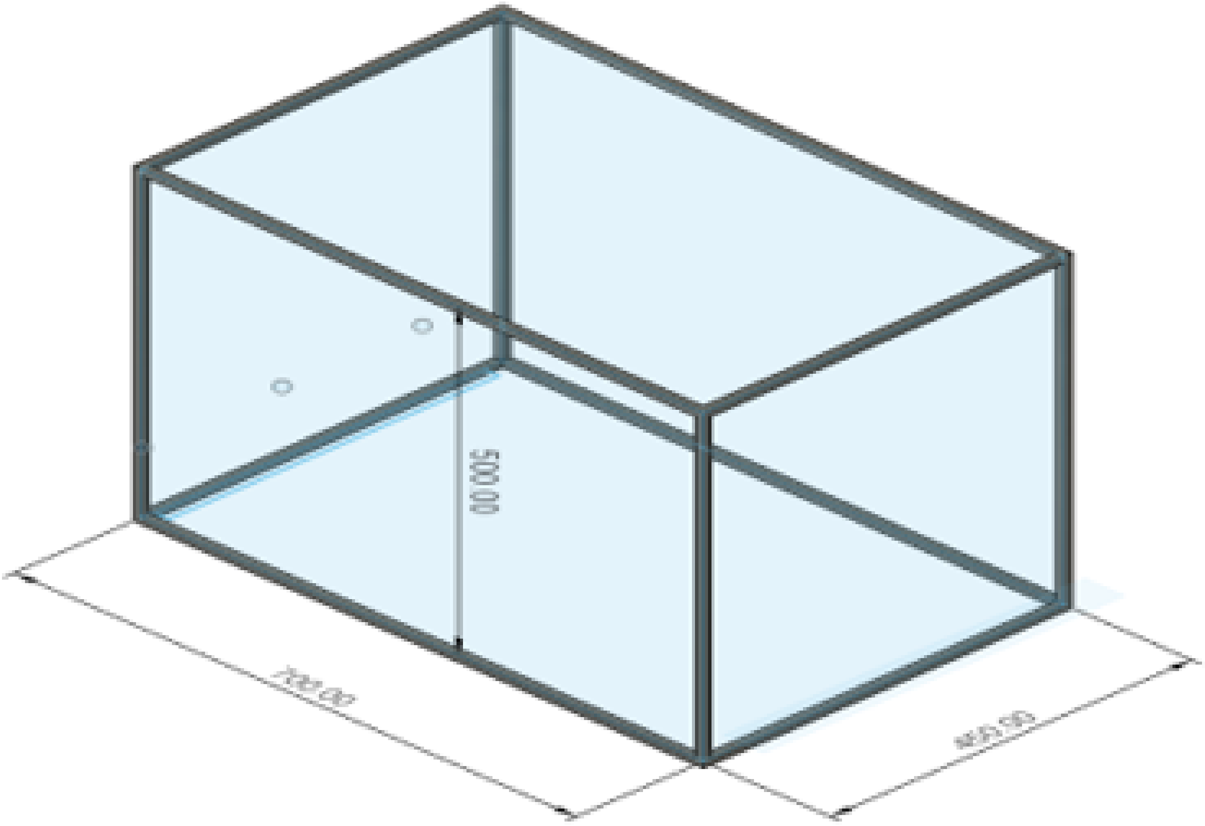


Figure 2: Frame of the 3DCP

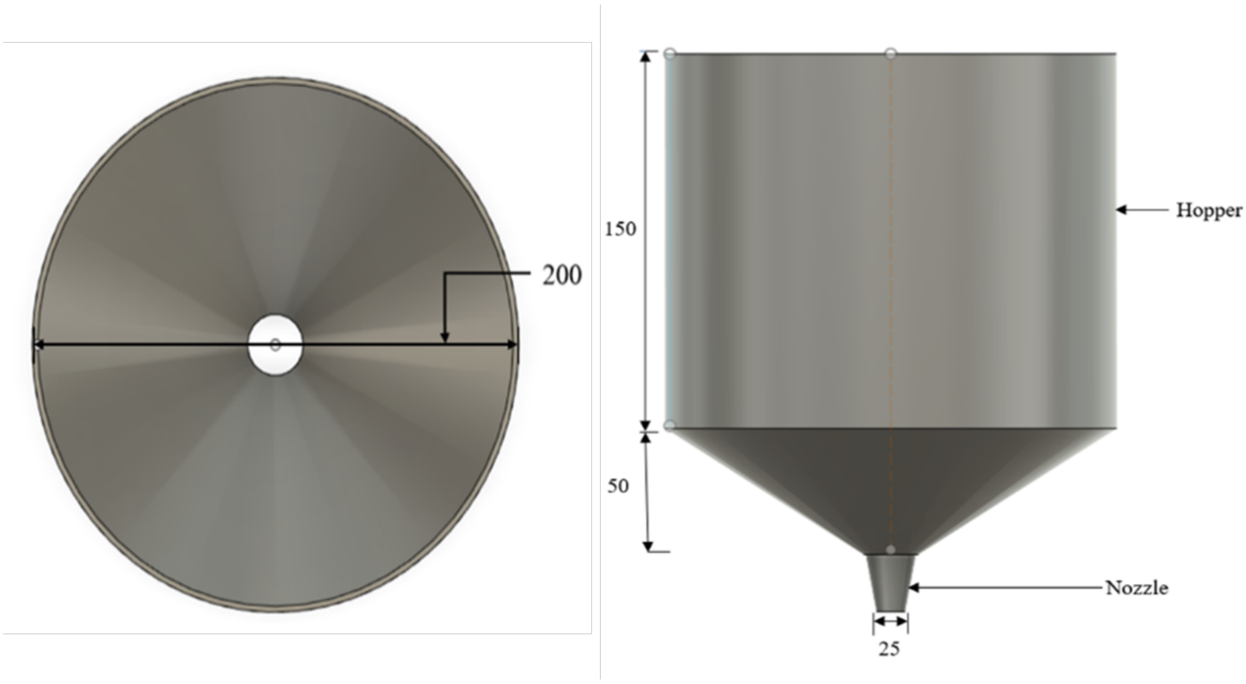


Figure 3: Top and Front view of Hopper

The extrusion system consists of an extruder, a hopper, and a nozzle [10]. In a laboratory, we tested the screw-driven and piston-driven extruder systems for the continuous extrudability of cementitious materials. The screw-type extruder is based on the principle of a rotating screw mechanism. As the screw undergoes rotation, it propels the concrete mix along the barrel of the extruder, subsequently directing it toward the nozzle. A piston in a piston-driven extruder displaces to push the concrete mixture through the nozzle.

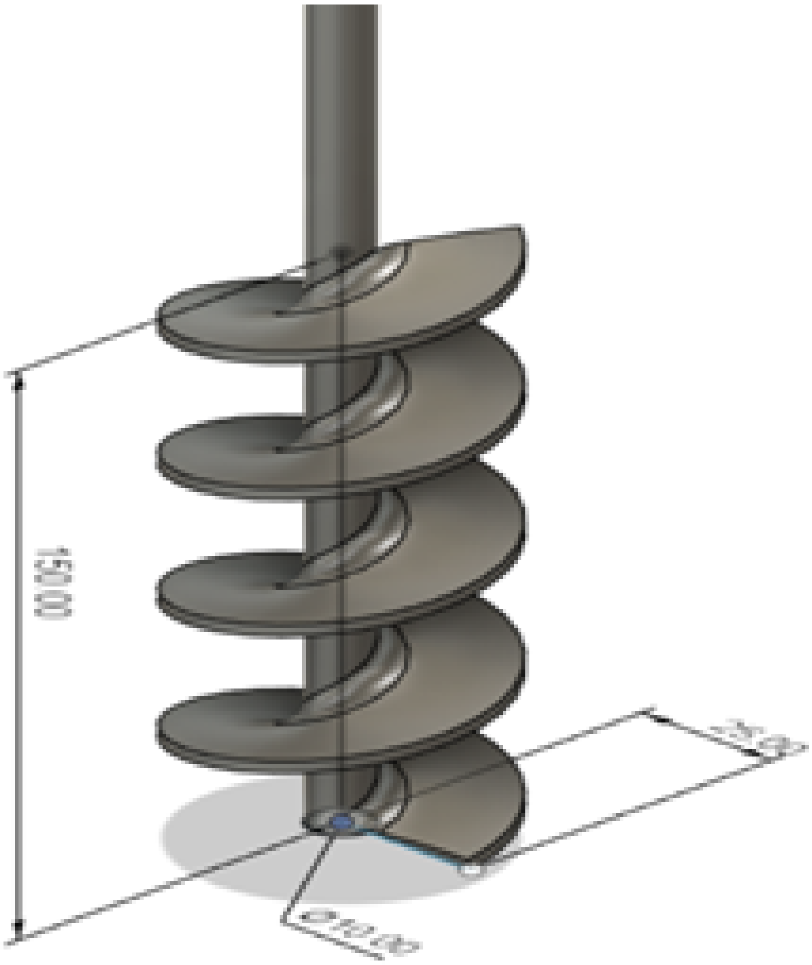

Figure 4: Screw Driven Extruder

The screw-type extruder demonstrated better material control and consistent extrusion of cement mortar compared to the piston-driven extruder. The latter exhibited some challenges in extruding the cementitious material (e.g., bleeding, segregation). Therefore, in the current printer we chose to use a screw-driven extruder. Figure 5 shows the screw-driven extruder used for the fabrication. The hopper is a part of the extrusion system that functions as a container to hold the concrete mixture for extrusion. The nozzle facilitates the controlled extrusion of concrete material, enabling the creation of shapes and structures as intended. Figure 4 presents the conceptual design and intended dimensions of the hopper and the nozzle, respectively.

