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A Review on Recent Studies on Concrete 3D Printer: Issues and Recommendations

[1] Husam A.Salah*, [1] Azrul A.Mutalib*, [1] Iskandar Bin Yahya
[1] Department of Civil Engineering, Faculty of Engineering and build environment, Universiti Kebangsaan Malaysia (UKM), Bangi 43600, Malaysia.
[1] p97967@ siswa.ukm.edu.my,[1] azrulaam@ukm.edu.my *,

Abstract— *Recently, 3DCP has received a lot of attention due to the advantage of reducing labour, formwork, and saving costs. This makes the 3DCP very popular for many researchers around the globe. Different studies on 3DCP have developed various shapes, sizes, and functions, with the objective of building the best performing machine in this technology field. As a result, there is a lack of description of the 3DCP component for the new researchers. Therefore, this paper has reviewed the recent 3DCP sizes, nozzle shapes, and parts for building a 3DCP machine. Further investigation must be carried out to improve the concrete filaments, the 3DCP design, and the machine's nozzle. This review of the recent advancements of this 3DCP will contribute to developing high-performance 3DCP.*

Index Terms—3D concrete printer; Building a 3D concrete printer; Type of 3D concrete printer; Additive Manufacturing; Process of 3D concrete printer.

I. INTRODUCTION

In recent decades, 3-dimensional concrete printing (3DCP) has highly impacted construction fields in its various applications, building, bridges and aerospace colonization buildings. Generally, the history of 3DP is back to 1984, when Charles Hull invented the technology. Following that, he started to call this method stereolithography. In the 1990s, the technology of 3D Printing had increased its popularity, which led to the introduction of other related technologies, such as selective laser sintering and Fused deposition moulding. During that decade, the technology name changed from stereolithography to 3DP Technology by MIT institute of technology in 1993. Generally, 3DP has been widely applied in different industries, including construction, prototyping and biomechanical. The uptake of 3DCP in the construction industry, in particular, was very slow and limited despite the advantages of less waste, freedom of design and automation [1]. New applications are emerging as novel materials, and additive manufacturing (AM) methods are continuously being developed. One of the main drivers for this technology to become more accessible is the expiry of earlier patents, which has given manufacturers the ability to develop new 3DCP devices. Recent developments have reduced the cost of 3DCPs, thereby expanding their applications in schools, homes, libraries, and laboratories. Initially, 3DCP has been extensively used by architects and designers to produce aesthetic and functional prototypes due to its rapid and cost-effective prototyping capability. The use of 3DP has minimized the additional expenses that are incurred in the process of developing a product. However, it is only in the past few years that 3DCP has been fully utilized in various industries, from prototypes to products [1]. According to Assoil et al.[2], fields of application of layer-by-layer manufacturing techniques are extending, that includes aesthetics building and functional prototypes to the production of tools and moulds for technological prototypes or pre-series. In practical, since 29 March 2014 when work began on the world’s first 3DCP house, large-scale 3DCP, as mega-techniques, is becoming more attractive[2].

In 2017, Gokhale et al. [3] presented a brief history of the main advantages and limitations of 3DP. Also, the author depicted the 3DP, the processes used in 3DP and the properties of the 3DP materials. The next year Mahdikhani.et.al.,2018 [4] review the subsequent nanotechnology used in the field of constructions Civil Engineering. In the same year, a benchmark for future development of 3D printing was developed, including an overview and a survey on the advantages and drawbacks [1]. R. Wolfs et al. in 2019 [5] compare the results from many research projects. Thus, to clarify the process parameters' duration time, it cannot be identified separately for the process parameters and the materials used in the research. To point it is required for the characterization of

3DCP and test methods to be standardized as highlighted in [6],[7]. T. Salet et al. [8] studied the structural applications for both the material and the structure scale. The research's importance is finding the best elasticity and tensile strength. The research has extended its focus to explore fiber reinforcement and in-printing embedded reinforcement. It is in the early stage to find the best results for the mixture. The research needed a substantial numerical and trailed orderly for the 3DCP in order to improve the concrete mixture and the movement control of the machine.

