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ORIGINAL ARTICLE

Analysis and Design of Control System for Desktop Size Concrete 3D Printer

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ABSTRACT – Concrete, in construction, structural material consisting of a hard, chemically inert particulate substance, known as aggregate (usually sand and gravel), that is bonded together by cement and water. Concrete is the world's second-most-used substance after water, and it is also the most extensively used building material. 3D printer has become a prominent method of additive manufacturing with its rapid prototyping capabilities and is able to reduce the time and cost of any complex manufacturing process. This paper describes work the process of 3D design, analysis, manufacturing and testing of a concrete 3D printer to explore the plausibility and sustainability of concrete 3D printing to replace the conventional construction method. A desktop size concrete 3D printer concrete 3D printer with 0.5×0.5×0.5 m print volume is developed for lab testing, which utilizes computer-based control system to layer-by- layer construct physical objects is developed to study the usability of the printer as well as the feasibility of replacing the conventional construction method. The development of the 3D printer is divided into two parts, Part A: Mechanical and Part B: Control System. Concrete 3D printing technology is not widely known and is expensive to be deployed. Thus, greater research and development of the technology is required to evolve into a more mature study that is accessible to consumers. The project output envisions as to lay a foundation for extended studies and applications of 3D printed concrete in Malaysia.

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INTRODUCTION

The goal of this study is to look at the possibilities of using a concrete 3D printer in a scientific environment as well as for commercial purposes. This project involves the construction of a lab-scale 3D printer to explore the science and material and its behaviour, as well as a mechanical system to manipulate the motion of the material dispenser. A gantry system, screw-driven with a print volume of 0.5 × 0.5 × 0.5 m is proposed for the 3D printer. An external control system using commercial software will be used to control the three-dimensional movement and printing sequence. To produce a smooth extrusion process, the printing system is a vital component of an extrusion-based 3D printer, and it must contain the subsequent features [1].

RELATED WORK

In recent decades, researchers from all over the world have been drawn to additive manufacturing, sometimes known as 3D printing. It is a method of converting 3D digital drawings into an object. 3DP, which has previously been employed in industrial design and production, now has a new use in medical, food, and construction. However, due to technical restrictions, 3DP is still in its early stages, with limited utility as the scale of the item grows exponentially, as does the difficulty of extruding complex material types. Additional research is needed within the construction industry to develop precise mechanical control, acceptable dispensed materials, and the mechanism that utilizes those materials. In the construction sector, technical constraints include rising unstructured building production costs and time-consuming construction methods. This would bring forth a unique era of construction, empowering users to develop complex concrete structures by utilizing production and manufacturing methods. Additionally, by avoiding duplicate production procedures, building time and cost might be greatly lowered [2].

Concrete is made from stone fragments mixed with concrete mix. Concrete is a frequently used building material on the globe due to its strength, durability, and inexpensive. Chemical admixtures can be added to the concrete mix to affect its properties. There are many distinct types of admixtures. The kind of cement, the amount of water used, and the mixing time all have an impact on the capabilities of the combinations [3]

Concrete 3D printing is a computerized and digitized method of construction that builds a structure from the ground up, layer by layer, using cement-based components [2], because it does not require formwork. Compared to traditional construction technologies, 3DPC may reduce complexity and maximize productivity. As a result, 3DPC technology offers a wide range of architectural applications. The evolution of printing machines, the advancement of cement-based substances, and the design of the printing method are all part of the 3DPC research [1].

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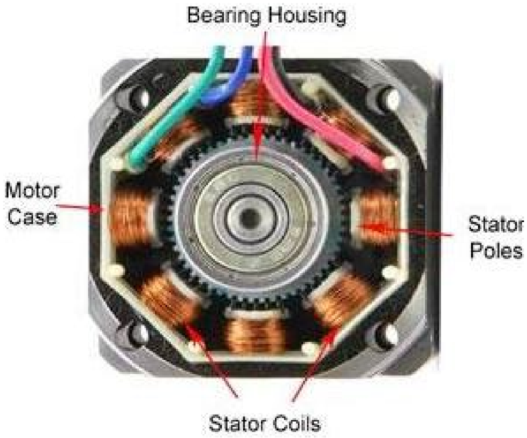
PART A: MECHANICAL