The linear motion system comprises lead screws, timing belt, and horizontal and vertical linear guides. Lead screws and timing belts are commonly used to achieve linear motion. The linear guides function as a designated pathway for facilitating movement, while the lead screws and timing belt transform rotational motion into linear motion. The following are the essential components of the developed concrete printer. Figure 6 presents the top, 3D, and front view of the conceptual design of the linear motion system, respectively. The complete assembled component of the printer is shown in Figure 7.

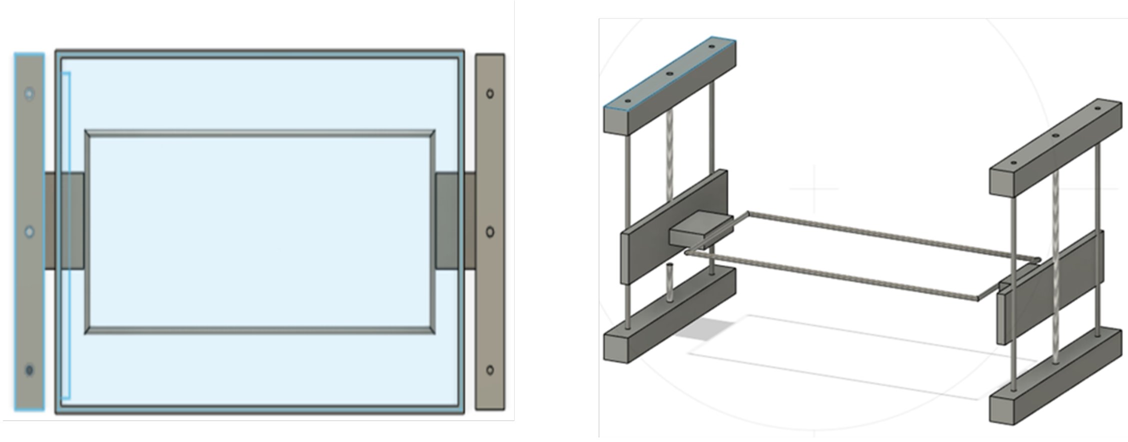

Figure 5: Linear Motion System, (LMS) (3D View)