Based on the research gap, a review of the recent 3DCP: issues and recommendations are yet to be conducted. This paper, therefore, provides a recent literature review that describes the 3DCP process, and its compounds, types of concrete, standards, challenges, and recommendations. The structure of this paper is as follows. Section 2 presents the overall of the 3DCP and the analysis of the compounds in the system. Section 3 illustrates the various materials used in the 3DCP, while section 4 shows the specification and standards of different 3DCPs. Section 5 provides some current challenges and recommendations for future research prospects in this field. Despite not all the issues and challenges in 3DCP can be immediately addressed, recommendations are provided on the current issues which can be potentially resolved. This review will provide clear and accessible guidance on a complete 3DCP and its materials and a thorough literature study of 3DCP together with the development, performance, improvement, and current issues with concrete recommendations.

Any 3DCP must have a process to achieve the highest quality of the printing design. Figure 1 shows 3DCP, the process used for construction. The process has two flows. The first one start with 3D modelling and ends with printing. This test is for the software work, which will be used in any 3D modelling software such as AutoCAD, SketchUp, etc. The drawing will be exported to STL file. Then the files will be sliced into dozens of layers depending on the scale of the design. Lastly, the 3DCP will build the 3D model after following the previous process. The second process is the materials. This process will start with supplying the ready concrete mix design with a grade designed by the engineering specialist. The second step will be mixing and pumping the concrete using a high-pressure pump. The third step will be attaching a flexible hose from one end to the pump, and the other end will be attached to the nozzle. The fourth step is the nozzle, which has many shapes and types depending on the purpose and designs the project requires. Figure 1 will illustrate the 3D concrete printing process used for construction.

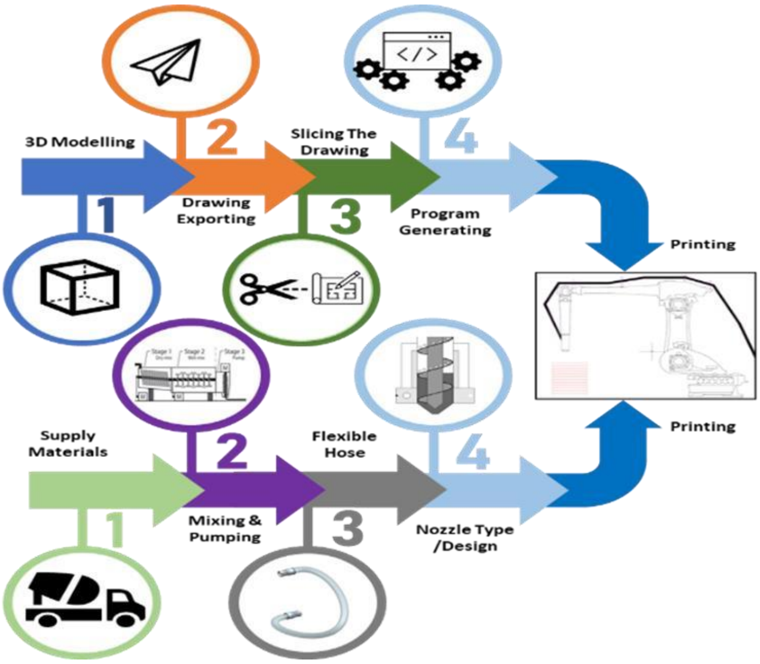

Fig. 1: 3D concrete printing process used for construction.

II. STATISTICS ACCORDING TO SCIENCE DIRECT

Fig. 9 illustrates the number of research articles and review articles published on science direct official website for the past 13 years. The statistics illustrate the increase in interest in 3DCP for over a decade, and researchers are developing more suitable concrete mix designs for 3DCP as it might be the next generation for the construction industries.

