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قسم الميكاترونكس

Design and Manufacturing large scale 3d concrete printer

تصميم وتصنيع الطابعة الخرسانية ثلاثية الابعاد واسعة النطاق

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Abstract

As a way to enhance Automation in the construction industry, 3D printed concrete has attracted more and more attention in recent years concrete. The 3D Concrete Printer presented in this project addresses the growing need for innovative and efficient construction technologies. The project focuses on designing a robust 3D concrete printer with specific dimensions of 4x4x3 meters (X, Y, Z) utilizing a gantry system.

The objective is to explore advancements in additive manufacturing for construction, enhancing precision, speed, and adaptability in the creation of complex structures.

The methodology involves a detailed examination of the gantry system, extrusion mechanism, control system, and safety features. Through rigorous testing and analysis,

the project aims to validate the printer's functionality and performance, contributing to the evolving landscape of 3D concrete printing technologies.

The findings and insights derived from this project not only contribute to the academic discourse but also offer practical implications for the future of sustainable and innovative construction methodologies

Acknowledgment

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Supervisor Certification

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Abbreviations	Definition
PET	Polyethylene terephthalate
3DCP	3D Concrete printer
FDM	Fused deposition modeling
PC	Personal computer
CPU	Central processing unit
CNC	Computer numerical control
PID	Proportional integral derivative
CAD	Computer-aided design

CHAPTER 1

OVERVIEW

1.1 Overview.

The emergence of 3D printing technology has led to a new era of innovation in various industries during recent years.

it is impossible forgetting to mention the important role of the construction industry in particular. The progress of society has always been linked to the construction industry. One of the most promising applications of this transformative technology has emerged in the field of construction, especially Through the development of 3D concrete printers, these pioneering machines are poised to revolutionize the way you build, offering a remarkable combination of sustainability, efficiency and design flexibility that has the potential to reshape the construction industry.

Although traditional construction methods that have served humanity for centuries can still meet the requirements. But the requires a lot of time and manpower and is characterized by resource-intensive operations, hard manual works, and significant waste.

Although the achievements of the scientific and technological revolution have been applied to construction, the consumption of time and human resources is unavoidable as the requirements of modernization of the construction industry extend, we must have solutions to solve the problem of time and complexity in construction works

Recently, the application of robots or automatic machines spread all over the world. Not only in construction but all areas which apply the achievements of the scientific and technical revolution to production. It is the application of robotics to the process of production. From there a series of existing problems such as time and human resources are solved and the result is improved labor and product productivity. The ultimate and economic efficiency is more and more. Robots must be responsive, flexible, and fit specific requirements.

Besides, there is a strong development of 3d printing technology with simple and flexible robotic structures. This is a positive signal for the idea of applying robotics in the field of construction. Due to the time efficiency in the prototyping process, 3d printing technology has become very popular in almost all fields. The construction industry consumes a lot of labor and time during the construction process. Thus, the 3D printing technology will contribute to work productivity. Currently, the 3d printing technology does not stop at repairing plastic cane models, but also uses more special materials. There are 3dvprinted works using civil materials, carbon fiber and ceramics.

.Studies should be announced on the use of new materials for 3d printing . Thus creating a breakthrough in the development of this technology. Therefore, if the materials in construction meet the technological requirements, it is possible to realize the idea of applying robots to 3d concrete printed.

the research and development of 3D concrete printer structures for the construction industry is a matter of great concern today, With the desire of our country trend of modernization in all fields, this issue is urgent.

This project is a study of serial robotic structures used 3d printing of concrete mortar along with research on construction materials for the final product which is House with Structural requirements and quality is guaranteed to be comparable to civilian houses using traditional construction methods.

1.2 Problem statement

Many construction processes have many problems, and this project solves many problems that traditional construction cannot deal with, such as the following problems:

1.2.1 Labor Intensity and Safety

In the traditional construction methods often require extensive manual labor, exposing workers to various safety risks. By offering a 3D concrete printer, you can reduce the need for labor-intensive tasks and create a safer working environment.

1.2.2 Complex Engineering

Many construction projects involve complex designs that are difficult to achieve using traditional techniques due to limitations imposed by templates that hinder engineers and designers from realizing their creative visions. A 3D concrete printer offers the ability to easily create complex, custom shapes.

1.2.3 Time Constraints

Traditional construction processes can take a long time, delaying the project and increasing costs. By automating parts of the construction process, a 3D concrete printer can significantly reduce construction timelines, resulting in faster project completion.

1.2.4 Affordability and accessibility

Traditional construction methods can be expensive, limiting access to quality housing and infrastructure in certain areas. By developing costeffective 3D concrete printing solutions, your project can contribute to making construction more affordable and accessible.

1.2.5 repairs and maintenance

Traditional construction often requires significant effort for repairs and maintenance. Structures built using 3D printing technology can be designed to facilitate maintenance and repair, reducing costs in the long term.

1.3 Project objectives

The following list might be used to outline the project's primary goals

- Reduction of construction costs by eliminating formwork.
- Reduction of injury rates by eliminating dangerous jobs (e.g., working at heights) which would result in an increased level of safety in construction.
- Creation of high-end, technology-based jobs.
- Reduction of onsite construction time by operating at a constant rate.
- Minimizing the chance of errors by precise material deposition.
- Increasing sustainability in construction by reducing wastages of formwork.
- Increasing architectural freedom, which would enable more sophisticated designs for structural and esthetic purposes.
- Enabling the potential of multifunctionality for structural/architectural elements by taking advantage of the complex geometry.

1.4 Research Methods

To accomplish the objectives of the project, during the implementation of which research methods were used, including.

1.4.1 Theoretical research methods

In this method, the first job is to Literature review and related work by analyze the robotic structure and the special features of the concrete. Synthesize documents related to the topic for analysis. Give the priority and weaknesses of each method to get an overview of the problems to be solved. On the basis of the proposed parameters and synthesis of data to proceed with the resolution of the objectives of the project

.Select the 3d concrete printer structure in accordance with the requirements in 3D.

Next is the design and calculation of the parameters of the 3d concrete printer . After completing the design, simulate the 3d printer spatial progression to change. Besides, based on the analyzed materials, presented elements of the photographed concrete for the process in 3D. From there, there is a solution to improve the quality of concrete and calculate the quality of the first author.

1.4.2 Empirical research methods

Besides theoretical research methods, experimentation is an important method in the topic. First, the experimental method is the most optimal method to formulate materials suitable for large-scale 3D printing goals. Provides an overview of the material properties that affect 3D printing. The results of the material testing process will form the basis for the design of the concrete feeding system and extruder. By experimental methods to come up with ideas and solutions for 3d concrete printer control problems. The experiment helps to test external factors that affect the operation of 3d concrete printer in practice. From there, adjust to make the machine more active. Besides, experimentation is an effective method to inspect the product after completing the concrete 3D printing process.

1.5 Limitations and task

1.5.1 Tasks.

From the problem posed and researched, the goal of the project is to design and process serial robot mechanics for application in construction. After completing the design and processing, the Robot will be controlled to perform 3D printing tasks to create the final product which is a model of a house or decorative architecture made of concrete mortar to serve the needs of customers. services in the field of construction. Specifically, the task is to study the operating principle of the serial robot, select a design plan suitable for the goal of large-scale 3D printing with concrete mortar. Depending on the task of the project, the first thing to do is to test the materials for the project. Testing common concrete materials to examine factors that affect applicability for 3D printing. The next task is to design a robotic structure that meets the requirements of large-scale 3D printing. Then, the mechanical processing process completes the Robot. Test run and test the mechanical part of the Robot to adjust accordingly. After calibration, design the electrical system and create the interface for the Robot. After perfecting the Robot, the next job is to test and calibrate the entire system. Operate the system with and without load in a real environment to check the results. The final product of the project is a concrete 3D printed robot system with an operating space of 4x4x3 m.

1.5.2 Limitations.

Applying mechatronics knowledges for large-scale concrete 3D printing is a huge project. Throughout the project, many complex problems must be solved. Due to the wide scope of research and limited time in the working process, the project only focused on solving the core problems of the large-scale concrete 3D printing project.

The first task in the project was to experiment to find the most optimal material mixing formula for large-scale concrete 3D printing.

Second, study the principle of operation of the 3d concrete printer according to the requirements of the project. Then proceed to calculate the dynamics of position, velocity, acceleration of the selected 3d printer mechanism.

The project required the 3d concrete printer structure to be serial and operational with a maximum weight placed on the working head of 50 kg. After completing the mechanical part of the machine , proceed to study the control algorithm of the 3DCP. With the goal of the 3DCP operating in the operating space of 4x4x3 m and the movement speed of the working head 50 mm / sec.

After completing the 3DCP control program, proceed to create an interface so that the user can interact with the 3DCP and monitor the activity. Next, create a manual for operation and maintenance of the 3DCP during use. Proceed to operate the 3DCP in an idle and loaded state to adjust accordingly. The final job is to evaluate the product of the concrete 3D printing process.

1.6 Literatures review.

1.6.1 Studies in the world

In the world today, there have been many research works on the application of robots to construction automation. Studies have used a variety of robotic structures. Parallel robots, cylindrical coordinate robots, spherical robots or robots with a three-axis reciprocating movement mechanism are the types of robots applied to the construction industry. The research is not only limited to building houses but also extends to the construction of large-sized statues, decorative architectural works, etc. In 2019, a project was built using the application of large-format 3D printing technology. The world's largest construction in Dubai was completed thanks to a 3D printed concrete mortar robot provided by Apis Cor as shown in Figure 1.1. The building has different characteristics from the traditional buildings built in Table 1.1 and Table 1.2.

Figure 1-1 The building was constructed using a concrete 3D printing robot in Dubai developed by the company Apis Cor [1].

Table 1-1 Dimensions of the building.

Element	Dimension
Height	9.5 m
Area	640 m2

Table 1-2 Breakthrough point of the project [1].

Elements	Character
Wall Structure	Built with concrete 3D printing technology
Material	The concrete mixture is mixed with the appropriate proportions
Reinforcement for the building	Formwork for columns is poured with reinforced concrete and heavy concrete
Roof, windows, insulation	Built and installed later

The walls of the building are finished by 3D printed concrete. With a cylindrical coordinate robot structure, it is possible to complete the entire large wall as **shown in Figure 1.2**. During construction, 3D printing technology has helped save time and labor. According to data, during the construction of the wall, only 3 operators and some supporting machines are needed. A surprising figure for such a large-scale project as a high-rise.

Figure 1-2 The wall of the building is being constructed using the 3D printing method [1].

3D printing is an additive technology. Layers of material will be stacked on top of each other to make up the structure of the model. In construction, the walls of the building will be made up of multiple layers of concrete as shown in **Figure 1.3** and **Figure 1.4**. In addition, breakthroughs in construction technology and materials are important issues of the project. The material is researched to meet the 3D printing requirements of concrete. The composition in the material mixture is adjusted according to the weather in the construction area.

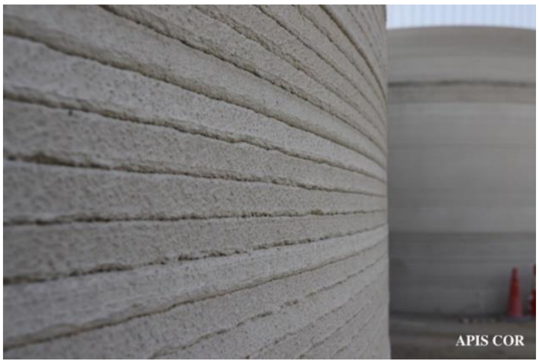


Figure 1-3 The wall is built using the concrete 3D printing method [1].

In 2021, another 3D printed concrete house was also completed. This is one of a series of 5 houses of the Milestone project implemented in the Netherlands as shown in Figure 1.5. The house has a living room and two bedrooms. Unlike the construction project in Dubai, the house is divided into 24 parts for 3D printing at the factory as shown in Figure 1.6. The parts will then be transported to the construction site for assembly. According to the manufacturer's announcement, the time to complete the wall of the house is 120 hours. The construction time is very short for a house with an area of 1000m2.

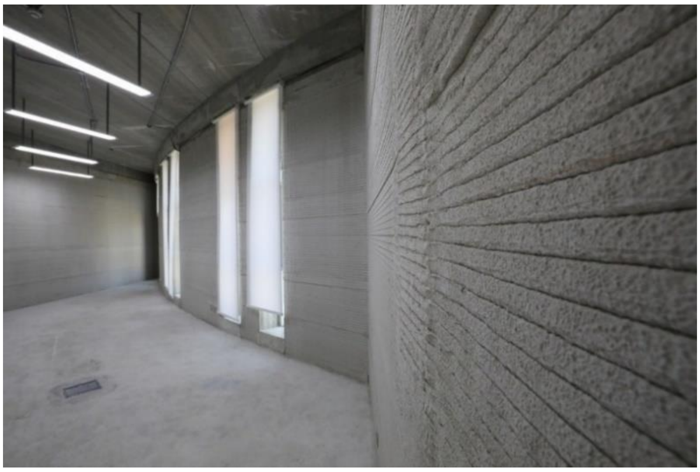


Figure 1-4 The wall in the house [1].

Figure 1-5 The house was built using concrete 3D printing technology under the Milestone project in the Netherlands [2].

Figure 1-6 . 3D printing process of building parts [3].

In addition to the architectural works that have been built in Dubai and the Netherlands, the US and some other countries have been researching concrete 3D printing technology applied to construction. Concrete 3D printing is a technology that promises to impact the construction industry in the future.

Figure 1-7 . Test materials in the study [4].

Materials play an important role in 3D printing technology. To complete the above-mentioned works, the study of materials is a must. These studies focus on concrete materials. A study on concrete 3D printing methods and materials used for this technology was conducted in Italy [4]. Research clarifies the concrete 3D printing process. Besides, this study presents the properties of concrete. Tests are then conducted to evaluate the material as shown in Figure 1.7 and Figure 1.8.

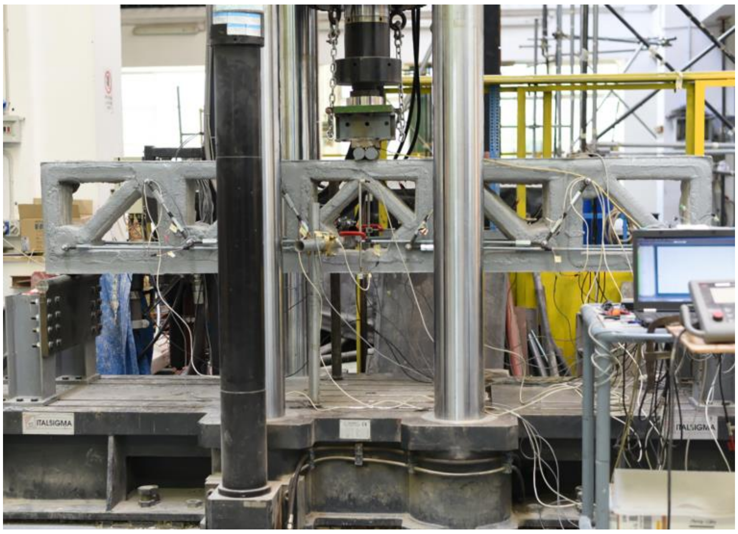


Figure 1-8 A method of evaluating materials [4].

In addition, PET plastic has been researched for the application of concrete 3D printing [5]. The study [5] presents the properties of PET resin. Then conduct a concrete experiment containing PET plastic particles to evaluate the results as shown in Figure 1.9.

Figure 1-9 Concrete containing PET plastic [5].

Research works related to concrete 3d printing technology are increasing in quantity and quality. The savings in time and labor have allowed this technology to flourish.