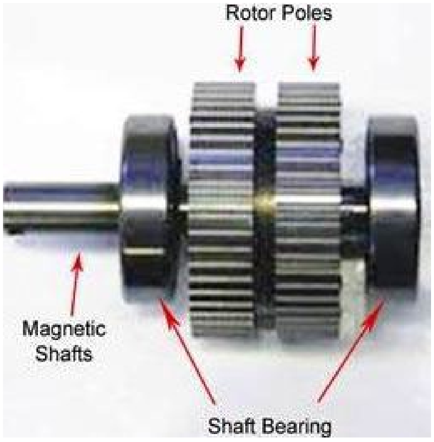
Stepper Motor

Stepper motors are a type of direct current motor with a number of coils that allows it to move in small steps. Stages are formed by grouping these coils together. By sequentially engaging each pulse phase, the motor will revolve single step at a time [4]. When these motions are controlled by a computer, they may be extremely precise. At low speeds, they're perfect for positioning, speed control, and torque.

They have certain advantages, but they also have some disadvantages. To begin, "Stepper motor current consumption is independent of load." A motor uses a substantial quantity of power even when it is not in operation. They may overheat as a result of this. As stepper motors spin faster, they lose torque as well. While certain stepper motors are optimized towards high-speed torque, their efficiency and performance depend on the stepper drivers they are partnered with. Stepper motors, in contrast to servo motors, are unable to give feedback on their location. It is vital to evaluate these constraints prior to incorporating them into a design.

Stepper motors are available in a variety of forms and sizes, as well as varied gearing ratios, wire configurations, step counts, and shaft types. Selecting the appropriate stepper motor for a particular application is highly reliant on those features.





(a) (b)

Figure 1 (a) Cross Sectional View of a Stepper Motor **(b)** Rotor of a Stepper Motor

Power Supply

The motors, control boards, and extruder of a 3D printer all require electricity to operate. The most common source of electrical power is typically from a standard wall outlet. The 3D printer, on the other hand, cannot be directly powered by the 220-240V AC power. The components require lower-voltage DC electricity to function, and the outlet's high voltage would quickly burn them out. As a result, a switching power supply unit (PSU) is required to convert the AC supply of 220-240V to the DC voltage of 12-24 V required by the printer. There are two types of power supply circuits: linear power supply and switch-mode power supply. To convert AC to DC, both systems rely on the same fundamental components: a transformer to reduce AC voltage, a rectifier diode, a filter capacitor, and a voltage regulator. The transformer receives a high-frequency AC signal from the switching power supply, which decreases power loss and heat output. Because it has less power loss and a smaller transformer, the switch mode power supply is more advanced than the linear power supply. It also allows it to provide more power at a lower cost and weight. The most popular form of power source used in 3D printers is a switch-mode power supply.

A variety of power sources may be used to power a 3D printer. Some power supplies are tailored to but not limited to CNC machines and 3D printers alike. These power sources are exceedingly reliable and well-designed, but they are also extremely expensive and uncommon. Other switch-mode power sources with no specific function are also available; the power source you select is mostly influenced by the printer's power requirements. To figure out how much power the printer consumes, the DC voltage is multiplied by the total of the component's amperage. At the very least, the power source should be capable of delivering all the printer's components with the electricity they require. Although the methods differ depending on the type of power supply utilised, the process of installing the power supply is simple and straightforward.

When interfacing with the power supply, adequate safety precautions must be taken regardless of how it is set up. If safety precautions are not followed, mains electricity can be harmful and cause damage. Make sure the power cord is disconnected from the wall outlet before working on the PSU. Wait five to ten minutes after removing the power source before working on it to ensure that the internal capacitors have totally drained. To limit the danger of fire, use components that are rated for power being applied. Finally, ensure sure any electrical connections are properly insulated and grounded while working with them. To avoid harm, you must follow these safety precautions

Endstop

Endstops are the components that ensure that when the print head reaches the end of the 3D printer's rail system, it stops travelling in either direction. Depending on the application, this type of sensing can be accomplished mechanically, magnetically, or optically. Optical or mechanical switches are commonly used in 3D printers, such as the one depicted in this study, since they are more precise and less expensive than magnetic switches.

Optical endstops measure the distance between themselves and the objects immediately in the line of their created light using infrared or other forms of electromagnetic radiation, as well as an optical sensor. These switches are advantageous in that they do not require any moving parts. Optical endstops can last far longer than mechanical endstops before they need to be serviced. Unfortunately, because they employ a fast-moving medium to measure small distances, they are typically found to be less exact and more difficult to calibrate.