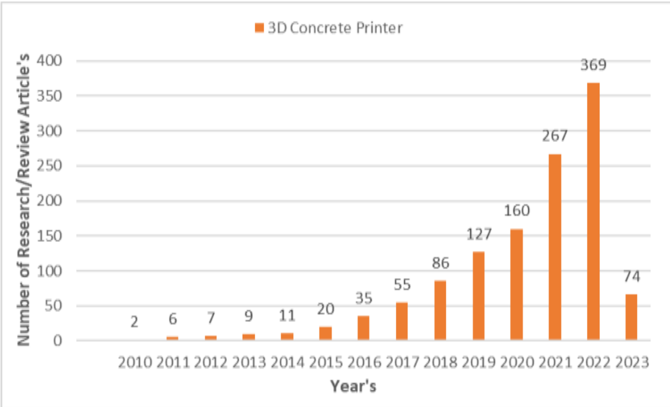

Fig. 2: Number of articles with the words graphene and concrete mentioned according to Science Direct[9].

III. 3D CONCRETE PRINTER SYSTEM OVERVIEW

A. Component 1 "Frame and design".

Concrete printing, 3D printing techniques, additive manufacturing, contour crafting, and D-shape are all similar terms used to describe 3D printing. However, the described terms has their own process the develop and manufacture new materials in which each technique has its own distinct advantages [10]. The process for each head mounting will have some differences to deliver and extrude filament, such as, robotic arm, crane mounted, or frame. A crane mounted device to extrude concrete for in situ application called contour crafting after getting some developments. Printing concrete and D-shape are both gantry-based in situ system. However, these systems continue to have more modifications, thus, both processes will not be used as in situ [10]. When the object is built from the bottom toward the top is considered under 3DCP, which has overhang challenge as the buildability require a standalone support to carry the load from the building. To handle the overhangs issues, there are two procedures to solve it for the 3DCP. The first procedure, utilizing the D-shape process, as the powder-base connect the unconsolidated concrete, which will equipped with support after dismantling the dried parts. The second method is to print the materials inside a container to generate a section of scaffold then dismantled as the support section is unnecessary [10]. The amount of material with the 13 mm contour crafting inserts, or "print resolution," is the final key distinction between the three methods. Layer depth versus build speed in each device pass was the main trade-off. Concrete printing and D-shape, on the other hand, place 4-6mm of material for each pass [11],[2]. When less material is laid, it takes longer to reach the desired height. A smaller amount of material laid means more precise control over detail and finish. Figures 3,4, and 5 show an example of an object that can be printed using each technique [10].

The machine shown in fig. 2 contains an aluminum frame designed and built on a house. This design has 3D axis X, Y, and Z with a size of 15, 9, and 40cm, respectively. The frames have been attached to slider and a stepper motor to control all axis to perform their task. Figure 3 is an indicator showing the four-load cell that is used to measure the farces from each direction. The sum of all individual load cells has been measured as the ultimate friction force to deflect the slipping. The table beneath allows rotation while the formwork stiffness illustrates vertically[12].

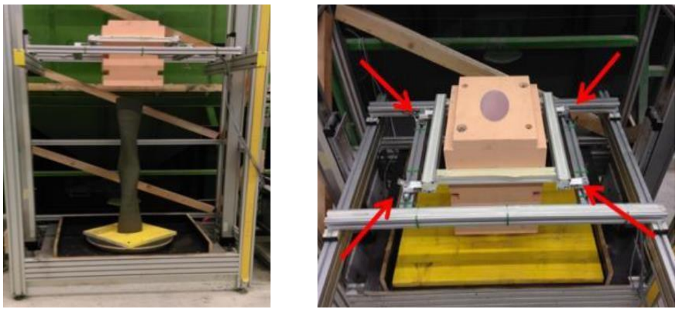

Fig. 3: Aluminum frame designed for 3DCP[12].