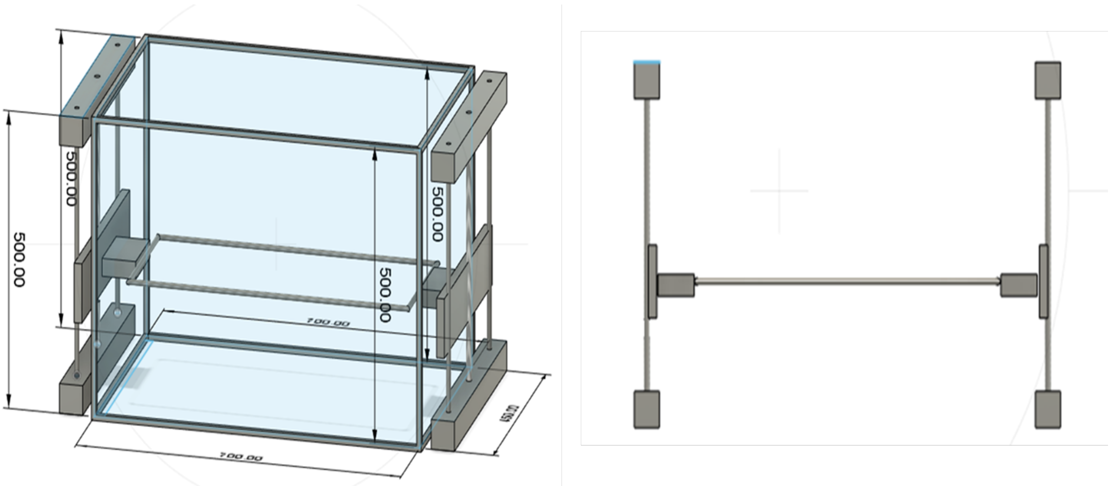


Figure 6: LMS, Small scale 3D-Concrete Printer

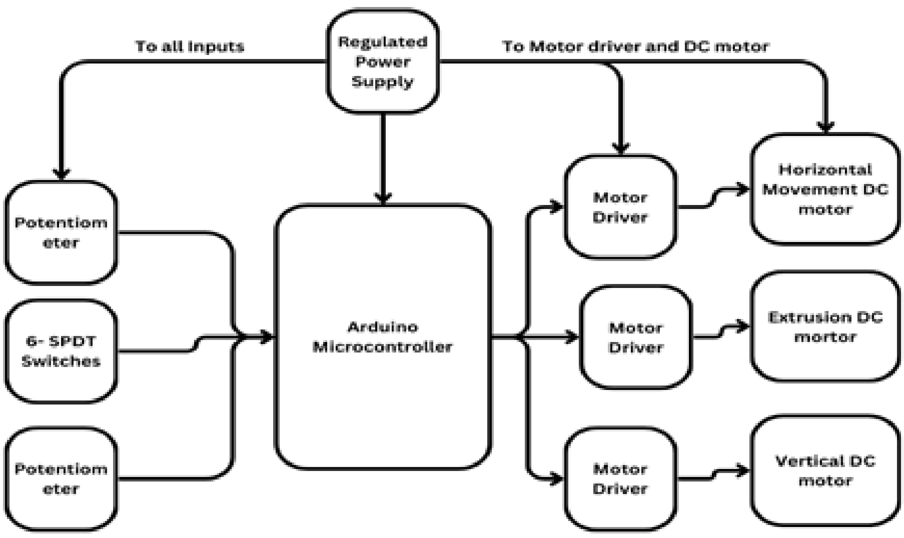


Figure 7: Block diagram of controller unit

## 3.2 Controller Circuit Design

The primary control unit for the electronic circuit of a 3D concrete printer is an Arduino Microcontroller based on ATMega328P controller. The developed system's functional block diagram includes a power supply unit that powers the controller, sensors, and actuators. Potentiometers help users control motor speed, while SPDT switches change motor direction and indicate the print endpoint in the integrated system. This setup synchronizes with motors that manage horizontal and vertical extrusion movements.

The motor driver regulates both the current and the motor's direction of rotation. It also features safety measures to prevent overheating and ensure consistent performance. These set up make the 3D concrete printer more efficient, user-friendly, and capable of producing precise and reliable prints.

### 3.2.1 Algorithm

**Step 1. Initialization**

- Declare and initialize all the variables, data types, and I/O pins where I/O devices are connected.
- For example, switches, potentiometers, motors and extruders.

**Step 2.** I/O configuration

- Configure and specify the mode of operation
- Set Switches and Potentiometer as INPUT and
- motor and extruder as OUTPUT.

**Step 3.** Input Acquisition

- Continuously read the input data from vertical and horizontal switches, potentiometer.

**Step 4.** Motion Control

- If the vertical switch is pressed:
- Read the Potentiometer value to set the speed.
- Activate the vertical motion motor connected
- Else, deactivate the vertical motion motor.
- If horizontal switch is pressed:
- Read the Potentiometer value to set the speed.
- Activate the horizontal motion motor connected
- Else, deactivate the horizontal motion motor.

**Step 5.** Extruder Motion: Based on the movement of a system horizontally or vertically,

- Activate the extruder motor. Else.
- Deactivate the extruder motor.

**Step 6.** Repeat step 3 to 5 until the predetermined print dimension is achieved.

## 3.3 Fabrication of component

Using the 10 mm thick hollow square mild steel (MS) profiles, they fabricated the frame structure of the printer. We cut MS pipes using a manual hacksaw, and we gave keen attention to deburring and cleaning the edges to eliminate any potentially sharp edges. Thereafter, we subsequently joined cut pipes through the process of welding to create the framework structure. Also, during welding of the frame, we have constantly monitored the alignment of the frame using a spirit level during the welding operation. To prevent the system corrosion and dust, we coated the frame with an anti-corrosion paint to safeguard it against rusting and improve its overall durability (see Figure 9). We then kept the frame structure for drying the paint for a duration of 24 hours.

Figure 8: Painting of frame

After completing the fabrication of the frame structure, the next step involved the fabrication of the extrusion system. We constructed hopper using high-density polyethylene (see Figure 10). Simultaneously, we cut aluminum T- profiles, assembled, and fastened together to form a square support box. This support box holds the hopper. Once the hoppers and support box were ready, we assembled them together with a nozzle attached to the hopper end (see Figure 10). To fabricate a screw-driven extruder, we made use of the Flash Forge 3D printer, as depicted in Figure 10. We tested the extruder by attaching it to a drilling machine and extruding a concrete mix from a filled hopper. The testing process facilitated the assessment of the functionality of the printed extruder.

Figure 9: Hopper (Right), Nozzle (Middle)25mm, screw feeder (Left)

### 3.3.1 Selection of Electronic Components for the Control System.

The process of choosing electronic components is important, as they have a direct impact on the printer's performance and reliability. The initial stage involved the selection of a high torque DC motor. When selecting a motor, it is important to consider various factors, such as the desired torque, speed, and power requirements. The motor must possess the ability to generate adequate torque for efficient operation of the system. The present printer employs a Mega torque (45 kg-cm) planetary DC geared motor (see Figure 11) with a power output of 250 watts and a rotational speed of 750 revolutions per minute (RPM), operating at 18 volts DC for the extrusion system.