Chapter 2

Materials

2.1 Introduce

Concrete 3D printing is an additive technology that uses concrete materials to build building structures. The material factor plays an important role. There have been studies around the world on the Behavior of Concrete with Poly Ethylene Terephthalate, the properties of polyethylene terephthalate (PET) in terms of concrete properties [17]. In addition, several studies have shown the evaluation of reinforced biosynthetic materials such as banana fibers [18]. The references[19][20] described an experimental study on the thermomechanical properties of recycled PET fiber reinforced concrete and 3D printing of particle layers in concrete construction. The printable properties of adhesives used in concrete 3D printing have also been given in materials [21][22]. There have been studies evaluating PET materials in concrete 3D printing technology [23]. For 3D printing technology, materials play an important role in affecting the structure of the building. This study presents a concrete grade formula suitable for projects involving concrete 3D printing. In this study, the properties of concrete are the improved properties of concrete for 3D printing by adding banana and PET fibers. This article presents the mechanical properties of concrete that affect its ability to layer and the characteristics of concrete when additives, PET resins, banana are added. Concrete 3D printed structural experiments are analyzed and evaluated based on the properties of concrete. The material mixing ratio affects the 3D printing capacity as well as the characteristics of concrete. Experimental tests aim to evaluate the properties of concrete materials with variable additives, PET resins and banana fibers to meet 3D printing requirements. Building structures are printed layer by layer in the vertical direction, after which mechanical tests are carried out on their samples. Finally, the results show the optimal formula of concrete materials for 3D printing. Concrete 3D printing has not replaced the need for construction workers, but they have made their jobs easier and safer. Using recycled plastic in concrete not only helps protect the environment but also enhances the performance of concrete. Due to the low specific gravity of recycled plastic, replacing a portion of natural aggregates such as sand with recovered thermoplastic waste can reduce the weight of concrete. One of the benefits of lightweight concrete is that the structural components have smaller dimensions. There are two reasons why we choose to use PET and banana fibers in concrete production. The first is that this is a friendly concept. During processing, these natural and recycled materials are not transformed into other pollution such as chemical pollution or air pollution [24].

Concrete 3D printing is a technology put into use by many researchers around the world. There is a promising industry in the construction industry. But the biggest challenge is the materials used for printing. Concrete is a material used a lot in construction due to its unique properties. Outstanding is high formability and adhesion, can form material flow for convenient transportation, high bearing capacity when curing, can bond a variety of materials together, meet the requirements of use. For traditional construction technology, concrete is a material that meets the properties of the building. Although for a new field such as 3D printing concrete technology, some special properties need to be added to meet the requirements of manufacturing a complete 3D printed material project. To improve these two important properties, the first method is to add additives to concrete. Besides, some other materials can also improve the properties of traditional concrete to meet the requirements of 3D printed concrete fabrication. It is a natural material from banana fiber and PET particles. These two materials not only improve the characteristics of traditional concrete, but also improve the environment. This is a solution that helps reduce a large amount of PET plastic to improve the environment. Besides, natural materials are used.

2.2 Additive manufacturing in home construction

Additive manufacturing is a process by which material is extruded from an extruder. 3d objects are created by extruding layers of material stacked on top of each other. The process works by computer control. The materials used in 3D printing are not bound by plastic and metal. The rapid progress in the field of concrete 3D printing demonstrates that the unrealized potential in the construction of economic buildings. 3D printing of concrete is a type of additive manufacturing that allows the creation of completely new shapes in buildings or structural components that were previously not possible using standard concrete formwork. Although concrete 3D printing will not completely replace current construction processes tomorrow. But the benefits of the technology are clear. Designing and building a home can be an expensive and time-consuming task. This is why concrete 3D printing is an attractive option for builders and architects. Concrete 3D printing based on fused deposition modeling (FDM) is comparable in some respects but differs in others. In fact, the main differences between FDM plastic and concrete printing are summarized in the material extrusion process

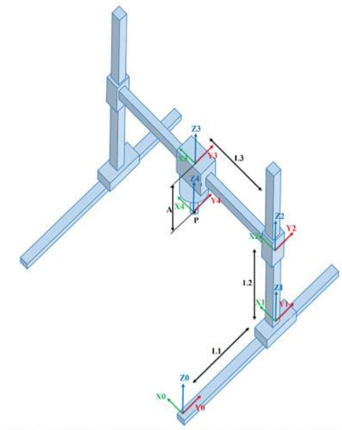


Figure 2-1 The mechanical structure of the concrete 3D printer during testing

The structure of active 3D printing uses a gantry system with a mechanical structure as **shown in Figure 2.1**. The machine has 3 degrees of freedom.

3D printing is a method of prototyping by creating layers of the designed object, then printing each layer on top of each other to create the object. 3D printing can be understood as an additive technology to create objects from designs on computer software. Similar to 3D printing methods that have been used in medical, fashion, decoration,... 3D printing in the construction sector is also additive technology. But construction 3D printing applications are still new, mainly used to create walls for houses or decorative objects with designs on computer software using concrete materials. The part similar to the house or decorations after designing on the software will be cut and printed on each layer of concrete stacked on top of each other to achieve the desired texture. Because 3D printing in construction is mostly used to construct walls and roofs, in the content of this article we do not cover. A house built by concrete 3D printing method must ensure the solidity of the walls, the wall after printing must not be tilted as guaranteed as the original design. Different from conventional concrete, the material used for 3D printing concrete must be high-strength concrete. More precisely, concrete ensures plasticity in accordance with the extrusion speed as well as the cross section of each print, curing time, formability after each printed layer and durability after complete curing. Ordinary concrete does not guarantee the above properties, so the specific goal is to improve the properties of concrete to meet the requirements of 3D printed concrete

2.3 New materials for additive manufacturing

As described in the introduction to concrete 3D printing applied in building materials. Materials play an important role in the feasibility of the project. The material for printing, specifically for this study, is high-strength concrete, which must have plastic properties in accordance with the speed of movement of the extrusion material. Besides, the concrete after printing must be shaped and stable so that the next printing layer can be layered. This process takes place continuously to create a structure that corresponds to the design. Curing time is also one of the factors that greatly affect the structure of the design after printing. If the curing time is too long, the stability of each printed layer is not guaranteed, resulting in deviations from the designed structure. Conversely, too fast curing time will cause structural cracking after printing. These properties of conventional concrete are not suitable for 3D printing applications. Therefore, additives are used to enhance the characteristics of concrete.

2.3.1 Features of PET materials

PET is a synthetic linear polymer that has a chemical formula $(C_{10}H_8O_4)_n$ and is a flexible plastic. PET plastic is often used in cans, bottles for food and drinks. PET plastic is a component that can create high-strength concrete for concrete 3D printing requirements. Salient features:

1. Good ductility at low temperatures.
2. High durability.
3. Low water absorption.
4. Insoluble in water, dilute acids, neutral salts and oils.

The value of the traction module is 2 - 4 GPa. And the tensile strength is 19 MPa. These are two outstanding mechanical properties that improve the properties of concrete.

Because PET has the above outstanding properties. It should be used to harmonize material applications for 3d concrete technology. In which the most outstanding advantage is the ability to retain the original shape. This superiority of PET is the anti-shrinkage method for concrete after extrusion.

After extrusion from the nozzle, the concrete goes into the curing process. During this process, concrete will appear shrinkage due to hydrochemistry. The shape of concrete would change much without PET. Therefore, PET can enhance the properties of concrete applied to 3D printing technology.

2.3.2 Features of banana fibers material:

Banana is an incredibly useful plant that is grown a lot in Egypt, Sudan, Yemen. Parts of this tree are used for a variety of purposes. Banana fiber is obtained from pseudo stems. Banana is used for many applications such as rope making, handicraft products. Salient features:

- It is stiff and lightweight.

- It is insulating.

- It is strength and durability.

- It is eco-friendliness.

Banana fiber is composed mainly of cellulose at a rate of 36–43% according to research [25]. Cellulose has the chemical formula found in all natural fibers. With a high percentage of cellulose, banana fiber can increase the thermal insulation of concrete after curing. Besides, if banana fiber can become a component of concrete used for 3D printing technology, it will benefit the environment. That will make the effective use of natural fibers in construction..

2.3.3 Combining PET and banana fibers materials

Concrete generally does not meet the properties used for 3D printing purposes with the main component such as **Table 2.1**. Therefore, the addition of PET plastic resins, banana fiber and superplastic additives will be the solution. Besides improving the properties of concrete materials, using granular PET plastic resins and banana fiber also makes sense for the environment when using natural materials and using used PET plastic. Concrete will have improved durability when PET plastic is included in the grade formulation. Due to the high strength of PET plastics, the good ductility at low temperatures described in the previous section creates a bond between materials. In addition, PET plastic also helps to increase the stability of each printing layer, ensuring shaping ability when laying the next layer of printing that occurs a chemical reaction (2.1).

$$(C_{10}H_8O_4)_n + nCa(OH)_2 \rightarrow nC_2H_6O_2 + nCaC_8H_4O_4 \quad (2.1)$$

The ductility of high-strength concrete is significantly enhanced when the mixture contains superplasticizers, reducing curing time as a study [26]. Besides PET plastic, banana fiber helps concrete improve its thermal insulation properties due to the fiber's properties. From there, walls after construction contribute to making the house more environmentally friendly, reducing energy use for the cooling system by chemical reactions (2.2) and (2.3).

$$(C_6H_{10}O_5)_n + nCa(OH)_2 \rightarrow nCa(C_6H_8O_5)_n + 2nH_2O \quad (2.2)$$

$$Ca(OH)_2 + SiO_2 \rightarrow CaSiO_3 + H_2O \quad (2.3)$$

Table 2-1 Chemical composition of cement

Chemical composition	Rate by volume (%)
Tall	64.6
SiO2	21.3
Al2O3	5.6
Fe2O3	3.3
Other ingredients	5.2

2.4 Experimental Setup

2.4.1 Machine and extruder

To test the material, the project uses a gantry coordinate robot with three degrees of freedom to create an orbit for the design structure as shown in Figure 2.1. With the machine operating space, the maximum printable wall height is 3000mm. The worksheet operator uses concrete extrusion screws to create print lines as shown in Figure 2.2. If the wall is larger, then the robot's operating space will be divided into several parts for printing and then assembly to finalize the final product. In this study, a screw was used to extrude concrete to create printed layers.

Figure 2-2 The machine and extruder are used during the test

2.4.2 Test wall structure

In this project, the wall is designed with two parallel prints forming the outline of the structure, the two prints connected by supporting lines as shown in **Figure 2.3**. Each print line measures 40mm wide by 20mm high, two parallel lines separated by 170mm from the center of each print. Thus, the wall structure will have free space as shown in **Figure 2.4**. These gaps are intended to contain insulation materials such as rice husks, natural fibers used to insulate houses, contributing to making houses built with 3D printed concrete more environmentally friendly. In addition, with the gaps of the wall structure after completing the 3D printing work, concrete will be supplemented with reinforcement to bond the wall segments to ensure the cross-sectional resistance of the structure.

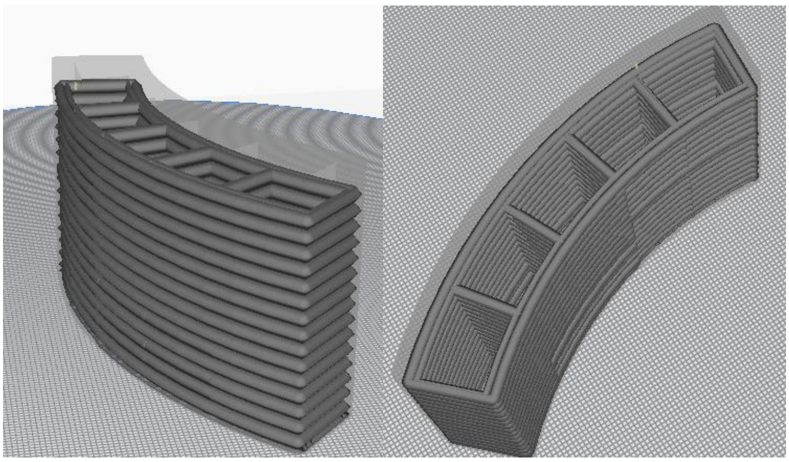


Figure 2-3 Wall structure on design software

Figure 2-4 Realistic wall structure after concrete 3D printing.

2.4.3 Test methods

For this study, the output of the extruder is a circle with a diameter of 28mm corresponding to the extruder's moving speed of 100mm/s and the flow rate of 0.22m3/h. To evaluate the wall strength after 3D printing, each printed layer will be measured in height, deterioration, deterioration after 28 days. Besides statistics on the size and shape of the printed layer over time, the compressive strength of high-strength concrete is calculated based on empirical equations [27].

$$f_{cm}(t) = \beta_{cc}(t).f_{cm} \quad (2.4)$$

$$\beta_{cc}(t) = \exp\left\{ s\left[1-\left(\frac{28}{t}\right)^{0,5}\right]\right\} \quad (2.5)$$

Where:

$f_{cm}(t)$: average compressive strength of concrete after t days.

f_{cm} : average compressive strength of concrete after 28 days.

s : The coefficient depends on cement grade and concrete grade.

In addition, the material mixture was tested for compressive strength and bending in parallel with the printed layers as shown in **Figure 2.5**. Two concrete samples containing PET plastic and non-PET plastic were compared. The size of each specimen is 40x100x200mm corresponding to 5 printed layers.

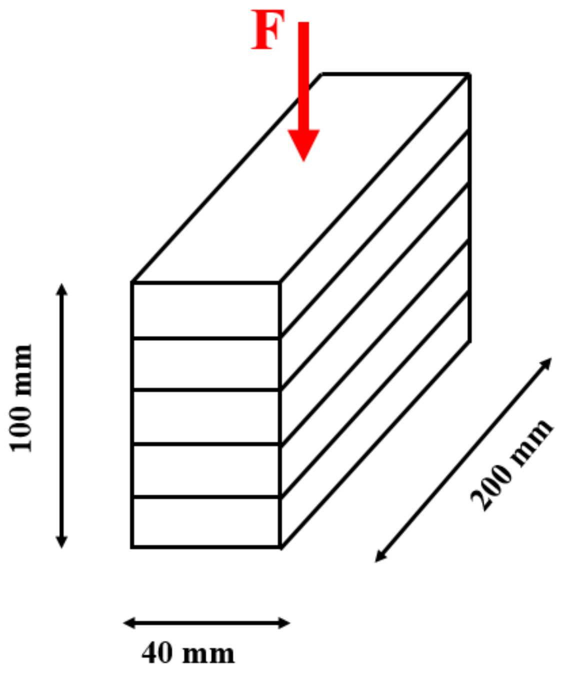


Figure 2-5 The size and direction of the force in the test.

2.4.4 Experimental parameters for additive production

To create high-strength concrete that meets the requirements of 3D printing of concrete in research works with materials such as **Table 2.2**. For cement, this study used PCB40 according to TCVN 6260-2009 standard for compressive strength of 40 MPa after 28 days. Additives used to create flowability for high-strength concrete are superplastic additives. For sand, choose a particle size of <2.5mm for all the different mixing ratios. With different mixing ratios, **Table 2.3** presents experimental comments. From the results of the experimental process, find the optimal formula that meets the requirements of the concrete 3D printing process.

Table 2-2 Material composition

Ingredient	Technical Requirements
Cement	PCB40 TCVN 6260-2009
Sand	Particle Size<2.5mm
Water	
Gypsum Powder	

Super plasticity Additives	
PET Plastic Granules	Particle Size<2.5mm
Banana fiber	Yarn length <10mm

Table 2-3 Material mixing ratio experiment

Name	Cement (kg)	Sand (kg)	Gypsum (kg)	Water (l)	PET plastic (kg)	Banana fiber (kg)	Superplastic additives (l)
C1	25	50	0	20	0	0	0
C2	50	50	40	20	0	0	0.13
C3	50	25	20	20	0	0	0
C4	50	60	20	20	0	0	0.13
C5	50	60	20	20	0.5	0.5	0.13

The results of the tests are shown in **Table 2.3**. C1 is composed of cement, sand and water creating a loose, amorphous mixture. C1 cannot be used as a material for concrete 3D printing technology. To eliminate the looseness of C1, gypsum and superplasticizers are added. But gypsum accounts for a high proportion, so C2 is dry and the rheology is not high. C3 mixtures have a smaller percentage of jelly than C2 and no superplasticizers. C3 becomes mushy, sticking to the pipe leads to difficulties in the extrusion process. Next, the C4 mixture has the same material composition as C3 and is supplemented with superplasticizers. The result obtained of C4 mixture is satisfactory. C4 has high strength after extrusion, suitable rheology and greatly reduces adhesion to the tube. Based on the composition of the C4 mixture, PET resin and Banana fibers are added. The C5 mixture gave the same results as C4 with the ratio of PET plastic resins and Banana fibers as shown in **Table 2.3**.