3D concrete printing at SC3DP as shown in Figure 4, contains two different types of 3DCP, in Fig. 4(a) shows the four-axis gantry attached to the nozzle, and 4(b) shows the six-axis robotic attached to a nozzle. These two types are the most utilized machines as 3DCP ([13],[6]). If there is a complex printing object, the robotic six-axis machine, as shown in fig. 4(b), is more likely to be used. However, the gantry machine will be utilised widely if the project requires a large-scale printing object [14].

The Eindhoven University of Technology facility, as shown in fig. 5, utilised a Contour Crafting technique for their 3DCP machine [13]. This machine is quite similar to other techniques in terms of printing, such as mixing the concrete and then pumping it by the mixer through the hose, which will be attached to the end of the arm nozzle (Refer to Fig. 3(b). The concrete mixture will be pumped through the hose and arrive at the vertical arm, exit through the hose nozzle, and be motion-controlled at 4 degrees of freedom (DOF). The robot design will have a printing area of 9 × 4.5 × 2.8 m [15].

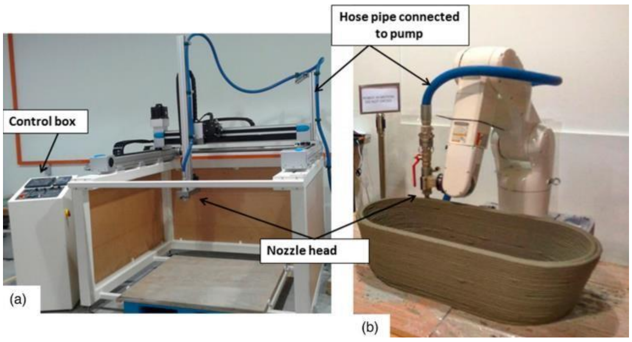

Fig. 4: (a) shows the four-axis gantry, (b) shows the six-axis robotic[14].

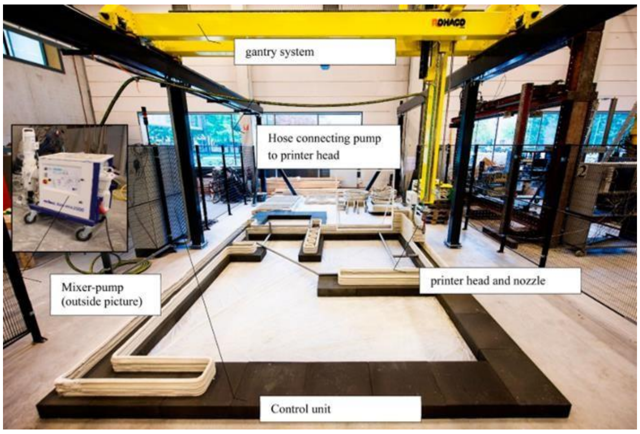

Fig. 5: 3DCP Facility at the TU Eindhoven[16].

B. Component 2 "Motors"

The motors utilized for the 3D concrete printer can be split into two parts. The first type is the stepper motor, as shown in fig. 5a. This type of motor has been used widely for the usage of small 3DP. However, there are some limitations when using this type of motor: the precision and the control of the nozzle to stop and move to the point according to the design required. The stepper motor has the lake of feedback on whether travel and the distance have been achieved. If the machine runs with a glitch, the machine will skip the mistake and move forward like nothing happened [17]. To utilize the stepper motor for large-scale printing, the stepper motor will come with a driver then connected to the controller which will be the second type of motor used for 3DP, as shown in fig. 6(b). Despite that, there will be some limitations in controlling the speed of the motor compared to the servomotor. The third type of motor, called servomotor with a drive, has a more substantial power and precise control of the 3DP, which is currently the recommended type of motor for large-scale 3D concrete printer construction. As shown in fig. 5(c), the servo motor with the drive are two devices, the servomotor will be connected to the drive then attached to the controller to function for the best great capacity and precision. A Stepper motor with a drive and a servo motor with a drive might look like this; however, the stepper motor with a driver still has some limitations compared to the servo motor with a drive. All the motors are the standard type of motor used for the gantry system 3DP.