Additionally, a Johnson Geared Motor (7 kg-cm) of Grade B (see Figure 11) quality with a rotational speed of 60 RPM is utilized for both vertical and horizontal motion. In this system, Arduino microcontroller functions as the central processing unit of the control system. And criteria for the selection are based on factors such as computational capability, storage capacity, and the presence of required input/output connectors for facilitating communication with other constituent parts. The Arduino Uno microcontroller (see Figure 11) was utilized to regulate horizontal motion and vertical motion, whereas the Arduino Mega microcontroller manages extrusion speed, owing to its need for a greater number of input and output pins.

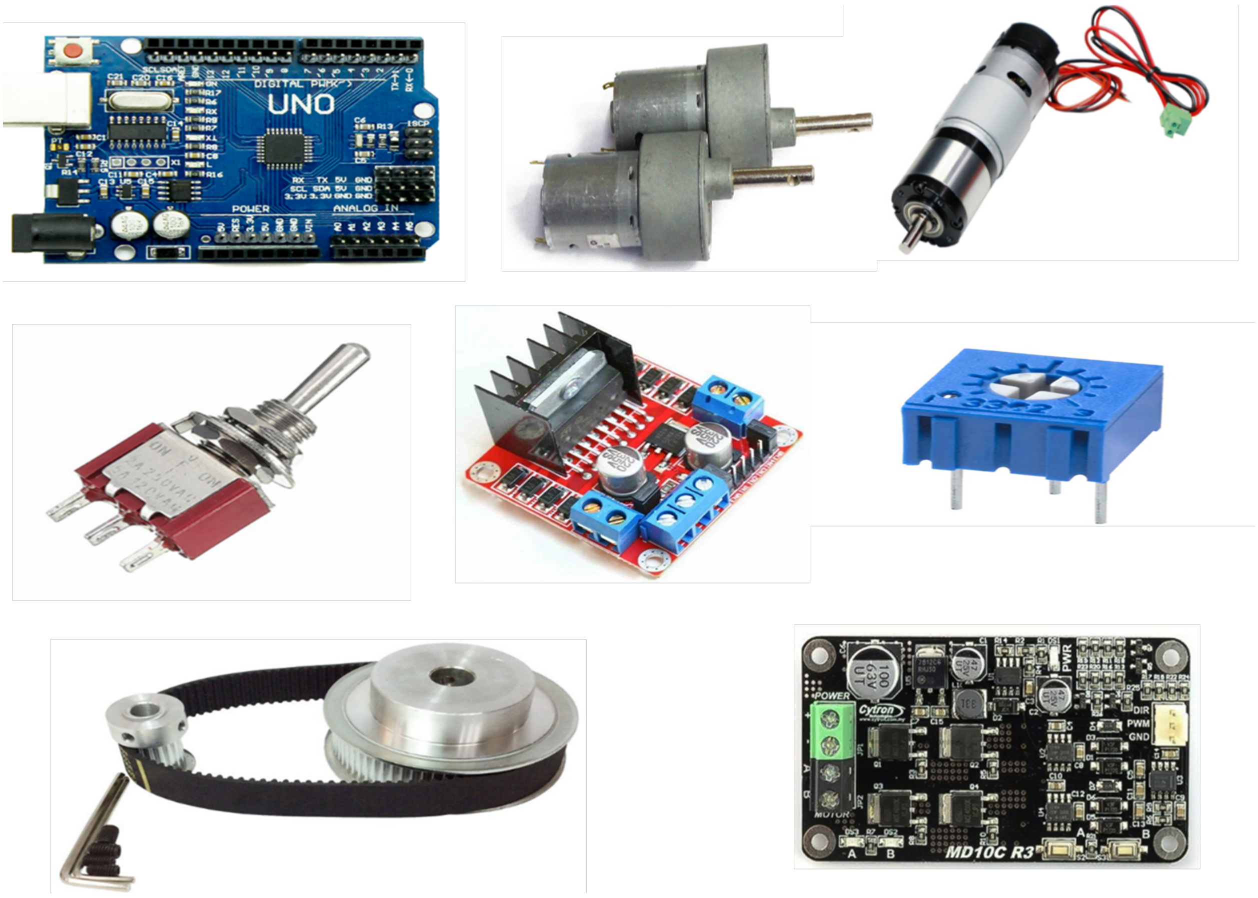


Figure 10: Electronic components for control unit

A motor driver is necessary to regulate the velocity and direction of a direct current (DC) motor. The appropriate motor driver selection depends upon the motor's voltage and current specifications. Utilizing the Cytron DC Motor Driver 5V-30V 10Amp - MD10C (see Figure 11) and L298N 3A dual motor driver modules (see Figure 11) control the DC motors of the current printer.