2.5 Experiments and Discussions

The study looked at several walls that create 3D buildings for experiments. According to equation (2.4), the average compressive strength strength of concrete is shown by the diagram of the relationship between the age of concrete and the average strength strength of concrete in **Figure 2.6**.

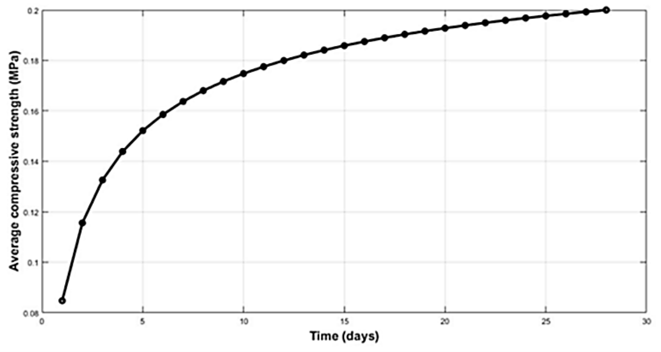


Figure 2-6 The relationship between average compressive strength and solidified concrete days.

The average compressive strength of concrete increases gradually over time, from the 1st to the 15th day the average compressive strength of concrete increases at a faster rate than the time from the 15th to the 28th day of the curing process. From the comments on the results of the mixture of ingredients after the experiment presented in **Table 2.3**. Two mixtures C4 and C5 give the best results with post-printing formability and meet extrusion requirements in concrete 3D printing. The ductility of concrete in C4 and C5 mixtures is improved compared to C1 mixtures. Experimentally the printed layers when using the C1 mixture after printing the overlapping concrete layers show signs of deformation and will fall down when printing to the 5th layer corresponding to the height of 100mm as **shown in Figure 2.7**. Superplastics create flowability for high-strength concrete to meet the requirements of 3D printing in construction. Using natural and recycled fibers instead of aggregates has also proven to be an effective method to prevent the formation of microcracks in concrete. Additional recycled PET, as well as banana fiber, are used to increase the efficiency of plastic recycling, ensuring that the compressive strength of concrete is costant or even improved.

Figure 2-7 Structural failure is caused by a mixture of materials that does not achieve ductility.

Also, when comparing products after extrusion between C1 and C2 mixtures. For C1 grade, do not use gypsum powder, which will make the mixture unmatched and uncontrollable the flow of concrete. The texture after printing appears deformed and subsident as shown in **Figure 2.8**. For C2 mixtures, gypsum powder is added to improve the hardness of concrete. But too high a weight ratio will cause the mixture to harden quickly, the printed mixture melts out unstable, and cracks appear on the printed layer. The mixture that is too dry after printing will appear layer separation between the printed layers, breaking the strength of the structure. Gypsum powder is a solution that improves the hardness of concrete if mixed in the right proportions. The addition of Banana fiber to the composition of materials used for concrete 3D printing is possible when comparing two mixtures C4 and C5. The addition of these two materials does not affect the extrusion ability. The wall after printing ensures the connection between layers and retains the design structure as **Figure 2.9 (a)** and **Figure 2.9 (b)**.

Figure 2-8 Deformation of the printing layer without gypsum powder.

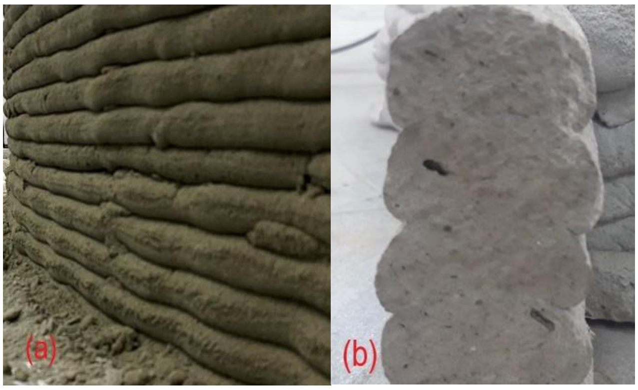


Figure 2-9 (a) The printing layer ensures formability when using a C4 mixture when printing is finished. (b) The printed layer ensures formality when using C4 mixtures after 28 days of curing.

The compressive strength of the test specimen is shown in **Figure 2.10**. The bending strength of the test specimen is shown in **Figure 2.11**. All test specimens have compressive strength and bending strength determined according to two timelines. It is day 1 and day 7 in the curing process of concrete.

In terms of compressive strength, concrete containing PET resin has lower compressive strength than concrete containing PET plastic. The difference value is approximately 14% of compressive strength. At the first and seventh day of the curing process, the compressive strength between C4 and C5 mixtures still has the difference as shown in **Figure 2.10**.

In terms of bending strength, non-PET concrete has higher bending strength than non-PET concrete. The difference value is approximately 10% of the compressive strength. Similar to compressive strength, the flexural strength of composites C4 and C5 is different on days 1 and 7 of the curing process as shown in **Figure 2.11**.

Although the compressive strength and bending strength of concrete containing PET resin are lower than that of concrete containing PET resin. But the spread is not high. Besides, concrete containing PET resin has high formability after printing and does not affect printability. Therefore, PET plastic can be completely applied to concrete 3D printing technology.

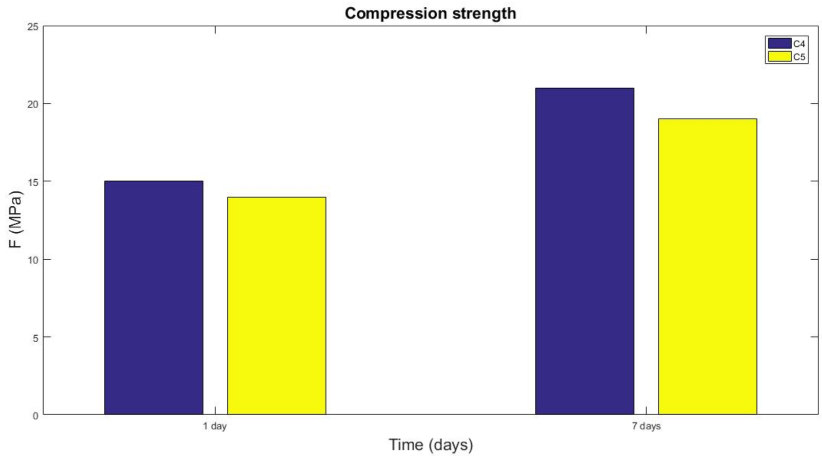


Figure 2-10 . Compressive strength after 1 day and 7 days.

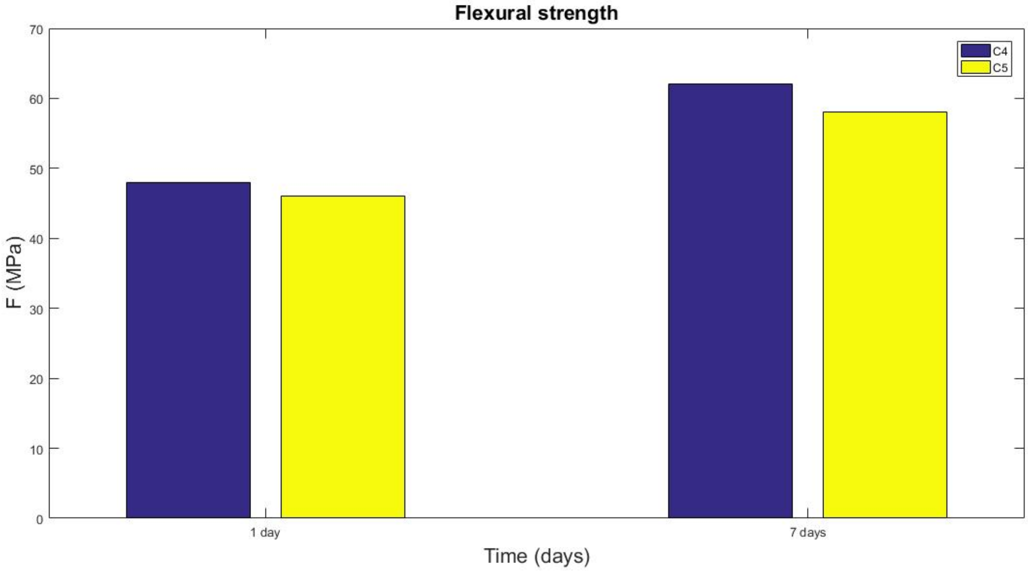


Figure 2-11 Bending strength after 1–7 days.

2.6 Conclude

Materials play an extremely important role in concrete 3D printing technology. Experimentally, research has demonstrated how the core properties of materials affect printability. In particular, the plasticity of the mixture after printing, the plasticity of the mixture are characteristics that need attention. Besides, there is the feasibility of using PET plastic, Banana fiber for concrete 3D printing applications. Concrete 3D printing technology is increasingly developing and being widely applied in the construction industry, so optimizing printing materials is a problem that needs to be solved.

CHAPTER 3

CONCRETE PUMPING AND MIXING SYSTEM

3.1 Introduce

Extruders are an important part of the robotic structure used for concrete 3D printing. In this study, the extruder was researched and designed to meet the task of large-scale concrete 3D printing. With concrete materials including materials such as cement, sand, Polyethylene terephthalate (PET), banana fiber,... The research process presents the characteristics of the material and the set parameters. From there, calculate and choose the extruder design plan. Based on extruder machining design. Then conduct a test run to evaluate the extruder's operation.

This research applies Fused Deposition Modeling (FDM) technology to create stacked print layers. Thereby creating the structure of the wall. For FDM 3D printing technology, the extruder plays an important role in creating material flow for the printing process. Specifically, in this study, extruders were used to extrude concrete. From the studied material parameters to the extruder design. The extruder must match the mechanical characteristics of the material mixture and the flow rate of the pumping system of the study.

A study of concrete 3D printing robotic structures presented a characteristic part of the extruder [6]. Research on computer-controlled concrete extrusion and pumping systems has been published [28]. For this study, concrete was pumped directly from a screw pump. Then it is compressed at the nozzle of the extruder to create a material flow. The pump flow is calculated and adjusted by the computer. In addition, an extruder using compressed air to compress concrete at the nozzle has also been studied [29]. Another study of the concrete extrusion process using loads to compress concrete [30]. In addition, studies on concrete used for concrete 3D printing technology were presented [31][32][33]. Study of the transformation of concrete containing Polyethylene terephthalate (PET) resin during concrete printing [34]. Another study of concrete using banana fiber [35]. The properties affecting extrusion capacity are given in the study [36][37][38].

3.2 Properties of concrete

The properties of the material have been studied and presented in chapter 2. Based on the properties affecting extrusion yield to design. The material is reinforced concrete with superplastic additives, gypsum powder, PET plastic, banana fiber,... It is a mixture with the properties as shown in **Table 3.1**. This mixture consists of materials of different particle sizes. The maximum particle size of the mixture is 2.5mm. The maximum length of banana fiber is 10mm. The characteristics of each material component will affect the extrusion ability.

Table 3-1 The composition of concrete

Cement (kg)	Sand (kg)	Gypsum (kg)	Water (l)	PET plastic (kg)	Banana fiber (kg)	Superplastic additives (l)
50	60	20	20	0.5	0.5	0.13

Mixtures with the components outlined in Table 3.1 are durable after printing. In addition, this mixture has a high continuity that creates concrete flow when exiting the nozzle. Through inspection, the concrete layers all reach the design height. The compressive strength on day 7 of the curing process reaches a value of approximately 18MPa. The bending strength on day 7 of the curing process is about 59MPa. The viscosity of the mixture was within 70 Pa-s during the test.

Extrusion capacity is an important factor. The requirement is that the extruder must produce a continuous flow of concrete. The constant flow of the material will ensure the alignment and shape between the layers. Also, make sure that concrete does not stick to the extruder during operation.

Extruder downtime is another factor that affects extruder performance. If the rest time is too long, the concrete will solidify. As a result, the flow of raw materials will be interrupted or lead to clogging of the extruder's nozzle. According to the experiment, the maximum time for concrete not to solidify is 6 minutes.

The print speed of the extruder is a certain value. For this study, the print speed was 100mm/s. According to the experimental method, the desired concrete flow rate is 0.22m3/h. The set line size is 20mm high and the maximum width 40mm. By experimental method, the nozzle size of the extruder is 28mm. All presented parameters are the basis for the design and selection of optimal solutions.

3.3 Extruder design

3.3.1 Design options

From the initial parameters, schemes are given to solve the problem. The plan for using a pneumatic cylinder to create material flow at the nozzle is as shown in **Figure 3.1(a)**. An amount of material will be contained in the cylinder. Compressed air will transfer pressure to the material that creates the concrete flow. The force is transmitted through an axis located inside the cylinder. This option has a simple design but the amount of raw materials is stored for a short time of operation. An important issue is the complexity of the material delivery system to the extruder. In addition, the pressure required to compress concrete to form the material flow when printing is calculated by the formula:

$$P = \frac{F}{A} \qquad (3.1)$$

where P is the pressure required to compress the material, (Pa). F is the force acting on the mixture of materials, (N). And A is the area of action of force F, (cm2). The pressure required to flow the slag material is 55Pa.

In addition to using pneumatic cylinders, screw extruders are also an option. The material is contained in a round tube. An extruded screw grows in size when it reaches the nozzle. The extrusion screw acts inside the tube causing the material to be compressed at the nozzle as shown in **Figure 3.1(b)**. This option creates a highly continuous flow of matter. But extrusion screws will be suitable for those materials that melt easily, have a low coefficient of friction and require high adhesion. The appropriate applications for this type of extrusion screw are plastic bottles. The concrete in this study has individual properties, so this alternative must be considered. In addition, the complexity of screw extrusion is a major drawback of this alternative.

The next option has similarities with the option of using extrusion screws. The biggest difference is that this embodiment uses one screw as shown in **Figure 3.1(c)**. The active screw creates material flow when it comes out of the nozzle. An advantage of the feeding screw is that it has a simpler design than the extrusion screw. Besides, the concrete used for this study has special properties. It is a mixture of bulk materials that is bonded with cement and chemical additives. Screws have high bulk material transport efficiency, so this option is very feasible.

Each alternative has its advantages and drawbacks. But given the advantages of using screws as already described, this option is most appropriate. In addition, the results of the test also give feasible results when using screw simmers.

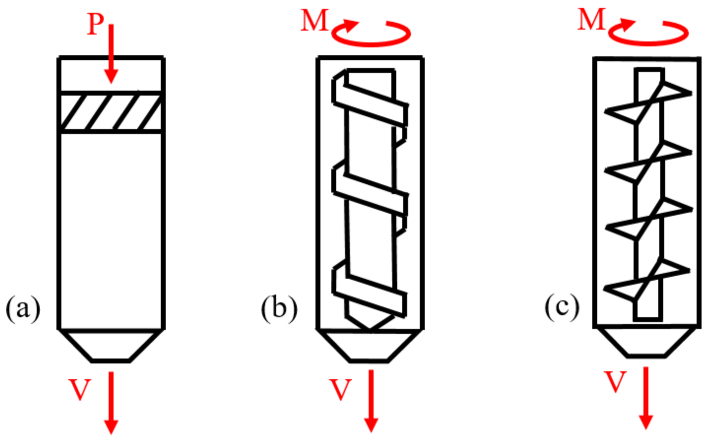


Figure 3-1 (a) Option to use pneumatic cylinder to extrusion material. (b) The option of using extrusion screws to extrude materials. (c) Option to use loading screws to extrude materials.

3.3.2 Parameters of the screw

3.3.2.1. **Initial parameters of the extruder**

From the results of the testing process, some parameter are given. The first value is density of material mixture ρ = 1.8 tons/m3. By experimental method the diameter of the nozzle is d = ∅28 mm. The set print speed of the extruder is V = 100mm/s. The height of each printing layer is 20mm. And the width of each printing layer is 40mm.