Mechanical endstops have the ability to produce exceedingly precise and reproducible results. This is due to the fact that, like a light switch, to allow an electron to flow, they rely on the physical interaction of two things, but with much lower pressures and movements necessary to alert the control board. Because mechanical endstops can wear down over time, they must be maintained on a regular basis. Mechanical switches, on the other hand, are inexpensive and may last for over 100,000 cycles. Even though a printer is used often, its replacement is infrequent.

Extruder

Due to the nature of concrete, traditional plastic extrusion is incompatible and is unable to extrude material such as concrete. Thus, an extruder that utilises a screw auger is required to extrude concrete. [5]

Process Planning

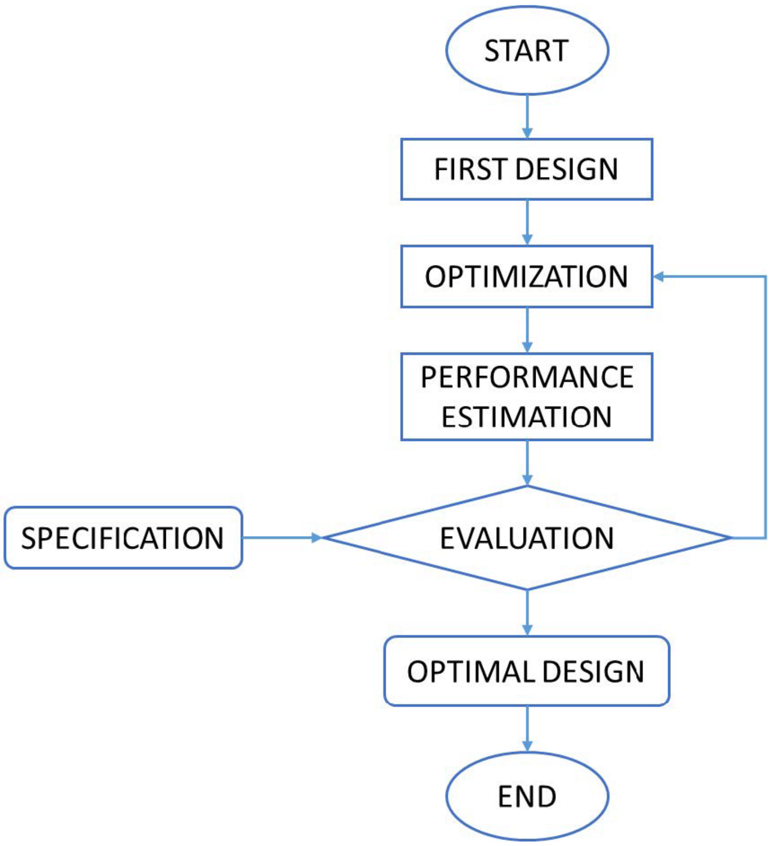


Figure 2 Flowchart of Concrete 3D Printer Development

PART B: CONTROL SYSTEM

Open-Loop & Closed-Loop

Mechanical systems can be driven in an open-loop or closed-loop approach from a control standpoint. Typically, conventional electronics are driven open loop by simple input signals. When these input signals grow more complicated as a result being generated from the dynamics of the system, we refer to these control approaches as pre-shaped open loop driving. The next step toward increasing precision and response time is to include feedback, e.g., closed-loop control [6].

Consumer 3D printers are open loop operated, which implies that the machine does not provide feedback on its present operational condition. Due to this lack of direct supervision, mistakes and misprints might occur because of external or internal sources. For instance, vibrations generated by the machine or other sources might cause the item to detach, resulting in a failure print. In an error situation, the 3D printer is occupied for the duration of the 3D print, but the required object is not produced [7].

Control Board

A microcontroller and a circuit board make up the Control board. These components can be integrated into a single board or can be joined to each other as independent modules. Both function in tandem to regulate and distribute electricity to all of the following components. The printer's control board are referred to as the brains and central nervous system. Nothing else would operate without it.

Despite the fact that there are several control boards on the market, they all fundamentally do the same thing. Their key distinctions are in terms of features, capabilities, price, and dependability.

Most control board supports up to four, five, or six stepper motor drivers, but are not designed to handle more than that. The number of motors that can drive the axes is limited as a result. The SKR PRO V1.2 board and the BTT OCTOPUS board are the two contestants in the study. Both include features that will help the printer meet the standards.