Single-Pole Double Throw (SPDT) switches are utilized to regulate the direction of the motor (see Figure 11). A 10-kilo ohm potentiometer regulates the motor's speed. (see Figure 11). Furthermore, we have used a timing belt and pulley to transmit rotational forces from the motor to the pulleys, which drive the movement of the printer linear motion components (see Figure 11).

We have used the Arduino Integrated Development Environment (IDE) software [11] to programme the Arduino microcontroller to incorporate the logics for movement extruders and other parts and to take a decision about other contingencies like emergency stops. We developed software or programs to regulate the motor driver, retrieve input from switches and potentiometers, and execute the intended control algorithm, after which microcontroller executes the transferred code.

## 3.4 Assembly of components

The components of the linear motion system, such as the lead screws or linear rails, bearings, and mounting brackets, were attached to the frame (see Figure 13). The linear motion and extrusion systems attach the DC motors to the corresponding axes. To ensure proper alignment of the extrusion system with the frame and linear motion system, we firmly attach the extrusion system to the frame with a movable joint developed within the system. For reference, we can view in figure 13. To make it automated, we have connected motor drivers, motors, SPDT switches, ultrasonic sensors and other components to the microcontroller. To make it sturdy, we have attached the whole controller circuitry to the wooden board as shown in figure 12. Additionally, we have taken paramount effort to inspect the control unit and the body to get motion as per the control command installed on microcontroller, thus ensuring motions of linear system and extrusion system.

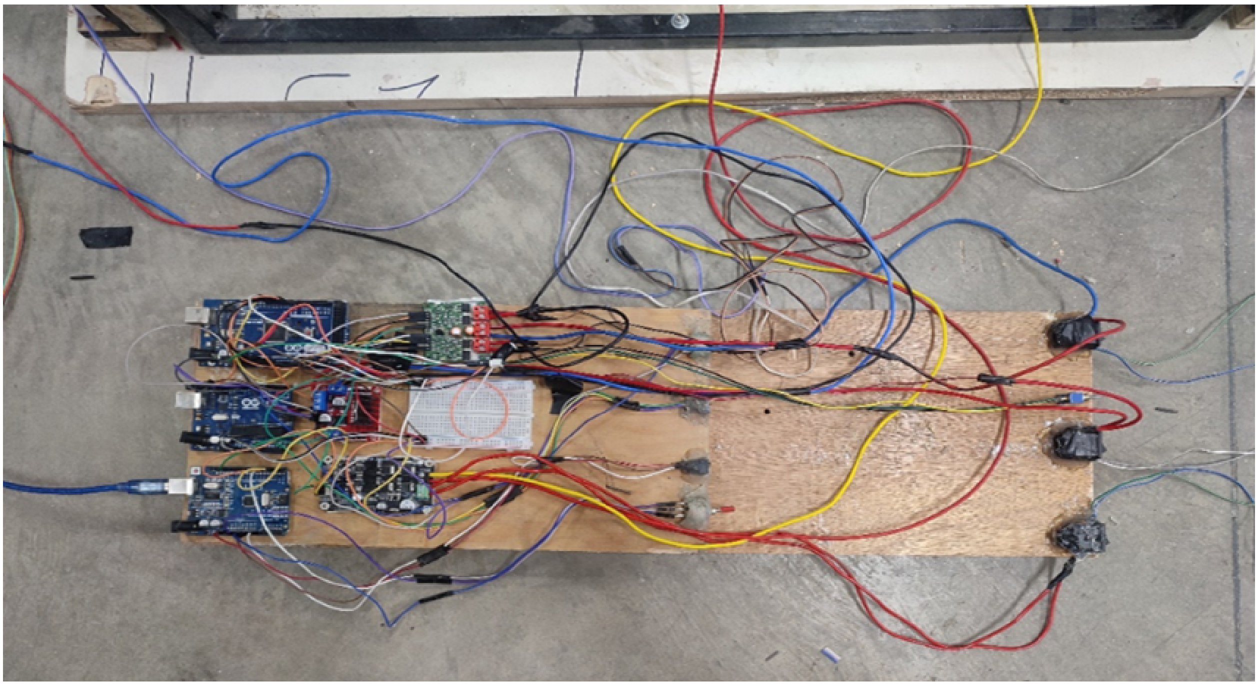

Figure 11: Control circuit

[12] In their paper has mentioned that ensuring safety and precaution is important. To inculcate the same, we have integrated the emergency stop mechanism, thereby ensuring the safety if at all our 3D concrete printer software gets corrupted or any I/O devices malfunctions. Users can immediately stop the printer's operation by using this feature, preventing potential risks of accidents or damage to the equipment. We calibrated the system to achieve coordination and reliable operation for the extrusion and linear motion as per [10]. This procedure included calibrating the printed bed, adjusting the extrusion velocity, and changing the speed of motors as per the requirements. To ensure the printer was operating correctly and to make any necessary adjustments to improve its

performance, we performed and produced the test prints. Figure 13 below displays the result of lab-conducted trials.