3.3.2.2. **Calculation parameters**

From the initial parameters, the power of the extruder is calculated by the formula:

$$Q = \pi \times R^2 \times V \times 3600 \text{ m3/h} \quad (3.1)$$

$$Q = \pi \times \left(\frac{14}{1000}\right)^2 \times \frac{100}{1000} \times 3600 = 0.22 \text{ m3/h}$$

Where: R is the radius of the nozzle, (mm); V is the print speed of the machine, (mm/s). From the power of the extruder, the outer diameter of the screw is calculated by the formula:

$$Q = 0.22 \text{ m3/h} = 0.22 \times 1.8 = 0.40 \text{ tons/h}$$

$$Q = 37.6 \times D^3 \times n \times C_\beta \times \rho \times \psi \quad (3.2)$$

$$Q = 37.6 \times D^3 \times \frac{K_t}{\sqrt{D}} \times C_\beta \times \rho \times \psi$$

$$Q = 37.6 \times D^{\frac{5}{2}} \times K_t \times C_\beta \times \rho \times \psi$$

$$\Rightarrow D = \left(\frac{Q}{37.6 \times K_t \times C_\beta \times \rho \times \psi}\right)^{\frac{2}{5}}$$

$$D = \left(\frac{0.40}{37.6 \times 30 \times 1 \times 1.8 \times 0.125}\right)^{\frac{2}{5}}$$

$$D = 0.08 \text{ m} = 80 \text{ mm}$$

Where: K_t is the experimental coefficient as shown in **Table 3.1**; C_β is the value corresponding to the screw lift angle as shown in **Table 3.2**; ρ is the specific gravity of the material mixture, (ton/m3); ψ is the filling factor of the material as shown in **Table 3.3**. The outside diameter of the screw is selected to be 80mm.

Where: is the empirical coefficient as shown in **Table 3.1**; is the value corresponding to the screw elevation angle as **shown in Table 3.2**; is the specific gravity of the material mixture, (tons/m3); is the fill coefficient of the material as **Table 3.3**. The outer diameter of the selected screw is 80mm.

Table 3-2 Empirical coefficient K_t.

Material	**K_t**
Light materials and without sharp edges (bran coal, cereals, flour, sawdust,...)	60
Heavy materials without sharp edges (coal, salt,...)	45
Heavy and sharp-edged materials (cement, sand,...)	30

Table 3-3 Coefficient value.

β	0	5	10	15	20	25	30	35	40	45
C_β	1	0.9	0.8	0.7	0.65	0.6	0.56	0.52	0.48	0.44

Table 3-4 Fill coefficient.

Material	ψ
Granular materials	0.35÷0.45
Powder material	0.45÷0.55
Tubular material	0.6÷0.7
Heavy material with sharp edges	0.125
Heavy material with less sharp edges	0.25
Lightweight material with less sharp edges	0.32
Lightweight and non-sharp material	0.4

The width of the selected screw blade is b = 29 mm according to the results of the experimental process. From the size value of the impeller, the diameter of the screw is calculated by the formula:

$$b = \frac{D-d}{2} \quad (3.3)$$

$$\Rightarrow d = D - 2\times b$$

$$d = 80 - 2\times 29 = 22 \text{ mm}$$

The number of revolutions of the screw to achieve a flow rate of 0.22 m3/h is calculated by the formula:

$$n = \frac{K_t}{\sqrt{D}} \quad (3.4)$$

$$n = \frac{30}{\sqrt{0,08}} = 106 \text{ r/m}$$

The screw step is calculated by the formula:

$$S = 0.8\times D \quad (3.5)$$

$$S = 0.8\times 80 = 64 \text{ mm}$$

The elevation angle of the screw blade is calculated by the variable formula:

$$\tan\alpha = \frac{S}{\pi\times D} \quad (3.6)$$

$$\tan\alpha = \frac{0.064}{\pi\times 0.080} = 0.25$$

$$\Rightarrow \alpha = 14^{\circ}17^{\circ}$$

The required power of the screw when bearing the weight of the material is calculated by the formula:

$$N1 = \frac{m \times g \times V}{1000} \quad (3.6)$$

$$N1 = \frac{50 \times 10 \times 0.22}{1000} = 0.11 \text{ KW}$$

Where: m is the mass of the material mixture during operation (kg); g is the gravitational acceleration (m/s2); V is the flow rate of the extruder, (m3/h).

The required power of the screw when transporting materials is calculated by the formula:

$$N2 = \frac{Q \times L}{367} \times (\omega + \text{Sin}\,\beta) \quad (3.7)$$

$$N2 = \frac{0.29 \times 0.8}{367} \times (4 + \text{Sin}\,0) = 2.53 \times 10^{-3} \text{ KW}$$

Where:

Q is the productivity of the screw, (tons/h);

L is the length of the screw, (m);

ω is the resistance coefficient of each material as shown in **Table 3.4**;

β is the material elevation angle of the screw relative to the horizontal.

Table 3-5 Material resistance coefficient.

ω	Material
1.2	Dry, non-abrasive (grain, grain, sawdust, bran coal)
1.5	Moist, non-abrasive (moist malt, cottonse, charcoal powder, chalk powder)
2.5	Semi-abrasive (soda, table salt, polar charcoal)
3.2	Abrasives (crushed stone, sand, cement)
4.0	Strong corrosion and stickiness (ash, moldy soil, quicklime, sulfur)

The total power of the screw is calculated by the formula:

$$N = N1 + N2 \quad (3.8)$$

$$N = 0.11 + 2.53\times10^{-3} = 0.11 \text{ KW}$$

From the required power of the screw, the required power of the motor is calculated by the formula:

$$N_0 = \frac{N}{\eta} \qquad (3.9)$$

$$N_0 = \frac{0.11}{0,8} = 0.14 \text{ KW}$$

Where: η is the transmission efficiency from the motor to the screw, $\eta = 0.8 \div 0.9$

For the convenience of the control process and based on the calculated parameters, the motor is selected as AC Servo Motor. The AC Servo motor used is 80 SY-M03230S1 SY Series. Also, to increase stability and torque, a gear reducer is used. The gearbox planetary has code AE90-010-N with a ratio of 1:10. The engine parameters are presented in **Table 3.6**..

Table 3-6 Specifications of SY Series 80SY-M03230S1-5 Ac servo motor.

Specifications	Values
Rated power	1 KW
The biggest moment	3.19 Nm
Rated speed	2000 r/m
Top speed	3000 r/m
Rated voltage	1 phase 200 – 230 VAC
Rated amperage	6 A
Voltage frequency(f)	50/60Hz ± 5%
Moment of inertia (J)	J = 8.41.10-4 kg.m2
Mass	8.4 kg
Input control signal frequency	0–200 KHz

The torque of the screw is calculated by the formula:

$$M0 = 975 \times \frac{N_0}{n} \quad (3.10)$$

$$M0 = 975 \times \frac{0.14}{106} = 1.29 \text{ N.m}$$

From the torque value of the screw, the axial force is calculated by the following formulas:

$$F_a = \frac{M_0}{\tan(\alpha + \delta) \times r} \quad (3.11)$$

Where: α is the torsional lift angle of the screw at radius r; δ is the angle of friction; r is the radius of action of the axial force, (m). The value of α , δ and r is calculated using the following formula:

$$\tan\alpha = \frac{S}{2\times\pi\times r} \qquad (3.12)$$

$$\tan\delta = f \qquad (3.13)$$

$$r = (0.35 \div 0.4)\times D \qquad (3.14)$$

Where: f is the coefficient of conductive friction of the material on the screw surface. The f-value in this study was 0.8. From formulas (3.12), (3.13), (3.14) instead of formula (3.11), the axial force has the value:

$$F_a = \frac{1.29}{\tan(14°17^{\circ} + 24°13^{\circ})\times 0.4\times 0.08} = 50.68 \text{ N}$$

The parameters of the loading screw are summarized and presented in **Table 3.7**. These are the basic parameters for the design and manufacture of extruders.

Table 3-7 Parameters of the extruder.

Specifications	**Values**
Outer diameter of the screw	80 mm
Inner diameter of the screw	22 mm
The width of the screw	29 mm
Screw step	64 mm
Torsion screw elevation angle	14°17°
The number of revolutions of the lead screw	106 r/m
Turn on the screw	0.0525 KW
Torque acting on the screw	4.73 N.m
Axial force acting on the screw	18.5826 N

3.3.3 Extruder design

From the parameters of the given screw in **Table 3.6** and the results of the experiment, a design was finalized. The extruder has a maximum capacity of 50kg of raw materials during operation as shown in **Figure 3.2**. The flow rate of the extruder is 0.22m3/h. The supply system is a synchronously controlled pump with an extruder.

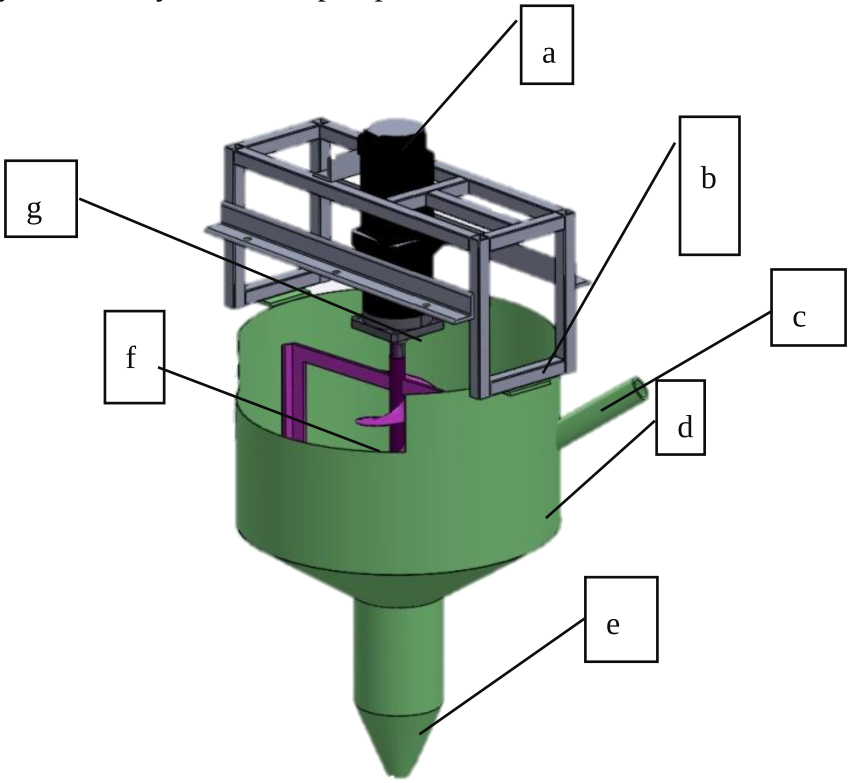


Figure 3-2 The extruder is designed to consist of the following parts: (a) Motor, (b) Frame, (c) Connection to ducts, (d) Material container, (e) Nozzle, (f) Screw, and (g) Reducer.

The extruder's container has a maximum capacity of 50kg of raw materials during operation. The container has a smaller diameter when it reaches the nozzle. The selected angle of inclination is relative to the vertical. The material will tend to slide down inclined to form a continuous flow. Due to the use of a pumping system that is controlled synchronously with the extruder, the connection location to the material hose is selected as shown in **Figure 3.2**. This position is suitable so that the duct does not twist, causing material flow to break during robot operation.

Because the raw material mixture has a high viscosity, the viscosity is approximately 70Pa-s, so there will be some materials adhering to the surface of the container. To overcome this phenomenon, a mechanical mechanism is installed on the screw. When the screw is working, this mechanism helps the flow of material to be directed to the center of rotation. Since then, the screw operation brings high efficiency and meets the flow requirement of 0.22m3/h of the extruder.

The nozzle is designed with a gradually smaller diameter. The diameter at the outlet of the nozzle is ∅28mm. The nozzle head is designed to be removable. This is convenient for cleaning and checking materials and extruders during maintenance. The structure of the nozzles is built from curves to ensure uninterrupted material flow during operation.

3.4 Pumping System

Since the extruder must produce a continuous flow of raw materials, a concrete pumping system is required to supply raw materials. The pumping system consists of parts as shown in **Figure 3.3**. The ingredients are mixed in the mixing drum as **shown in Figure 3.4**. The rotating impeller mixes the ingredients well for 10 minutes. The mixing drum has an approximate volume of 0.45m3. If the printing process is long and requires a large amount of concrete, then the amount of concrete is divided into several batches.

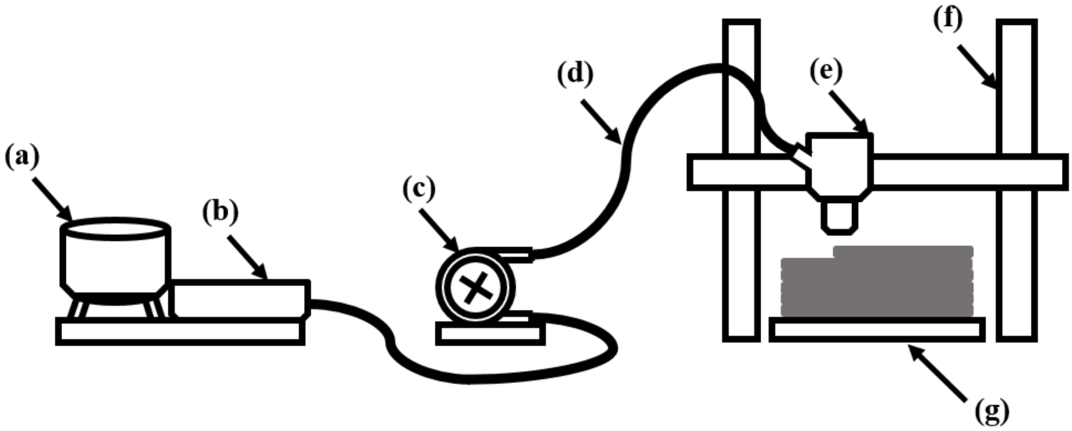


Figure 3-3 Concrete pumping system used: (a) Mixing tank, (b) Reversing tank to avoid material stratification, (c) Concrete pump, (d) Piping, (e) Extruder, (f) Mechanical structure, and (g) Operating space.

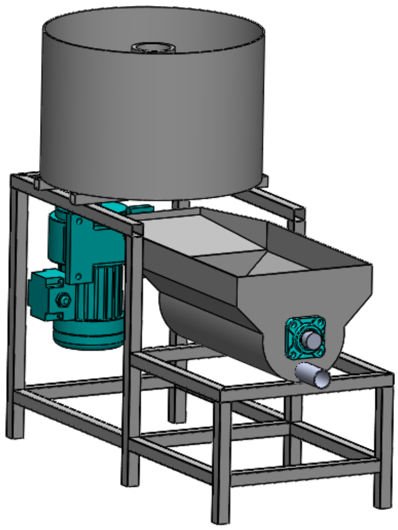


Figure 3-4 Mixing System

The concrete after mixing will be taken to the storage tank to feed the concrete into the pump as **shown in Figure 3.5**. Here the concrete is mixed with tamarind screws to avoid material stratification. In addition, solve the phenomenon of stratification of screw materials when the operation of creating pressure to bring concrete into the pipeline leading to the pump. The amount of concrete is continuously extruded into the screw pump.