There exist six drivers and the drivers can be interchangeable depending on the requirements and if the drivers were to fail it would be easy to swap which makes it more serviceable than a two-in-one combination. However, the board is now discontinued and is unavailable for purchase locally. This is a major setback as the parts must not only serviceable but also be accessible locally for ease of sourcing the components.

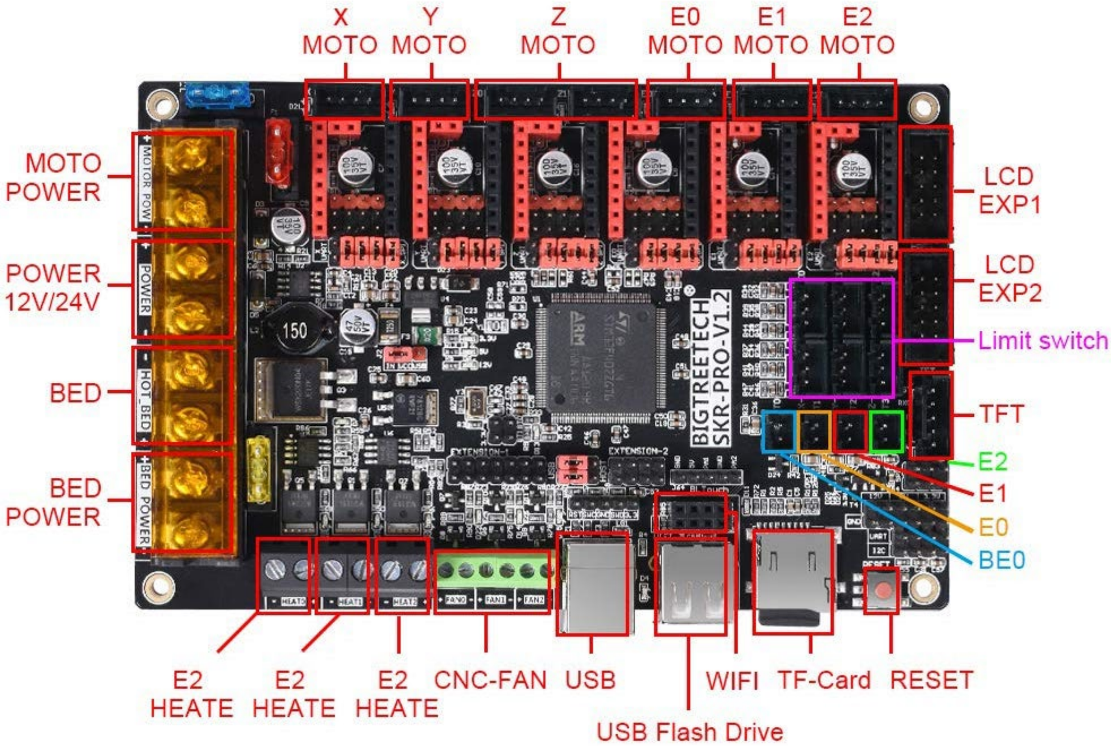


Figure 3 SKR PRO 1.2

For this printer, the BTT OCTOPUS board was chosen as the best alternative. Eight stepper motor drivers can be used on the board. Furthermore, the TMC5160 stepper drivers used on this board are strong and reliable to drive the Nema 23 motors, with a 2.5-amp limit. This would allow us to connect several stepper motors to each their respective driver, which would be handy if we wanted to add more motors to the axis for more rigidity and stability when printing concrete.