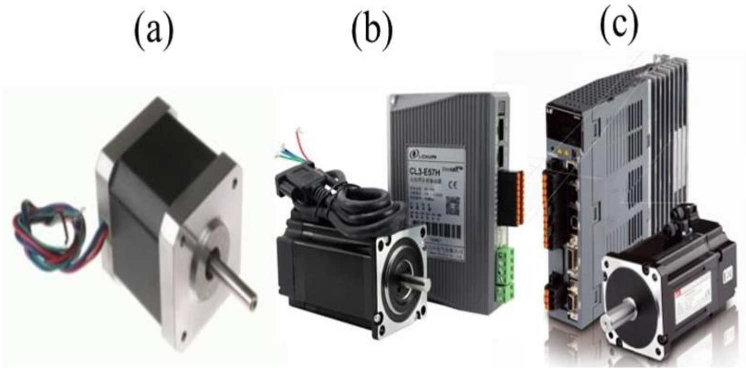

Fig. 6: Type of Motors used for 3DCP (a) Stepper Motor [17], (b) Stepper motor with a drive. (c).Servo Motor with a drive [18].

C. Component 3 "Controllers"

Every type of 3D concrete printer requires a controller; however, the type of controller will vary based on the design of the 3D concrete printer. If the 3DP is used for a small project, the stepper motor will be connected to a controller called Arduino, the most utilized tool for a small 3DP, refer to figure 6a. Another type of controller has been utilized for the large-scale 3DP. This type of controller will contain multiple pieces of equipment to control the servo motor to achieve the optimum and desired design, refer to fig. 7.

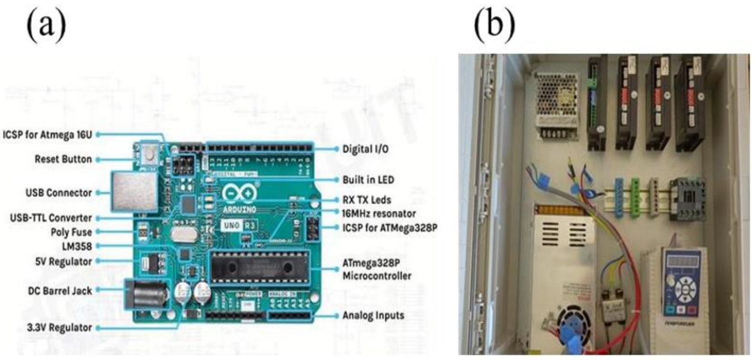

Fig. 7: (a) shows the Arduino controller [19], (b) shows the controller contains servos and other electric parts for large-scale 3DCP [20].

D. Component 4 "Nozzles"

The nozzle is an essential aspect of printing (fig. 6). The nozzle, a hollow shape at the end of the printing head made of plastic or steel, will extrude the concrete paste through the nozzle to complete the final printing process, and buildability. Many researchers have developed various types, sizes, and shapes of nozzles; however, each nozzle has limitations and advantages in achieving the project's design.

i. Single nozzle

Fig. 8(a) illustrates direct pushed-out materials by the load of the piston, which does not include any screw shape to move the particles toward the nozzle without using any pumping system. Fig. 8(b) shows another method of extruding concrete through the tip, in other words, through the nozzle. With this method the extrudability will be consistent. However, there will be an issue if the printing shape is on a large scale, and then the layers' consistency and smoothness will be poor. Fig. 8(c) is similar to the previous method and has the advantage of a cone shape at the top to fill more concrete to build a mid-size scale project. Building a large scall building pressure air nozzle head is the best method as it includes the pumping system, which will then be attached to the nozzle, as shown in fig. 8(d).