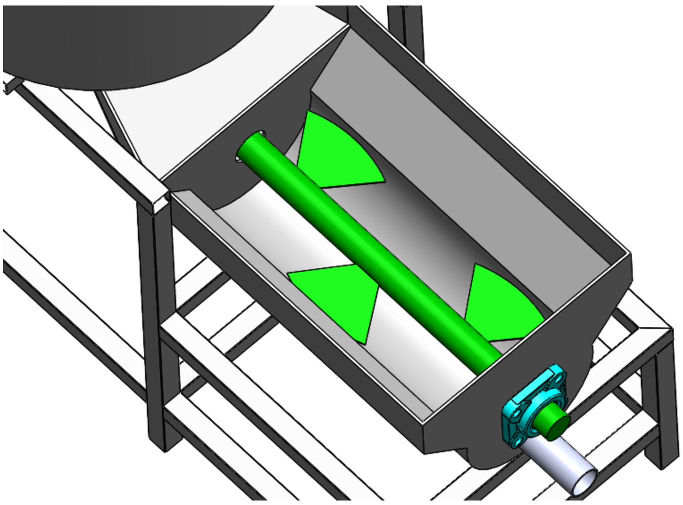


Figure 3-5 Concrete Island System

Concrete is fed into the pump to deliver the concrete to the extruder. The pumps used are peristaltic pumps as shown in **Figure 3.6**. This type of pump can be used for a variety of materials. The results of the testing process evaluate that this type of pump is suitable for concrete pumping requirements. A peristaltic pump is a type of positive displacement pump used to pump a variety of fluids. Concrete is contained in a hose or hose installed inside the pump housing. The pumping principle is based on the compression and alternating expansion of the pipe. Thanks to this, the concrete siphon enters and pushes the concrete out of the pump. During operation. The rollers move along the length of the tube. And the hose creates a temporary seal between the suction and discharge sides of the pump. As the rotor of the pump rotates, this sealing pressure moves along the concrete pusher moving away from the pump and into the discharge line. When the concrete comes out of the tube, the pressure is released, the tube returns to its original state creating a vacuum, sucking the concrete into the inlet of the pump. This cycle is repeated to help the pump deliver the concrete to the extruder. This combination of suction and discharge principles results in a powerful self-priming active displacement activity. This is the advantage of peristaltic pumps. The drawback of peristaltic pumping systems is the intermittent flow of raw materials. To overcome this problem, an amount of concrete is kept fixed at the extruder. The control signal of the pump is synchronized with the flow of the extruder. The pressure in the pipes of the pump during operation is 3MPa. The maximum height that the pump can accommodate is about 6m. The maximum flow rate of the pumping system is 2m3/h. The calculation of the actuator and the selection of the motor are presented in the appendix

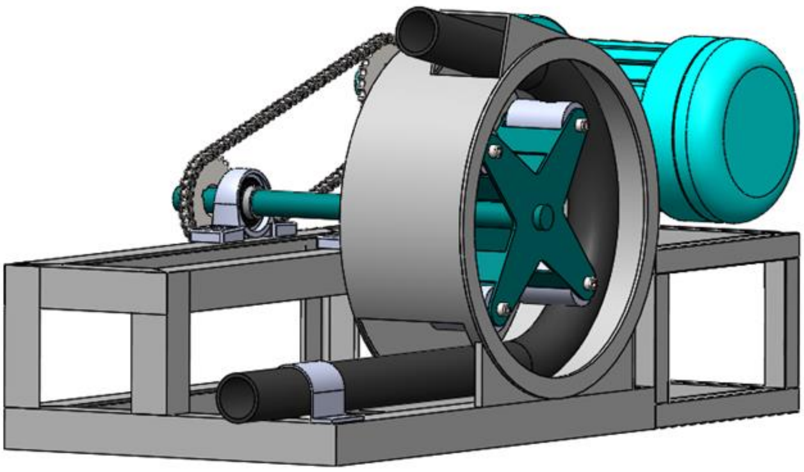


Figure 3-6 Perstaltic pump

CHAPTER 4

MECHANICAL DESIGN OF CONCRETE 3D PRINTER

Chapter 1 has introduced the objectives and tasks of the thesis. Next, the study of materials and extruders as well as feeding systems is presented in chapters 2 and 3. In this chapter on mechanical system design calculation, the design and power transmission options will be presented in detail, thereby providing an optimal design and power transmission plan for the robot manufacturing plan in accordance with actual conditions. The problem of robot kinematics and dynamics will also be solved.

4.1 Overview of serial structures in concrete printers 3D

Currently, serial mechanisms used in concrete 3D printing are divided into 3 main types: truss systems, robotic arms and crane systems (**Figure 4.1**). Successful use in concrete 3D printing at commercial research and construction scale. In terms of structural characteristics, the truss system and the crane system have a relatively similar structure, both move the working head with 3 degrees of freedom. Meanwhile, the commonly used robotic arm has 6 degrees of freedom that allow the robot to operate on complex print profiles, which is not possible for gantry and crane systems.

However, the benefit of using a gantry and crane system is that it is easy to adjust the size, resulting in a much larger working space and load capacity than the robot arm that is difficult to adjust and has a small size, low load. Therefore, robotic arms are often used to print large objects by dividing them into small blocks and then reassembling them. As for the drying rig system and crane system, it is often used to directly print large objects (houses, bridges,...).

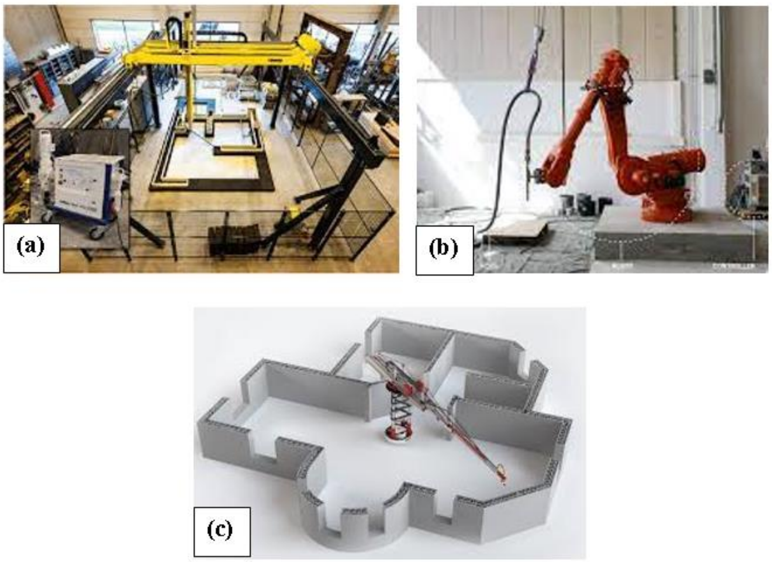


Figure 4-1 Current 3D Concrete Printers, a) Gantry Printers [39], b) 6-Axis Robot Printers [40] c) Crane Printers [41].

4.2 Design plan

As mentioned above, the serial profiles are used in the 3D concrete printer and with the original purpose of the project is a printing space with a size of 4x4x3m along with the profile. Uncomplicated printing is suitable for the 3-degree freedom mechanism. Therefore, the configuration of the truss system is preferred. In practice, gantry configurations have been used with various variations based on the drive structure. These types of variants were reviewed by the research team and selected 3 design ideas below.

4.2.1 option 1

The structure of the gantry system is the same as a gantry crane running on 2 rails (in the x-direction). The working head (P) is moved on the horizontal beam (in the y-direction) and the height will change by sliding up and down 2 vertical bars (in the z-direction) as shown in **Figure 4.2**

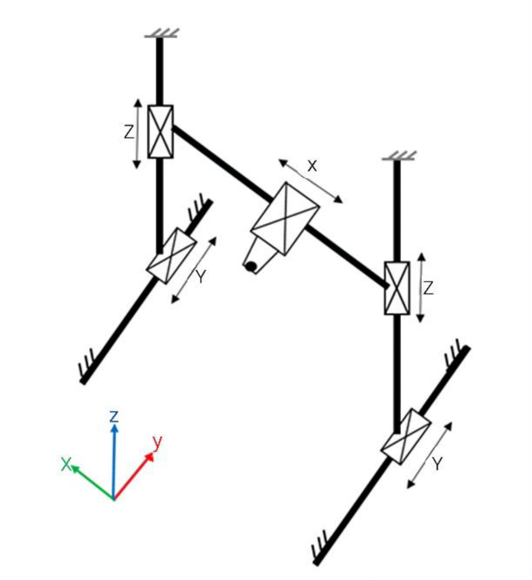


Figure 4-2 Option 1

In this option 1, the rack and pinion helical gears used to create movement in the x and y directions. Meanwhile, chain and sprocket are used to create an up-and-down motion for the z-direction.

4.2.2 **Option 2**

A more complex truss system with 4 linear z-axes carries two side beams and a transverse beam that moves in the z-direction as shown in **Figure 4.3**. In terms of x, y, the transmission and movement mechanism as in option 1.

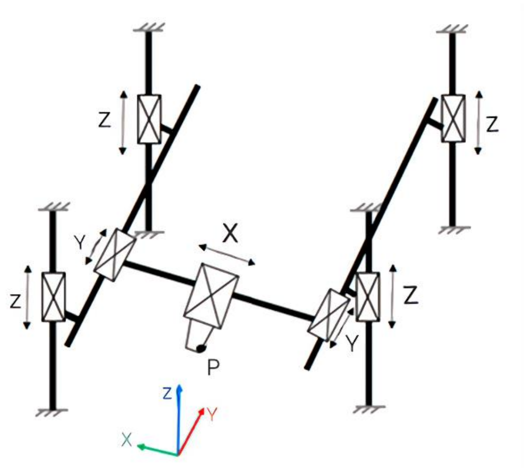


Figure 4-3 option 2

With this concept, when done with a large operating space, the structure of the whole system is very complex to ensure stability.

4.2.3 **Option 3**

In this embodiment, a truss system is placed and moved onto the frame with dimensions according to the operating space, thus following the x-axis, y drive and move as option 1. In the z-direction, a vertical rod bears the working head. are moved up and down as shown in Figure 4.4.

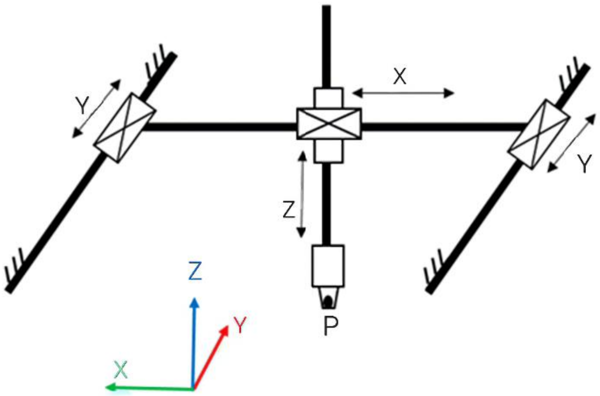
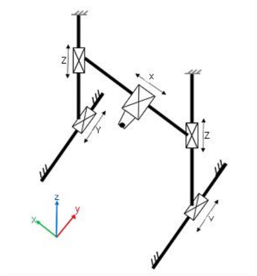
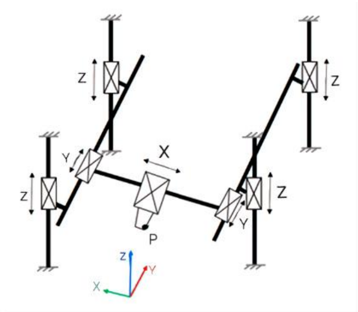
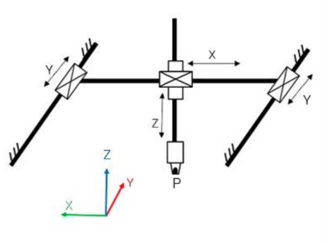


Figure 4-4 Option 3

With 3 options given, the choice of a design idea will be based on the optimal characteristics of that idea. The characterization is based on the objective and subjective factors of each option presented in **Table 4.1**.

With 3 options given, the selection of a design idea will be based on the optimal characteristics of that idea. The characterization based on the objective and subjective

Table 4-1 factors of each option is presented in 3DCP.

Project	Character
 1	A simple truss structure. The operating length in the y-direction can be extended by lengthening the track length. It is necessary to use 5 drive motors.
 2	A complex truss structure. Difficult disassembly requires high-precision synchronization in 4 longitudinal pillars. It is necessary to use 7 drive motors.
 3	A complex truss structure. It is necessary to use 7 drive motors. Takes up more space in height than the above two concepts.

4.2.4 The optimal choice of design plan

With the structural requirements of the machine with a large working space and the accuracy of the working head is not high (with a deviation of 2mm), ensuring stability when operating, along with the flexibility in disassembly needs to be a top concern.

For option 3, the overall size of the machine will increase significantly in height when the z-axis is raised, and the complex gantry, assembly and disassembly frame face many limitations.

In option 2, the overall size of the machine will also be very large with 4 stages of translational movement up and down of 4 cylinders along the z-axis, and the synchronous control of 4 engines will become complicated.

Limiting the disadvantages of the above two concepts with concept 1, a printer will be moved on two parallel rails. This will also lead to a disadvantage when inertia is created by the machine when traveling on large rails. But if this problem is well controlled, there will be other advantages to mention such as the structure of the machine is simpler, the flexibility in disassembly will be more optimal than the above 2 concepts, especially the use of rails will not be limited. Print length when extending rails to increase workspace is feasible.

From the above conclusions, the team chose option 1 as the design idea of the project.

4.3 Design and simulation.

4.3.1 3DCP Design Modeling

Option 1, after being selected as the design option of the project, the team modeled using a dynamic diagram as shown in **Figure 4.5**. Dynamic schematic modeling helps to better understand the design as well as calculate the kinetic problem more conveniently.

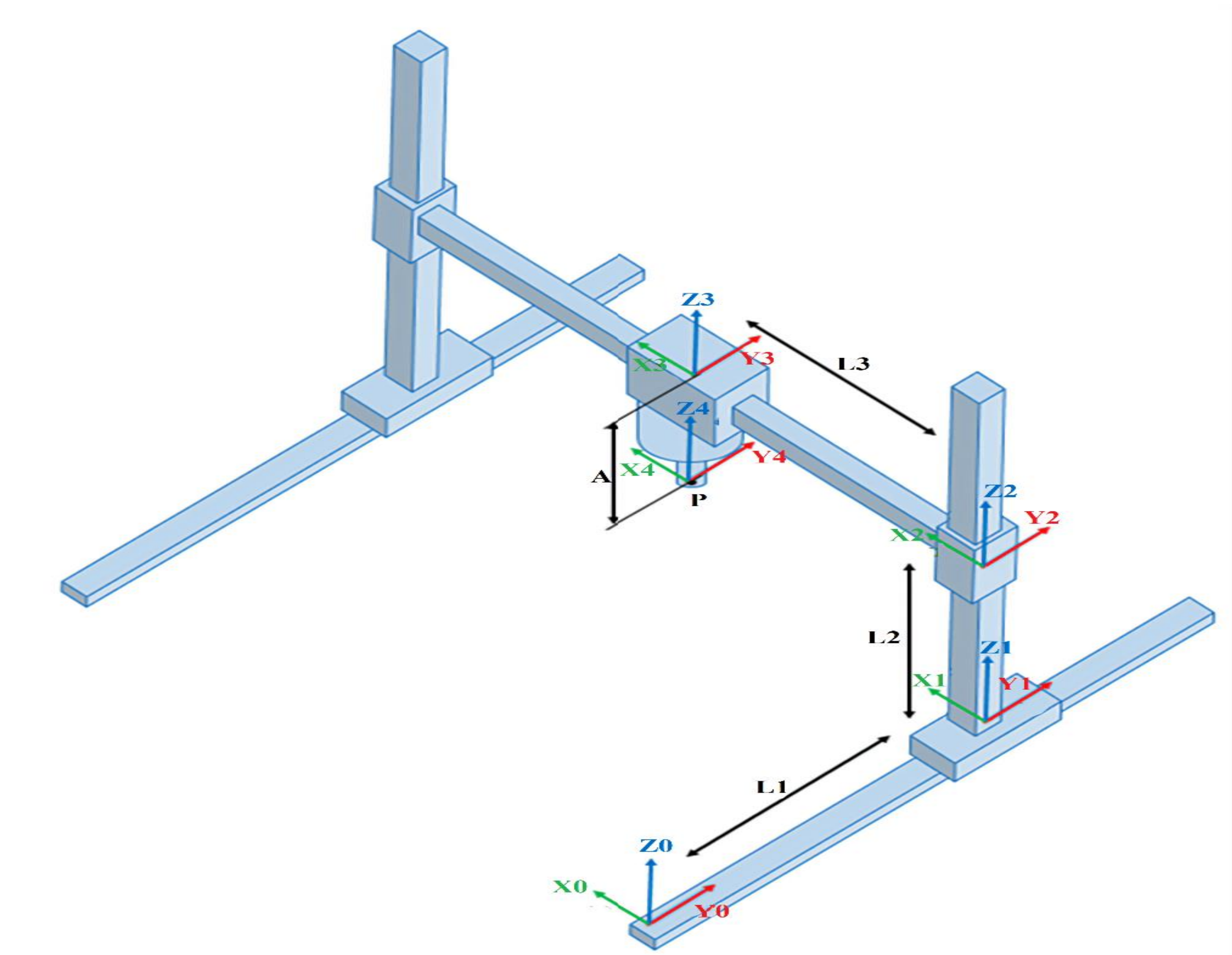


Figure 4-5 3DCP Model.