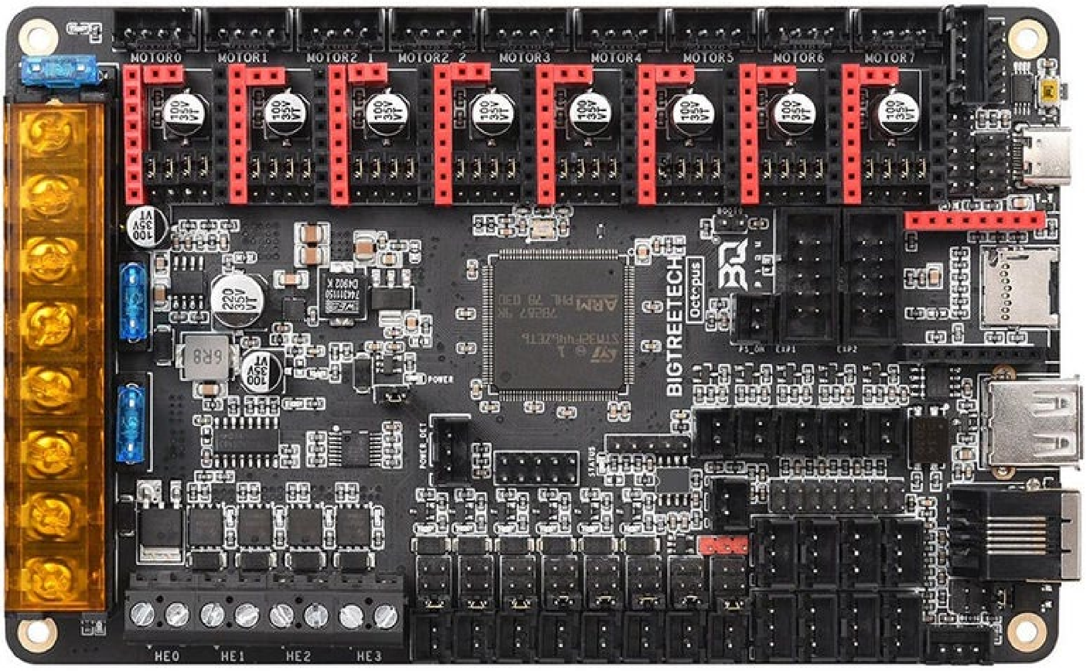


Figure 4 BTT Octopus

Drivers

To produce a high-quality print, the stepper motors of a 3D printer must be precisely managed. One of the components responsible for this function is the stepper motor driver. A stepper motor driver is a chip that controls the flow of power to a stepper motor, allowing it to move accurately. The microcontroller sends a signal to the drivers informing them of the stepper motor's required travel distance. Because the CPU does not have enough power to drive the stepper motor, it does not supply power directly to the motor. With the aid of a driver, the CPU can control the speed and position of the stepper motors while powering them directly from the power supply. The most popular type of motor driver is an integrated circuit (ICs). Motor drivers act as current amplifiers in electronics because they receive a little signal from the controller and output the same signal at a higher current. This technique allows motors to run at high currents while avoiding damage to the control board.

Stepper motors are rotated in steps that represent a fraction of the motor's revolution using stepper motor drivers. The stepper motor determines the number of steps; the more steps, the more precisely the motor may be regulated. The ability to deliver fractional steps is another feature of stepper motor drivers. The drivers for a 3D printer generally utilise 16 microsteps, or 1/16th of a step. The stepper motor moves more smoothly when fractional steps are used, and the placement of the motor is much easier to manage. One element to consider when choosing stepper motor drivers is the amount of microsteps. The current limit of the stepper motor driver is another element to consider. The driver's current limit should be higher than the stepper motor's maximum current consumption with an appropriate factor of safety. When the stepper motor driver's current limit is exceeded, the device is at risk of being burnt out.

Firmware

The programming that runs on the control board of a 3D printer is known as firmware. The firmware's main task is to decode G-code signals and control the movement of the stepper motors based on them. The G-code is a set of movement commands created by a slicer programme based on the CAD model and followed by the printer to make the finished object. These commands are transferred from a computer to the control board, where the firmware decodes the code and sends signals to the stepper motor drivers, who then move the print head as needed to finish the object. To work properly, each 3D printer's firmware must be configured independently. There are several firmware alternatives for use in a 3D printer. Some of the most prevalent forms of firmware found in 3D printers are listed in Table 2.

Marlin firmware was chosen because of its popularity and widespread support. Sprinter and Sailfish are two popular firmware choices. Teacup is a user-friendly firmware for beginners. Each firmware has its own set of features and may be used with a wide range of control boards. The firmware for the printer should be selected based on the functionality required, compatibility with the control board used, and the degree of support supplied.

EXPERIMENTAL RESULTS

This experiment investigates the performance of the 3D printer virtually by utilising Solidworks to visualise the FEA on the 3D printer. The most mechanically critical part of the printer or any structure is the frame and thus the simulation will be done accordingly. The distributed load simulated is 100N which is approximately 10kg on the Z axis (top view) of the printer.