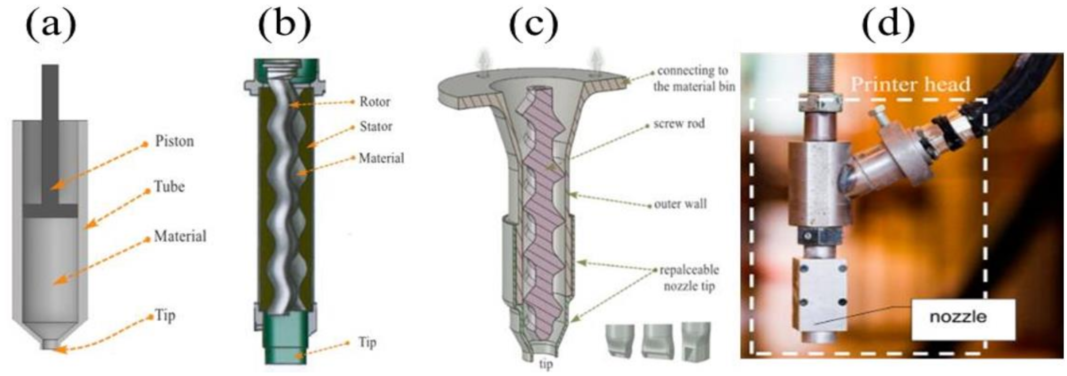

Fig. 8: (a) Ram extrusion [21], (b) Screw pump [22], (c) Direct screw [23], (d) Pressure air nozzle head [16].

Fig 9: Twisted Filament [16].

According to [16], the research has tried several type and sizes of nozzles in which the round Ø 25mm opening produce a round shape filament. However, the buildability was hard to stack. Another square shape 25 x 25 mm was used to check the filament's buildability, and the results have been enhanced. For this type of shape, the machine has to be programmed in that the movement will be disturbed and twisted in the corners, as shown in (figure 9). The current size the research is using is 40 x 10 mm.

i. Multi-nozzle integration

One of the new technologies introduced to the 3DCP is multi-nozzle integration (Figure 10). This new printing method could transform the traditional nozzle for 3DCP. Additional nozzles will be added to the existing nozzle to print certain parts of the building, as this part of printing requires excellent communication between the added nozzles to achieve a rapid and rigid filament [16][24], as shown in fig. 10(b). During the printing process, the filament will be cut, and the cable-concrete bond extruded through the nozzle (a, d), which will be attached with a reinforcement cable. A back-flow nozzle may solve this problem (b, e). On the other hand, an incorrect geometry design will generate a disastrous issue, when the filaments extrude through the nozzle and affect the concrete layers. To solve and improve the issue that occurred during printing by designing the nozzle and have a hybrid down/back-flow as shown in fig. 10(a). (c, f) [8].

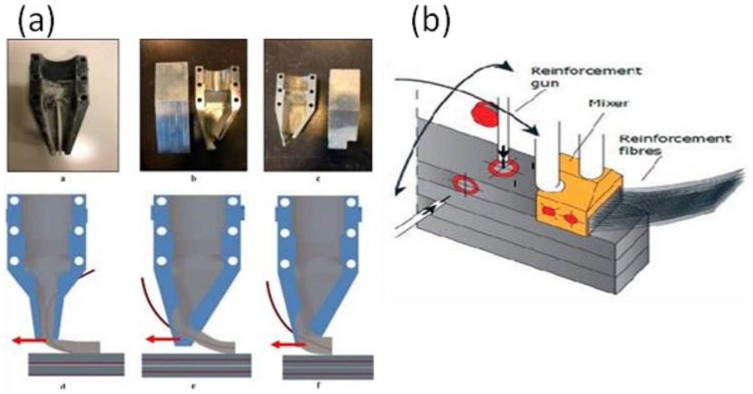

Fig. 10: (a). Multi nozzle used for 3DCP[8], (b).Multi nozzle for Reinforcement 3DCP[24]

Table 2: Comparison between different types of 3DCP.