4.3.2 Drive plan

With a large operating space and high load capacity, choosing the right actuator (motor) option is crucial. With three degrees of freedom according to the Cartesian coordinate system as shown in **Figure 4.5**, translational motion along the y and z axes requires 2 actuators in parallel and controlled synchronously with each other, translational motion along the x-axis requires only 1 actuator. The team chose the rack and pinion gears transmission for the x, y, and z-axis because of the advantages listed in **Table 4.2**.

Table 4-2 Transmission characteristics of each shaft.

	Drive characteristics
x,y,-axis rack and pinion gears	Large length of motion. Large load capacity. Average speed and acceleration. Quiet drive, low noise. Easily adjust the working stroke when the machine structure changes.
z-axis chain and sprocket	Large length of motion. Large load capacity. Easily adjust the working stroke when the machine structure changes

4.3.3 Structural simulation 3DCP

After modeling the design and selecting the drive option. Based on the dimensional parameters of the operating space along with material printing speed requirements, the team calculated, analyzed, and designed the 3D model as **shown in Figure 4.6**. With truss structure, the frame of the details has **crossbars** to increase the rigidity of the machine's structure.

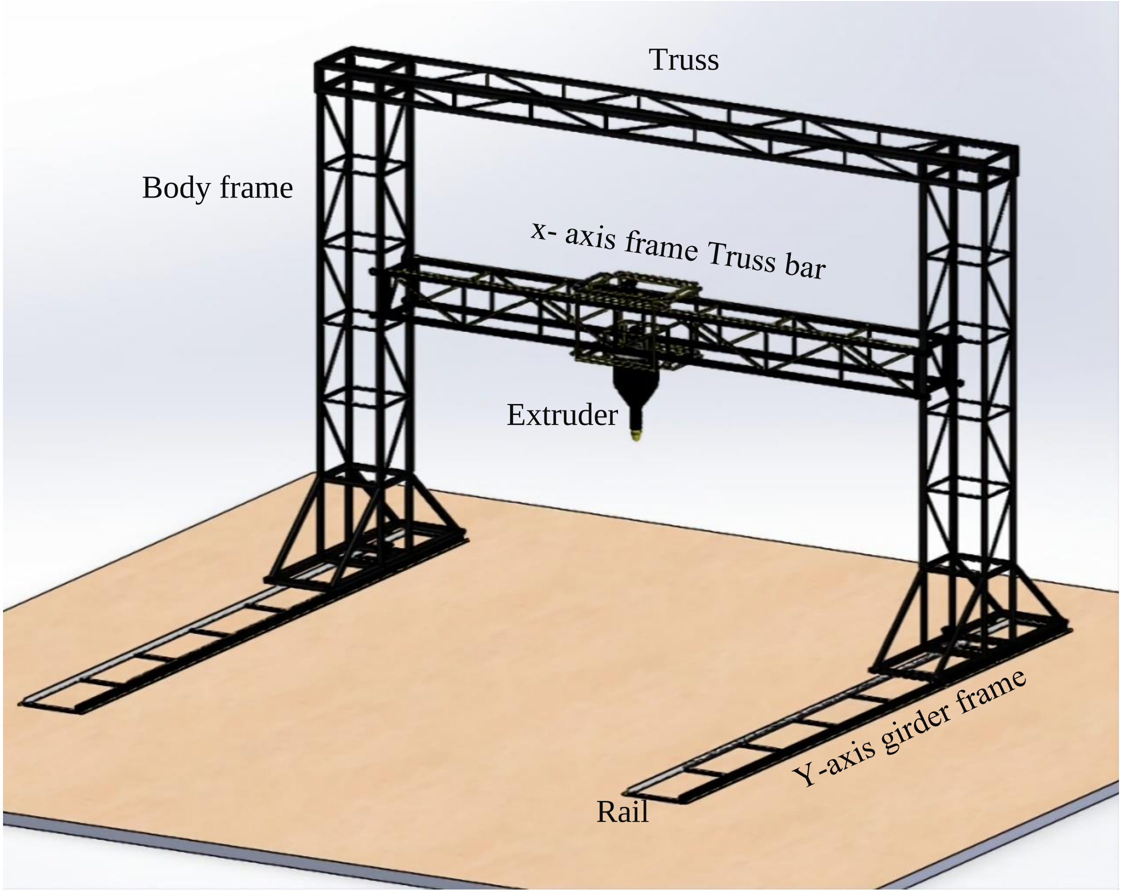


Figure 4-6 The design of the machine

In this 3D model, the details and parts of the machine must ensure durability, resistance to deformation as well as must know in advance the points with the greatest stress to have plans to adjust the design for the machine, suitable to help ensure the durability of the machine.

The mass of parts and parts greatly affects the finding of stresses and displacements at the time of simulation. In addition, finding out the mass will make it possible to determine the load for the transmission process accurately. Thanks to simulation software, we can predict the mass of the parts in **Figure 4.6** listed in **Table 4.3**.

Table 4-3 Mass of the machine.

No.	Part	Amount	Mass
1	Body	2	~ 410 kg
2	X-axis transverse beam	1	~ 105 kg
3	Extrusion	1	~ 101kg
4	Fixed transverse beam	2	~ 70 kg
5	Railway	2	~ 300 kg
Total		~ 986 kg	

The analysis of the strength of the entire chassis is considered difficult due to its many complex shapes and assembly from many parts together. Therefore, the team used software to assist in analyzing the strength of critical bearing components. From there, durability testing work becomes more convenient and easier.

Below are **Figure 4.7** and **Figure 4.8** showing the strength of the X-axle crossbar and the V-wheel. The two most important load-carrying details that the team was interested in.

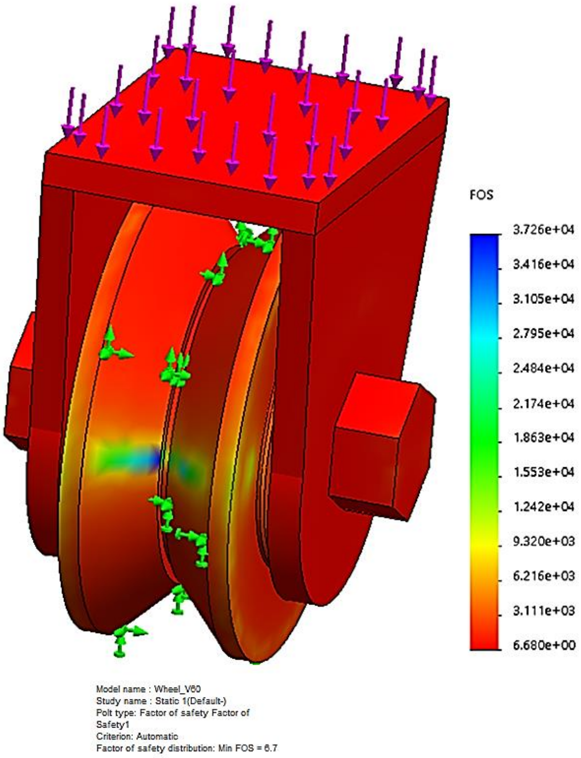


Figure 4-7 Results of V-wheel strength analysis.

The V-shaped wheel element rolling on the guide rail moves the machine along the x-axis and experiences a vertical force perpendicular to the plane of the wheel support. This force is the mass of 3DCP under gravity with an estimated value of 1250N because the load is divided equally among the 8 V-wheels. The above analysis results show that the safety factor achieved is 6.7, this value satisfies the load requirement.

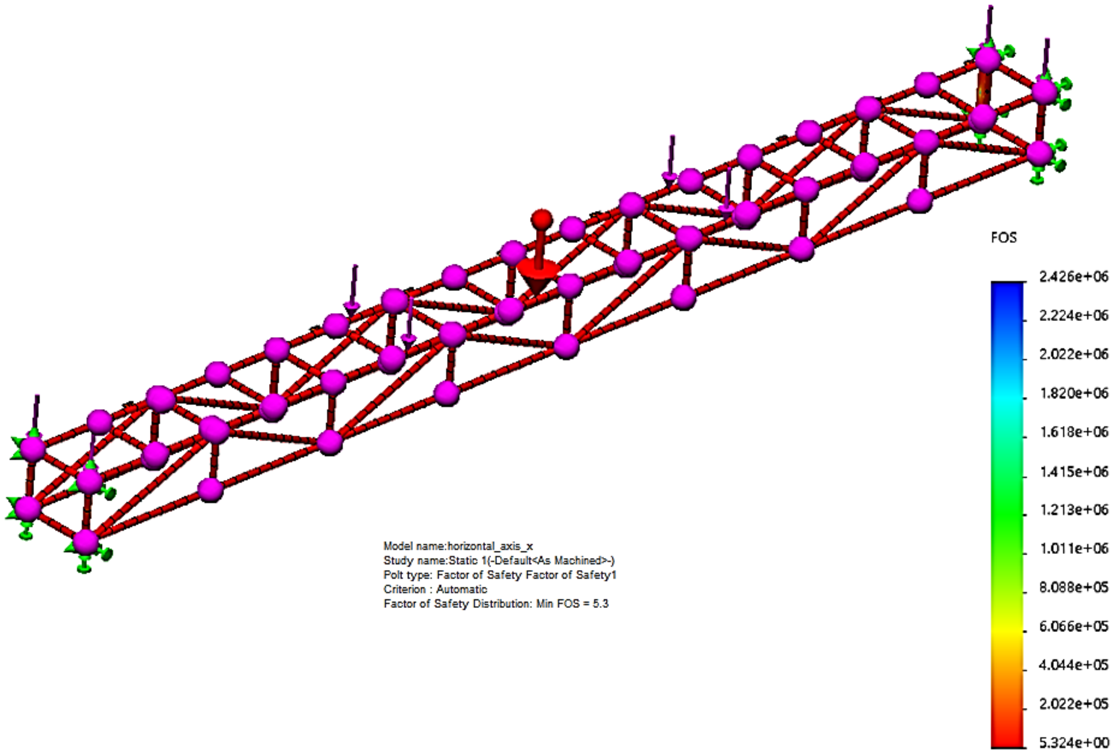


Figure 4-8 Results of x-axis strength analysis.

The x-axis horizontal beam bears the force of the extruder moving on it. This force is the mass of the extruder along with the mass of the material inside, in addition to taking into account the weight itself of the beam. The two edges of the beam are fixed with bolts. The results of the above analysis show that the safety factor achieved is 5.3, this value satisfies the requirements of loads and operating conditions.

4.4 Kinetics

After designing the muscle part to match the set configuration. Next is kinematic calculations. For the robot kinematics problem, analyzing the position of the working head is the most important problem. There are two types of position analysis problems: forward problems and inverse problems. **The translational problem** determines the position and direction of the working head when the length of the link is known. **The inverse problem** calculates the reasonable length of the links when knowing the position of movement of the working head. Finding the right forward and reverse problem will make the control problem easier and more accurate.

In order to easily determine the kinematic problem of the machine, modeling (**Figure 4.5**) will easily visualize the coordinates and distances of the links, thereby making it more convenient to determine the kinetic problem. With this model, there will be 3 degrees of freedom, which are translational motions along the 3 axes of the Cartesian coordinate system.

4.4.1 Forward kinetics

To determine the kinematics of the robot, it is first necessary to determine the displacement matrix from the origin point to the point P.

$$^0T_4 = T(0, L_1, 0).\ T(0, 0, L_2)\ .\ T(L_3, 0, 0)\ .\ T(0, 0, -A)$$

$$=> {}^0T_4 = \begin{bmatrix} 1 & 0 & 0 & L3 \\ 0 & 1 & 0 & L1 \\ 0 & 0 & 1 & L2 - A \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4.1)$$

4.4.2 Inverse kinetics

From the forward kinematics problem, we can easily calculate the inverse kinematics problem as follows:

$$^0P = {}^0T_4\ .\ {}^4P$$

$$=> {}^0P = \begin{bmatrix} 1 & 0 & 0 & L3 \\ 0 & 1 & 0 & L1 \\ 0 & 0 & 1 & L2 - A \\ 0 & 0 & 0 & 1 \end{bmatrix} \text{x} \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} L3 \\ L1 \\ L2 - A \\ 1 \end{bmatrix} \quad (4.2)$$

From the results can determine:

1. $P_x = L3$
2. $P_y = L1$
3. $P_z = L2 - A$

From here derive the values of variables L1, L2, L3

- $L_1 = P_y$
- $L_2 = P_z + A$
- $L_3 = P_x$

4.5 Dynamics

The dynamics problem is very important in robot design, from the dynamics problem will determine that we need an actuator capable of generating a force or torque large enough to bond the robot to create motion with the necessary acceleration and velocity. In this model, the team ignored friction and electromechanical dynamics.

The Lagrangian equation is used in this dynamical model because of its effectiveness in complex systems. The Lagrangian equation based on differential calculus of energy components with system and time variation is given as follows [42]:

$$\frac{\partial}{\partial t}\left(\frac{\partial L}{\partial q^{'}}\right)-\frac{\partial L}{\partial q}=\tau \qquad (4.3)$$

where q is the vector n of the general system with component axes qi, τ is the vector n of the combined force with the component forces τi, and the LaGrange function is the difference of kinetic energy minus potential energy.

$$L = K - P \quad (4.4)$$

For the 3DCP model of three degrees of freedom similar in structure to the Cartesian system depicted in **Figure 4.5**, the dynamics problem is calculated as follows:

Kinetic energy of bond 1: $K_1 = \frac{1}{2}\times m_1 \times (l_1^{'})^2$

Kinetic energy of bond 2: $K_2 = \frac{1}{2}\times m_2 \times [(l_1^{'})^2 + (l_2^{'})^2]$

Kinetic energy of bond 3: $K_3 = \frac{1}{2}\times m_3 \times [(l_1^{'})^2 + (l_2^{'})^2 + (l_3^{'})^2]$

The total kinetic energy of the system is:

$$K = \frac{1}{2}\times m_1 \times (l_1^{'})^2 + \frac{1}{2}m_2 \times [(l_1^{'})^2 + (l_2^{'})^2] + \frac{1}{2}m_3 \times [(l_1^{'})^2 + (l_2^{'})^2 + (l_3^{'})^2] \qquad (4.5)$$

Potential of the system:

$$P = (m_2 + m_3)\times g \times l_2 \qquad (4.6)$$

Lagrange function:

$$L = \frac{1}{2} \times m_1 \times (l_1^{'})^2 + \frac{1}{2} m_2 \times [(l_1^{'})^2 + (l_2^{'})^2] + \frac{1}{2} m_3 \times [(l_1^{'})^2 + (l_2^{'})^2 + (l_3^{'})^2] - (m_2 + m_3) \times g \times l_2$$

(4.7)

Simplify the expression and return it to vector form

$$\begin{bmatrix} F_1 \\ F_2 \\ F_3 \end{bmatrix} = \begin{bmatrix} m_1 + m_2 + m_3 & 0 & 0 \\ 0 & m_2 + m_3 & 0 \\ 0 & 0 & m_3 \end{bmatrix} . \begin{bmatrix} l_1^{"} \\ l_2^{"} \\ l_3^{"} \end{bmatrix} + \begin{bmatrix} 0 \\ (m_2 + m_3)g \\ 0 \end{bmatrix} \qquad (4.8)$$

4.6 Select engine and drive parameters for 3DCP

4.6.1 Analyze technical resistance at each link

The analysis of technical resistance at all links is really necessary to help calculate and select the correct and appropriate engine and actuator parameters, ensuring that the machine always operates at the right capacity. The physical parameters of 3DCP are shown in Table 4.4.

Table 4-4 Physical parameters on three degrees of 3DCP

Describe	Symbol	Values	Unit
Z Block Link 1	m1	480	kg
Y Volume Link 2	m2	105	kg
X Block Link 3	m3	150	kg
Gravitational acceleration	g	9.81	m/s^2
Link acceleration 1	$l_1^{"}$	0.5	m/s^2
Link Acceleration 2	$l_2^{"}$	0.2	m/s^2
Link Acceleration 3	$l_1^{"}$	0.5	m/s^2

From the Dynamics equation above (4.8) along with the parameters of the masses and accelerations of the bonds in **Table 4.4**, we find the required force at each link as follows:

$$\begin{bmatrix} F_1 \\ F_2 \\ F_3 \end{bmatrix} = \begin{bmatrix} 480+105+150 & 0 & 0 \\ 0 & 105+150 & 0 \\ 0 & 0 & 150 \end{bmatrix} . \begin{bmatrix} 0.5 \\ 0.2 \\ 0.5 \end{bmatrix} + \begin{bmatrix} 0 \\ (105+150) \times 9.81 \\ 0 \end{bmatrix} = \begin{bmatrix} 367.5 \\ 2552 \\ 75 \end{bmatrix} (N)$$

4.6.2 Motor selection and y-shaft drive parameters

With the force required to link 1 movement defined above is F1 = 367.5 N. With the power transmission plan using the tooth rod and gear on both sides of the rail, the force applied to the tooth rod (Fr) will be reduced. 2 times. The calculation of the selection of tooth rods and rods is selected by the team according to the manufacturer's instructions. With the force acting on the price Fr = 183.75 N, the coefficients KA, SB, fn, LKHB are provided by the manufacturer to calculate the force required on the price (Frct) [43].