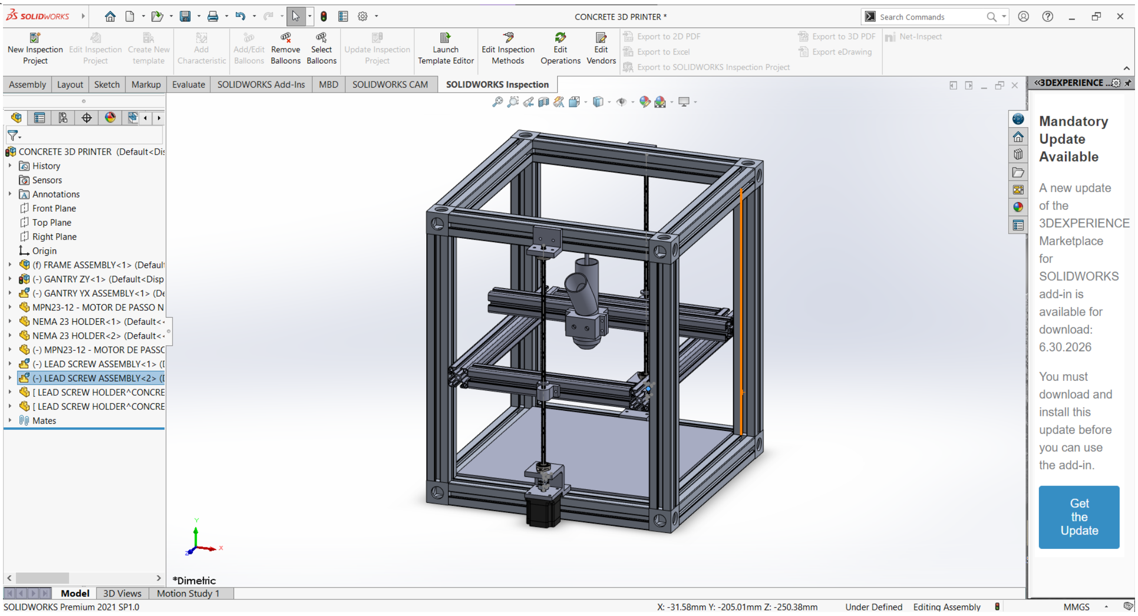


Figure 5 Concrete 3D Printer Design

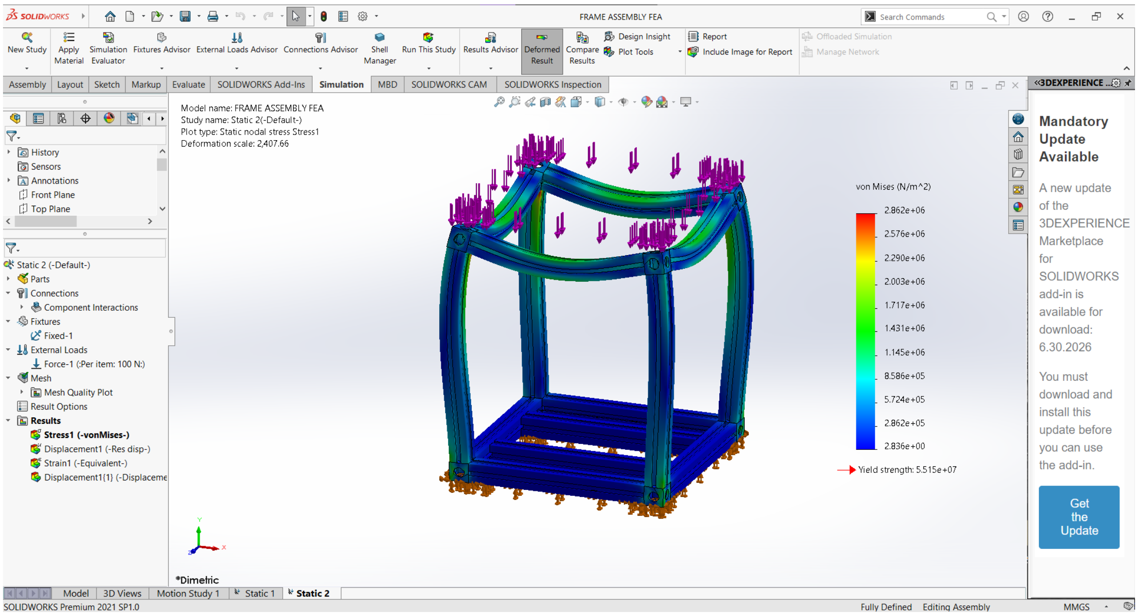


Figure 6 Stress Analysis

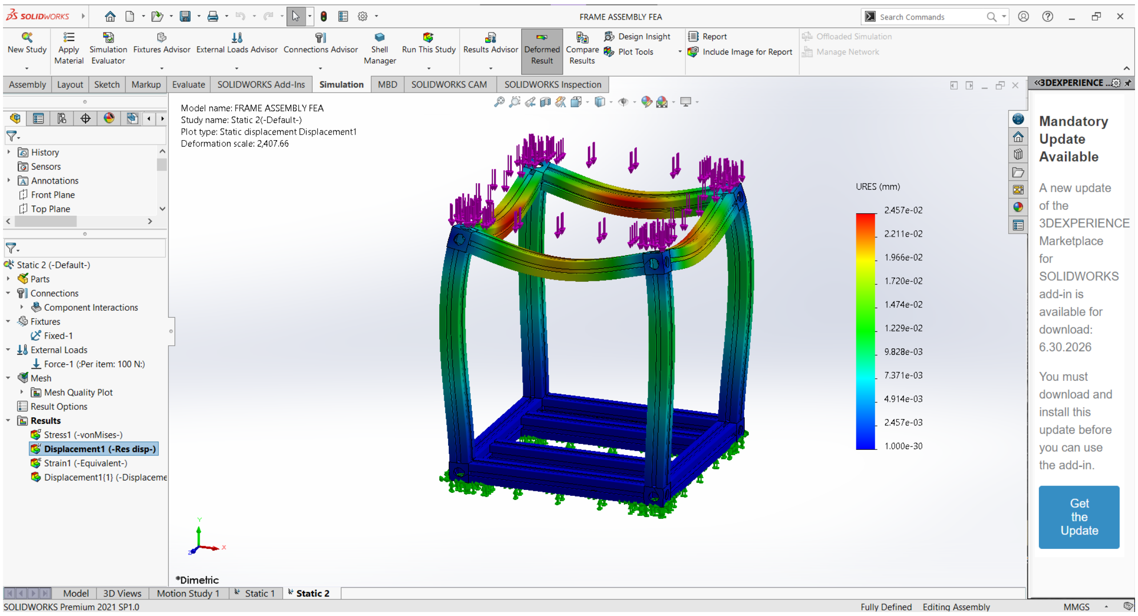


Figure 7 Displacement Analysis

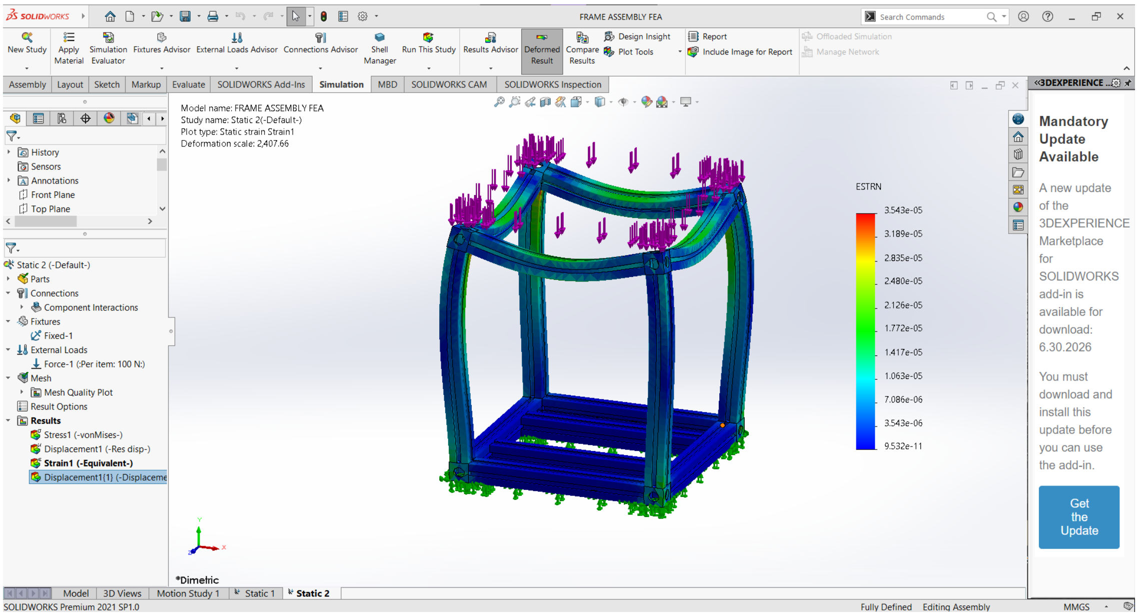


Figure 8 Strain Analysis