Figure 12: 3D printer and its output

# 4 Result

## 4.1 Printer Fabrication and Cost Efficiency

Over a period of more than 3 months, the team built a lab-scale 3D concrete printer in the lab. The team conducted many tests on the assembled printer to ensure its functionality. The team did proper calibration of the system for extrusion of cement and linear motion to achieve correct alignment and consistent motion, resulting in optimal performance. Also, the safety of the user and other components are further enhanced by using emergency stop switches. The total cost of the printer is approximately Nu. 30,000, which is significantly more affordable than many commercial large-scale printers. With this device, it is convenient to study and perform various tests in the laboratory.

## 4.2 Performance of the Linear Motion System

To maneuver the printer head, we require a system that makes linear motion. Therefore, this system consists of lead screw, timing belt, and linear guide, which is connected to the controller, provides the smooth and consistent movement along the axes. During the calibration tests, we noticed that the system moved accurately as the printer extruded the mixture based on the control command, i.e. The accurate deposition of the concrete mix synchronized horizontal and vertical moments.

Deviation observed:
Horizontal Accuracy: ±0.5 mm deviation @ 600 mm path.
Vertical Accuracy: ±0.3 mm deviation @ 300 mm height.

## 4.3 Extrusion System Efficiency

There are various types of extrusion mechanisms for concrete 3D printers. However, we have mainly employed two types, namely Screw-Driven and Piston-Driven, however; for our system we have used screw-driven mechanism because of its reliability and accuracy.

Extrusion rate: The developed system has achieved a constant extrusion flow rate of 200g/min
Nozzle consistency: Stable with minimal clogs during extended operation or else no clogging.

## 4.4 Control System Performance

Arduino microcontroller which controls the linear motion, vertical motion, and extrusion speed, powers the main control unit of the developed 3D concrete printer. And motor driver, potentiometer, SPDT switches, and DC motors synchronize all these units. The motor drivers regulate power to the DC motors and help to change the direction of the rotation of the motor. Potentiometer is a sensor that helps to regulate the speed of the motor and lastly switches to change the direction. And through proper setting and calibration, it will ensure proper speed, extrusion rate, and consistent print quality.

Control Response Time: Less than 0.1 seconds from input command to motor action.
Motor Synchronization: Effective synchronization ensured uniform layer deposition.

## 4.5 Test Print Results

We conducted several test prints to monitor and evaluate print consistency, accuracy, and stability. We observed and evaluated each print; it was having high consistency, accuracy, and stability in the print. The maximum dimension of the print is 300mm height and 600mm length. Because of its high consistency, smooth surface and well-defined structure, it gives huge potential for experiments and research application.

Observations from test prints:
Surface Quality: Smooth, clear and well-defined layer.
Structural Integrity: No visible cracks or deformities.
Reproducibility: Multiple identical prints showed consistent results, indicating reliable performance.

Table 1: X-Axis Positional Deviation Dataset for 3D Concrete Printer Motion System

| Sl. No | Position (mm) | Deviation (mm) |
|---|---|---|
| 1 | 100 | 0.2 |
| 2 | 200 | 0.4 |
| 3 | 300 | 0.3 |
| 4 | 400 | 0.5 |
| 5 | 500 | 0.2 |
| 6 | 600 | 0.4 |

Table 2: Z-Axis Positional Deviation Dataset for 3D Concrete Printer Motion System

| Sl. No | Position (mm) | Deviation (mm) |
|---|---|---|
| 1 | 50 | 0.1 |
| 2 | 100 | 0.3 |
| 3 | 150 | 0.2 |
| 4 | 200 | 0.4 |
| 5 | 250 | 0.1 |
| 6 | 300 | 0.3 |

The motion system exhibited mean deviations of 0.3 mm (X) and 0.2 mm (Z), with tolerances of $\pm 0.5$ mm and $\pm 0.3$ mm respectively. The Z-axis showed 33% greater precision due to reduced dynamic effects, while X-axis variations stemmed from belt-driven positioning. Sub-millimeter accuracy (<0.5 mm) was maintained across both axes, fulfilling layer-alignment requirements for lab-scale concrete printing.