Frct = Fr x KA x SB x fn x LKHB = 183.75 x 1.5 x 1.2 x 1.1 x 1.5 = 545.7 (N) (4.9)

From the force applied to the required tooth rod, we proceed to select the maximum load parameter of the tooth rod so that it is greater than Frct. With this condition, the team selected a 1.25 gear modular rack , a 1.25-gear module with a number of teeth of 30, the manufacturing material is C45 steel that can withstand a maximum load of 4500 (N) [44].

Motor power required to move the machine along the y-axis at a maximum speed of 200mm/s

$$\Rightarrow P_{qt} = \frac{F.v}{1000} = \frac{183.75 \times 0.2}{1000} \approx 0.04kW \quad (4.10)$$

- Efficiency of the reducer: $\eta_{hs} = 0.8$
- Open gear transmission efficiency: $\eta_{br} = 0.93$
- Overall transmission performance: $\eta = \eta_{hs}.\eta_{br} = 0.8 \times 0.93 = 0.744$
- Engine power:

$$P = \frac{P_{qt}}{\eta} = \frac{0.04}{0.744} \approx 0.054kW$$

We have the formula:

$$v = m \times z \times \pi \times n \quad (4.11)$$

Where:

v : travel speed (mm/s)

m: modulus of gear

Z: the number of teeth of the gear

π = 3.14

n: gear revolutions (RPS)

$$\Rightarrow n = \frac{v}{m \times z \times \pi} = \frac{200}{1.25 \times 30 \times 3.14} \approx 1.69\ rps$$

With a selected reducer with a gear ratio of 1:10, the number of revolutions of the engine:

$$n_{dc} = n \times 10 \times 60 = 1.69 \times 10 \times 60 = 1014 \text{ rpm}$$

From the two power and rotational speed parameters required with the existing motor, the team selected the SY series 80SY-M03230S1-5 AC servo motor with the parameters in **Table 4.5**.

Table 4-5 80SY-M03230S1-5 AC servo motor

Rated power	1000 W
Maximum torque	3.19 Nm
Rated speed	2000 rpm
Top speed	3000 rpm
Rated voltage	1 phase 200 – 230 VAC
Rated amperage	6 A
Voltage frequency(f)	50/60 Hz ± 5%
Moment of inertia (J)	J = $8.41.10^{-4}$ $Kg.m^2$
Mass	8.4 Kg
Input control signal frequency	1 – 200 KHz

4.6.3 Select motor parameters and x-shaft drive

The force required for the 3-motion link as defined above is F3 = 75 N. With the power transmission option using tooth rods and tooth rods. The calculation of the selection of tooth rods and rods is selected by the team according to the manufacturer's instructions. With the force applied to the tooth rod Fr = 75 N, the coefficients KA, SB, fn, LKHB are given by the manufacturer to calculate the force acting on the tooth rod (Frct)

Frct = Fr x KA x SB x fn x LKHB = 75 x 1.5 x 1.2 x 1.1 x 1.5 = 222.75 (N)

From the force applied to the required tooth rod, we proceed to select the maximum load parameter of the tooth rod so that it is greater than Frct. With this condition, the team selected a helical 1.25-tooth rack tempering module, a helical pinion 1.25-gear module with a number of teeth of 30, the manufacturing material is C45 steel that can withstand a maximum load of 4500 (N).

Motor power required to move the machine along the x-axis at a maximum speed of 200mm/s

$$\Rightarrow P_{qt} = \frac{F.v}{1000} = \frac{75 \times 0.2}{1000} = 0.015kW$$

- Reducer performance: $\eta_{hs} = 0.8$

- Open gear transmission efficiency: $\eta_{br} = 0.93$

- Overall transmission performance: $\eta = \eta_{hs}.\eta_{br} = 0.8 \times 0.93 = 0.744$

- Required power of the motor:

$$P = \frac{P_{qt}}{\eta} = \frac{0.015}{0.744} \approx 0.02kW$$

We have the formula: $v = m \times z \times \pi \times n$

Where: v is the speed of movement (mm / s)

m: modulus of gear

z: the number of teeth of the gear

π = 3.14

n: gear revolutions (rps)

$$\Rightarrow n = \frac{v}{m \times z \times \pi} = \frac{200}{1.25 \times 30 \times 3.14} \approx 1.69\ (rps)$$

With a selected reducer with a gear ratio of 1:10, the number of revolutions of the engine:

$$n_{dc} = n \times 10 \times 60 = 1.69 \times 10 \times 60 = 1014 \text{ rpm}$$

From the two parameters of power and rotational speed required with the existing motor, the team chose SY series 80SY-M03230S1-5 AC servo motor for synchronous and convenient control of the x and y axes.

4.6.4 Select motor parameters and z-axis drive

With the force required to link 1 movement defined above is F1 = 2552 N. With the power transmission plan using the tooth rod and gear on both sides of the rail, the force applied to the tooth rod (Fr) will be reduced. 2 times.

The calculation of the selection of tooth rods and rods is selected by the team according to the manufacturer's instructions. With the force acting on the price Fr = 1276 N, the coefficients KA, SB, fn, LKHB are provided by the manufacturer to calculate the force required on the price (Frct) [43].

Frct = Fr x KA x SB x fn x LKHB = 1276 x 1.5 x 1.2 x 1.1 x 1.5 = 3789.72 (N)

From the force applied to the required tooth rod, we proceed to select the maximum load parameter of the tooth rod so that it is greater than Frct. With this condition, the team selected a chain and sprocket with a number of teeth of 30, the manufacturing material is C45 steel that can withstand a maximum load of 4500 (N) [44].

Motor power required to move the machine along the y-axis at a maximum speed of 200mm/s

$$\Rightarrow P_{qt} = \frac{F.v}{1000} = \frac{1276 \times 0.2}{1000} = 0.255kW$$

- Reducer performance: $\eta_{hs} = 0.8$

- Open gear transmission efficiency: $\eta_{br} = 0.93$

- Overall transmission performance: $\eta = \eta_{hs}.\eta_{br} = 0.8 \times 0.93 = 0.744$

- Required power of the motor:

$$P = \frac{P_{qt}}{\eta} = \frac{0.255}{0.744} \approx 0.343kW$$

We have the formula: $v = m \times z \times \pi \times n$

Where: v is the speed of movement (mm / s)

m: modulus of gear

Z: the number of teeth of the gear

π = 3.14

N: gear revolutions (RPS)

$$\Rightarrow n = \frac{v}{m \times z \times \pi} = \frac{200}{1.25 \times 30 \times 3.14} \approx 1.69\text{Rps}$$

With a selected reducer with a gear ratio of 1:20, the number of revolutions of the engine:

$$n_{dc} = n \times 20 \times 60 = 1.69 \times 20 \times 60 = 2028 \text{ rpm}$$

From the two parameters of power and rotational speed required with the existing motor, the team chose SY series 80SY-M03230S1-5 AC servo motor for synchronous and convenient control of the x , y and z axes.

Thus, in this topic, configuration design options for 3DCP have been given along with the selection of the most optimal option suitable for the purpose of the project has also been mentioned. Besides, there is a way to calculate problems of kinetics, dynamics, drive options, motor selection, drive parameters for each link of the machine. The next chapter will detail the electrical control system for 3DCP, which is an important and integral part of any mechatronic system.

CHAPTER 5

CONTROL SYSTEM DESIGN

5.1 About AC Servo

The structure of the 3DCP control system and hardware devices such as Windows-based computers are used as the main controller. Other devices such as AC Servo drivers and motors, Mach3 circuits,...

Overview diagram of the system:

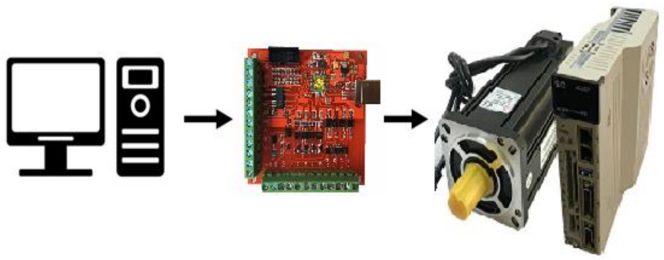


Figure 5-1 An overview diagram of the devices of the system.

The serial configuration machine controller includes computer-like parts including the central processing unit, memory, in addition to a Mach3 board connected to serve as an interface between the computer and peripherals, this is the controller for servo motors as well as sensors mounted on the machine.

5.1.1 Controller

- Central Controller:

The central controller plays an important role in interacting with the user's system through the Control Panel. The central control block consists of a signal control CPU and a central control circuit. The signal control CPU operates with a voltage of 220VAC-50Hz with the characteristic of stable operation under continuous conditions.

The central control circuit operates with a voltage of 5-24VDC 5A, for the purpose of supplying and receiving control signals of actuators, sensors,...

- Main controller:

The main controller has a very important role in control, taking on the role of receiving data from the central controller then executing complex commands to control the actuator at the request of the controller and responding to the necessary data information about the central controller processing. The central controller can be a microcontroller, a high-speed processor ...

Since the 3DCP has a Cartesian coordinate system, for ease of control, the team decided to use the Mach3 CNC Board. Mach3 CNC is now very popular in the industrial market because it can control multiple axes at the same time with high speed, high safety and reliability, the price is also very reasonable, not too high as the high-speed microprocessor boards available on the market. It is for these reasons that the team uses the Mach3 board as the main controller to play the role of high-speed pulse output to control the motor to comply with user requirements.

5.1.2 Drivers and motors

The main actuator of the system is 6 motors mounted with tooth rods and gear transmissions, and extruders. For these mechanisms to work, it is necessary to provide power as well as control power to the driver. Therefore, with the motor power calculated in chapter 4. I chose the right motive. Attached to the motor is the Driver controller, the voltage supplied to the controller is 220VAC, the control signal uses a voltage of 12VDC.

5.1.3 Other equipment

12VDC power supply: In order for Mach3 and devices such as Drivers to work, there must be a suitable power supply for the device.

5.2 Central control system design

After selecting the appropriate necessary equipment, the team proceeds to arrange and install the Electrical Cabinet. Due to the large size of 3DCP, using many motors, the system slides over long distances, so it is imperative to install an electrical cabinet on the body to easily control and receive the signal returned from the encoder in the most accurate way and avoid interference or loss of pulse. Electrical cabinet installation location in **Figure 5.2**.

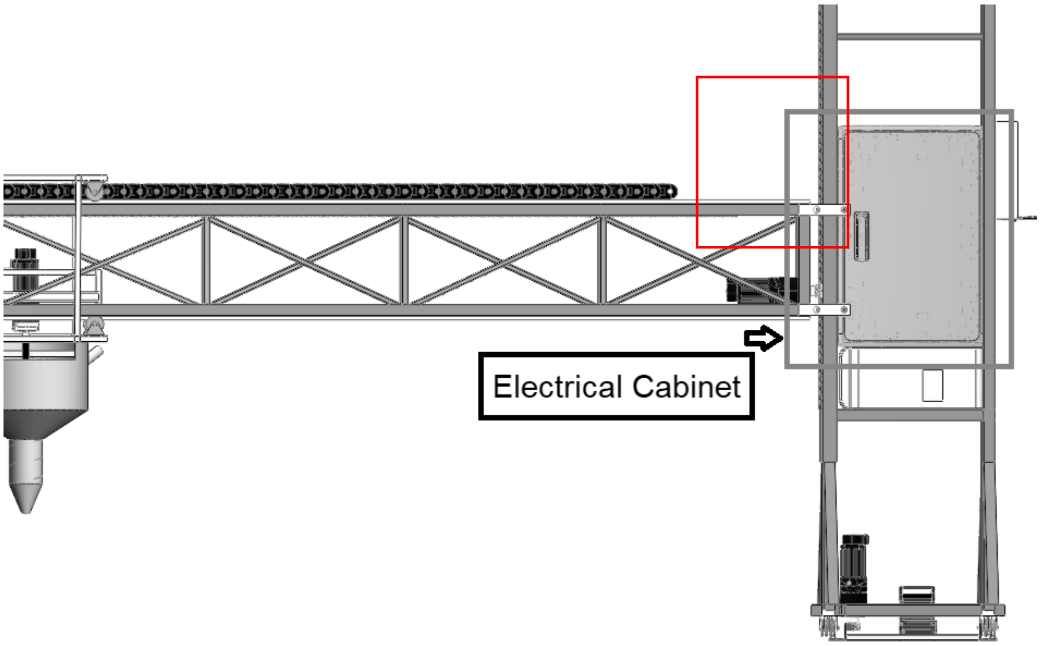


Figure 5-2 Installation location of electrical cabinets.

In the cabinet arranged equipment such as Mach3 Board, Driver, 24V power supply, other equipment ... The central control cabinet has parts made from galvanized steel and is also powder sprayed. This type of electrical cabinet has a local mechanism of operation, that is, it can be controlled remotely in case you want to reverse the motor, change the rotational speed of the motor, and switch the motor.

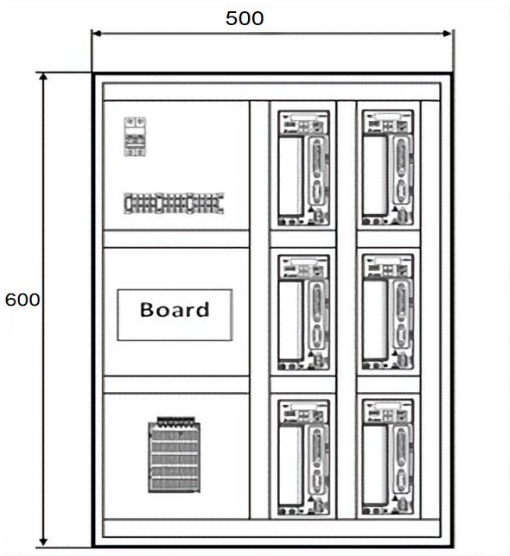


Figure 5-3 Diagram of the layout of devices in electrical cabinets.

In order for the devices to run properly and correctly, the devices must connect. Power needs to be supplied to the Mach3 board, driver, motor and pulses will be output from Mach3 to control the motor via div

er as well as receive signals from sensors to set position the original of the extruder. Therefore, we need to draw the dynamic circuit to make the process of connecting electrical cabinets simpler.