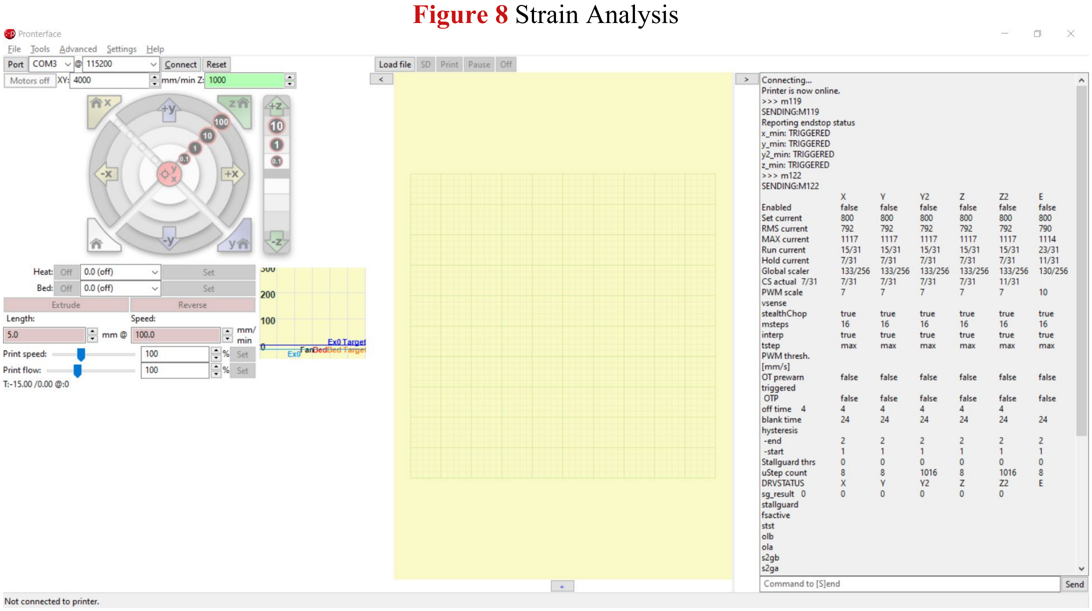


Figure 2 Pronterface Testing

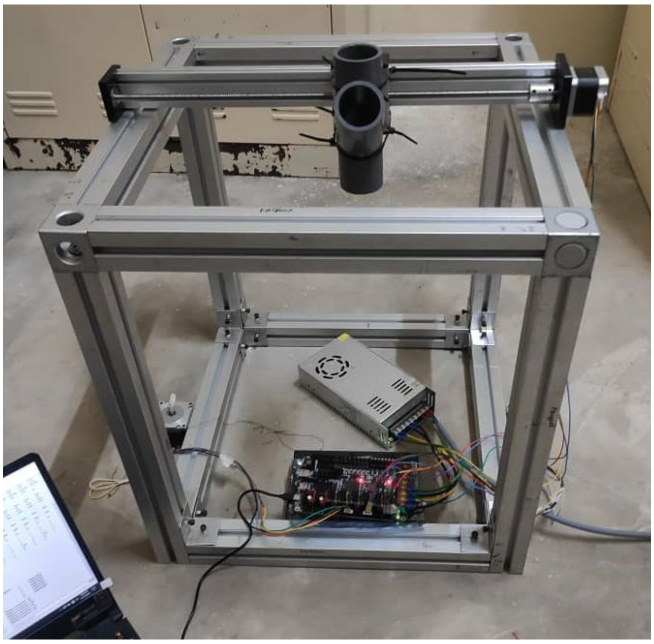


Figure 10 Concrete 3D Printer Assembly & Testing

CONCLUSION

This paper reports the first attempt to enhance the exploration of concrete 3D printer and its viability in future use and study. In addition, this research hopes to develop and enhance the understanding of Additive Manufacturing (AM) process mainly 3D printing concrete and serve as a foundation for future research and development of this technology.

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