Ref	Description	Advantage	Disadvantage
[25]–[28],	Gantry in-situ 3DCP to build walls for a low-rise house	Printing with large-capacity house	-Limited to build in X, Y, and Z axis without any degree angles. -Base slap and proper alignment is required before the concrete printing commencing.
[29]–[31]	Robotic arm 3DCP to build an arch bridge	Printing complex designs	-Require continuous movement to complete large-scale designs. -Require Reconfiguration whenever the machine moved to complete the large-scale design
[32]–[34]	Mobile gantry 3DCP to build low-rise buildings rapidly	Printing multiple houses rapidly	-Unable to print complex designs. -Require having base slap and proper alignment before commencing the concrete printing.
[35]–[37]	Mobile robotic arm to build dome/arch roofs/park art design	Printing complex designs	-Require continuous movement to complete large-scale designs. -Require Reconfiguration whenever the machine moved to complete the large-scale design.

IV. CHALLENGES AND RECOMMENDATION

The review paper has reviewed a varied type of 3DCP used for construction, therefore, for building 3DCP using gantry type or motorised method to control the motion of the 3DCP is utilizing servo motor as it contain the full command over the speed and precision during printing to achieve the best quality. This research has faced challenges in finding a suitable mix design to achieve the workability, flowability, and buildability for high-performance concrete, as much research has recommended a suitable mix design. To design and build a 3DCP, the researchers must make sure the type of nozzle has been chosen carefully to ensure proper printing during the extruding process. The lack of researchers on nanomaterials to describe the full potential of utilizing nanotechnology for 3DCP.

V. FUTURE WORKS

This paper is dedicated to design and built a 3DCP to test the concrete extruded filaments. Fig. 11 shows prototype design of the 3DCP that will be built to examine the concrete mixture for their workability, extrudability, flowability, and buildability. In addition, the extruded filament will also be tested for its compressive, and flexural strength tests, in which the mixture will incorporate nano-graphene and graphene tube to produce UHPC.

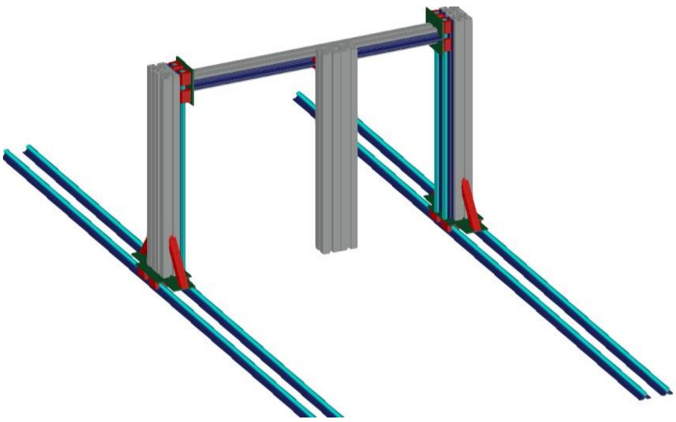

Fig. 11: Prototype design for the 3DCP.

VI. CONCLUSION

The future need to utilize different methods to achieve a complex design, reduce labour, and save time has increased the attention for the 3DCP. This paper has described a different type of 3DCP available for construction use. However, if a researcher needs to design and build a new system, further investigation is required to choose the best equipment to suit the project's needs. There is enormous attention from the construction industries to eliminate the formwork, saving costs, human labour, etc. 3DCP allows the construction to achieve complex designs which previously were hard to construct. The application of 3DCP has been reviewed, and the available usage of this technique in the building and other designs and shapes produced by the researchers. Many researchers have been exploring the usage of 3DCP. Therefore, limited materials have been used as a replacement to increase the strength of the cementitious and the lake of benchmark, as well as a guideline for a successful usage of the materials in the 3DCP. The different types and shapes of the nozzle suggested by different researchers have to be further investigated, as each type of nozzle functions for a particular design and purpose. Thus, to strengthen the 3DCP filament, many researchers have to work to improve the printed surface area of the layers and microstructure characteristics of the extruded 3DCP paste. There are limitations and advantages to the large-scale 3DCP techniques, D shape, concrete printing, and contour crafting, which future work has to be done to improve 3DCP technology.

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