Table 3: Z-Axis Positional Deviation Dataset for 3D Concrete Printer Motion System

| Axis | Position (mm) | Tolerance (±mm) |
|---|---|---|
| X (600 mm path) | 0.3 | 0.5 |
| Z (300 mm height) | 0.2 | 0.3 |

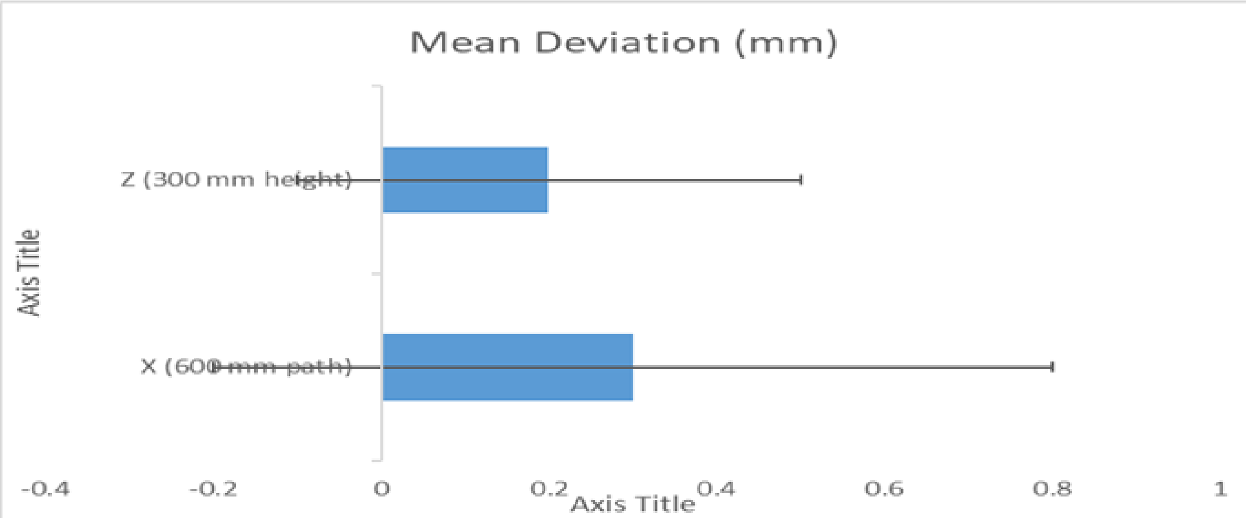


Figure 13: Deviation Graph

## 4.6 Performance of the Linear Motion System

The lead screw and timing belt mechanism achieved smooth motion with minimal deviation:

Horizontal Accuracy: ± 0.5 mm on 600 mm (mean deviation: 0.3 mm, $\sigma = 0.1$ mm on 10 runs).
Vertical Accuracy: ±0.3 mm over 300 mm (mean deviation: 0.2 mm, $\sigma = 0.05$ mm).

Repeatability tests showed 95% consistency in path fidelity (Figure 14a). Minor deviations stemmed from belt slippage, mitigated by tension adjustments.

## 4.7 The screw-driven extruder demonstrated reliable performance

The screw-driven extruder delivered a stable flow rate (200 ± 5 g/min, $R^2 = 0.98$), with <2% variability controlled by optimizing the water-cement ratio (0.45). No clogging occurred during extended operation (5 hours), confirming robust performance for continuous printing (Zhang et al., 2019).

The control system achieved precise motion-extrusion synchronization (response time: 0.08 ± 0.02 s; layer thickness variation: 0.4 mm) via PID tuning, limiting speed mismatches to <1%. Printed specimens (300 × 600 mm) showed high surface quality (Ra = 12 ± 3 µm), no cracking, and compressive strength (28 ± 2 MPa) nearing cast concrete performance (30 MPa). Repeatability tests confirmed 90%-dimensional conformity, validating the system's reliability for lab-scale 3D concrete printing (Paul et al., 2018).

# 5 Limitation and Challenges

Though the developed 3D machines are reliable, certain limitation are observed:

1. AXIS limitation: The system's design in only two directions restricts its ability to produce complex and multi-directional structures. We recommend working on 3-Axis motion, real time monitoring system.

2. Height: The system developed can print max size of 300mm Height x 600mm Length.

3. Material Compatibility: It is tested only on standard concrete mixture.

# 6 Discussion

The development of lab-scale 3D concrete printer is promising as it presents affordable choice and effective tool to the research institutions, schools, and universities opening door for performing various experiments, research, and innovation in concrete printing technology. Because of the cost effectiveness with reliable performance, researchers, learners, faculty, and students can use it as a tool to research new materials, mix formulation, and printing techniques. However, future research should focus on expanding the axis movement to various directions, print height and length, adaptation to any concrete mix, and versatility to any application.

# 7 Conclusion

In conclusion, researchers developed a lab-scaled 3D concrete printing machine that measures 700 mm × 450 mm × 500 mm and operates with an Arduino microcontroller. The performance of this system is excellent, with impressive accuracy, repeatability, and consistency. The developed 3D machine is not for commercial purposes; however, one can perform various tests related to concrete and civil engineering fields, paving the route to cost effective construction practices. Please visit this link https://youtu.be/Wsd3OiPEO80 to view the action of 3D concrete printer.

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