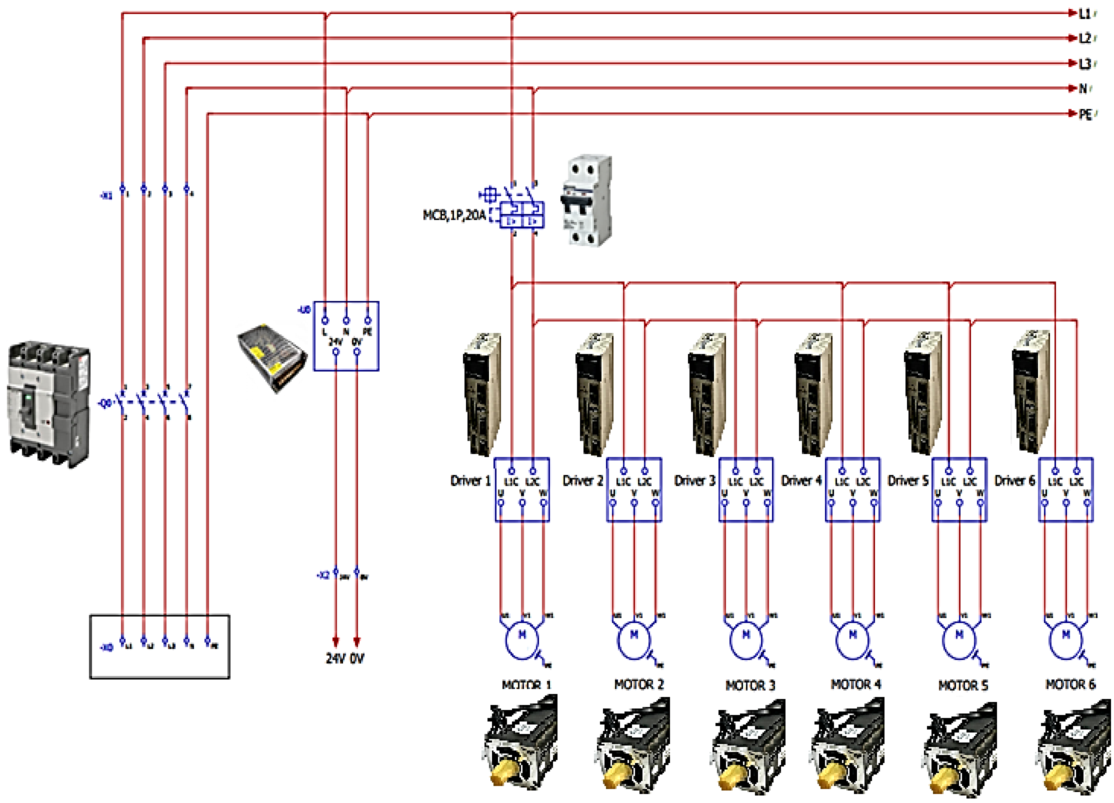


Figure 5-4 Dynamics circuit diagram.

In addition, the CPU is located under the electrical cabinet, the monitor and keyboard are placed on the frame as shown in Figure 5.5 will minimize the connection cable between the CPU and the control board for best communication.

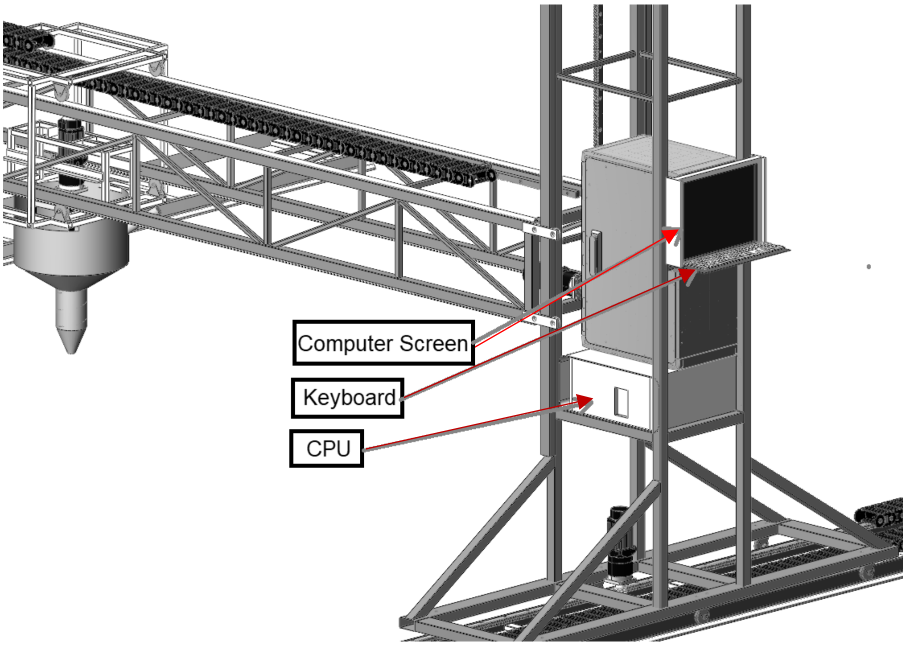


Figure 5-5 Where to install the CPU, computer monitor, and keyboard.

5.3 Controller structure

The controller of the 3DCP consists of many different components. The most important task of the controller is to control the position and speed of the drive motor through gear transmissions, screws, the speed of the extruder so that the cement stream is extruded continuously, in the right size and accurately.

The 3DCP control signal comes from computer software, the command chains are sent to the controller via Mach3 software installed on the computer to control the position, motor speed, as well as the extruder's control commands. At the same time, the system also attaches limit switches at the ends and ends of the shafts to bring feedback signals, rely on that to set the initial Home location, avoiding the situation that the machine goes over the limit causing risks. Figure 5.6 is the overall diagram of the entire robot control system.

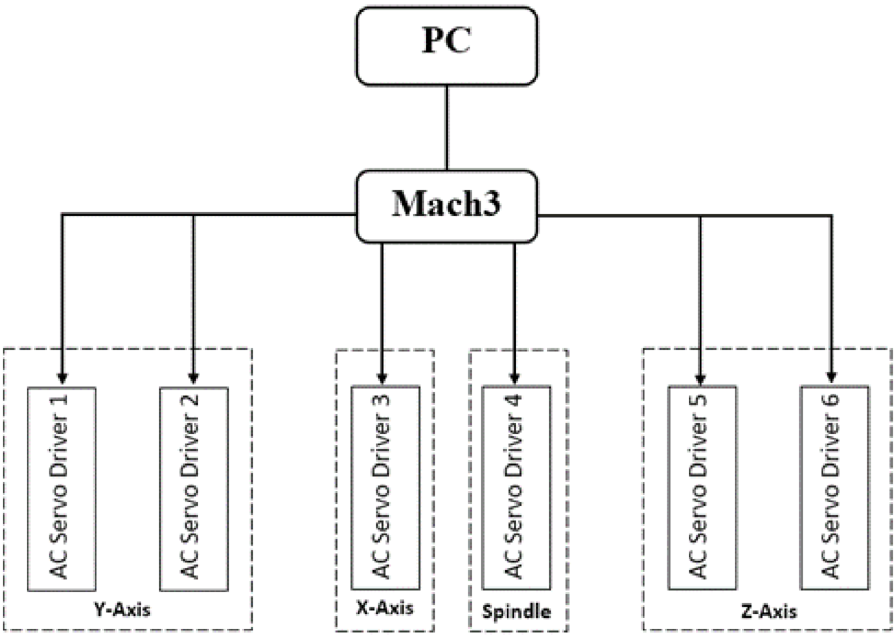


Figure 5-6 Overview diagram of the controller structure.

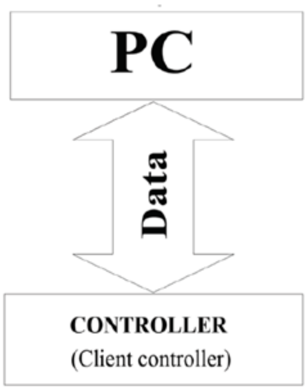


Figure 5-7 Communication diagram between PC and controller.

The central controller receives commands from the PC via Mach3 software. When the user asks the robot to perform a certain job, by entering G-code coordinates into the control screen, the software will immediately transmit and execute the operator's requests according to the instructions entered in the previous value.

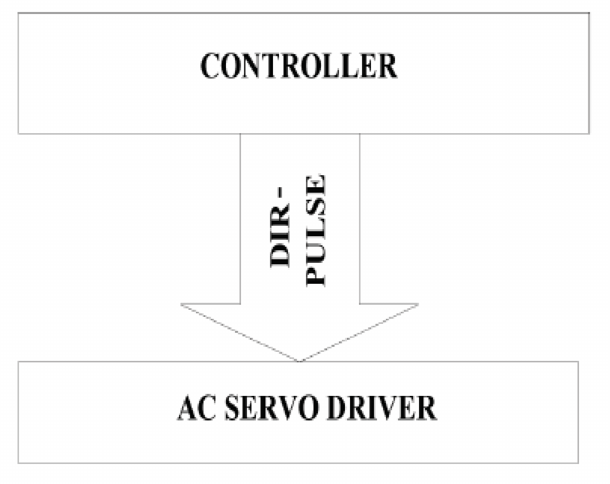


Figure 5-8 Driver diagram receiving signals from Mach3.

After receiving data from the PC, the Mach3 board proceeds to send signals to AC Servo Drivers, namely sending PULSE and DIR as shown in **Figure 5.9**.

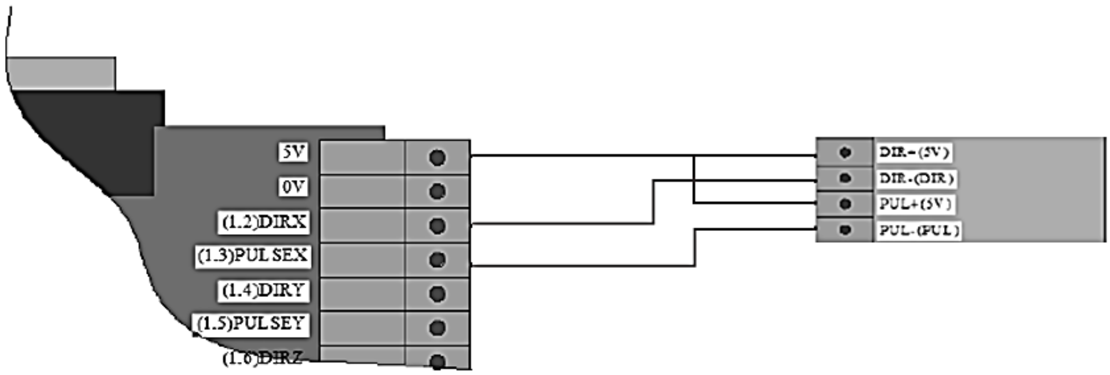


Figure 5-9 Diagram of connecting the pins from Mach3 to the control pins of the driver.

It can be said that the driver controller has certain advantages such as operation in position control mode (Dir - Pulse), speed control, torque control, ... Inside there is a pulse buffer (softening intermittent movements caused by the control process) to achieve. highest pulse receiving speed. In addition, the driver also integrates a PID controller and intelligent pulse compensation to make control easy and accurate,...

5.4 Communication methods

5.4.1 Mach3 overview

Mach3 is ArtSoft's software, originally designed for custom CNC machine builders, but has quickly become flexible control software in industry.

Some features and basic scores offered by Mach 3

- Turn your PC into a full-featured 3-axis controller.

- Display G-code visually.

- Fully customizable interface according to user preferences.

- Spindle speed control, here is an extruder for extrusion of cement materials.

- Control multiple switchgear relays.

5.4.2 Communication between the computer and Mach3

Communication between the control software on the computer and the Mach3 board, in this case, the computer controls the operation of the circuit, thereby controlling 6 motors that bring the extruder to the desired position.

To implement communication between the computer and the Mach3 board, our team used the USB printer Cable to connect the computer to the board.

The shaft control system of 3DCP consists of 1 Mach3 board used to control 6 SY series AC Servo motors including 2 Y shaft motors, 1 X shaft motor, 2 Z-shaft motors and 1 extrusion motor through 6 SY-series AC Servo motor.

The tasks of the system are as follows:

Control the speed and position of the axes through the number of output pulses and output pulse frequency.

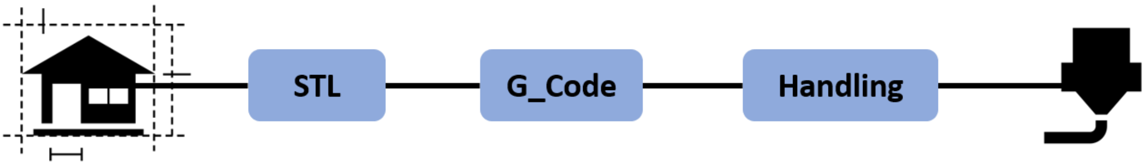
Communicate with the computer using the USB printer Cable to send signals to control the motors through software on the computer.

But because the transmission distance was limited to within 1m from the USB printer Cable, the team decided to install the computer CPU underneath the electrical cabinet to ensure the best data transfer.

CHAPTER 6

SIGNAL PROCESSING PROCESSES AND SOFTWARE ARCHITECTUR E

In the previous chapter, the topic presented the design and calculation of the mechanical part of the machine, kinematics, dynamics, control systems as well as understanding the theoretical basis of 3D printing of concrete materials. In this chapter, the team presents the structure of the microprocessor along with the control software. For stable operation of the robot, the processing of commands before starting and the control software is complete. Pre-processing of the command consists of steps, creating 3D drawings on 3D software, exporting STL format, and generating G-code path files, finally processing the path command for stable and optimal operation as shown in Figure 6.1.



6.1 Create 3D drawings

The development of technology gives architects the freedom to design with unprecedented complexity and detail. Requires thinking about how fabrication meets complex design. New digital design tools offer opportunities for architects and engineers to perfect structures that are less material but more sustainable. Path control as part of the control allows shaping without the need for molds and simply placing the material in place to create the texture. Concrete 3D printing (3DCP) is the most common fabrication method studied as part of digital concrete [49]. From curing to curing, 3DCP printing is completely different from the traditional way concrete has been used so far. Modernize the construction industry with free architecture, reduce material waste, lower construction costs and enhance worker safety. 3DCP, contour construction [2] is an accretion method that uses stacked concrete to form complex designed shapes [50]. To increase the practical effectiveness of the 3DCP methodology, technical challenges in material formulation, rheology, processing, and reinforcement make design a top priority. Automation methods may be different, to complete a specific building by different construction methods. A path follows the entire contour of the entire building or is refinished from the assembly of wall sections. The works in development mostly use extruders ranging in diameter from ~6mm to 50mm, mounted on a truss or robotic arm to position the material in the process. The material used is usually mortar with high cement content, fine grain size ~3mm. The shape of the press head also varies from round, rectangular, or even ovoid with a steady speed of about 50mm/s to 500mm/s [51].

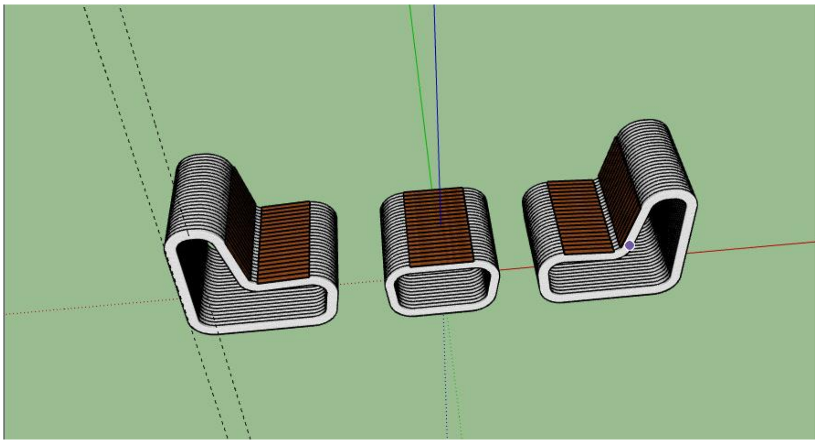


Figure 6-1 3D drawings on design software.

With the requirements of the machine used in construction. It is for that purpose that the machine is created with a large resolution (> 1mm). The large size of the output material results in a sufficiently large piling of materials. The minimum arc radius must be greater than or at least equal to the diameter of the extruder. The wall size must be greater than or equal to the extruder size. For the two basic reasons mentioned above, the overall shape, as well as the details in reality compared to 3D drawings are closely related.

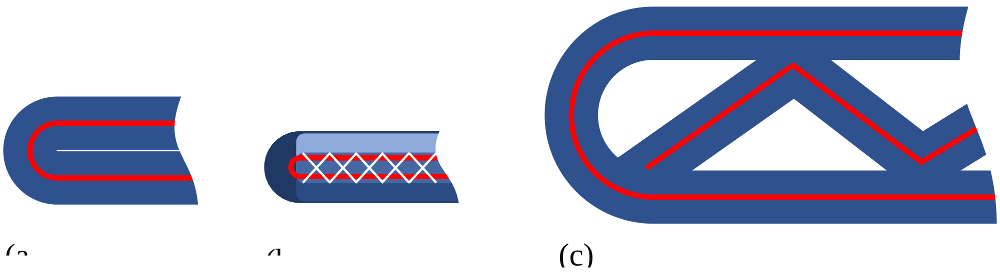


Figure 6-2 print path.

As can be seen in Figure 6.3 (a), the printed line has an arc radius greater than the diameter of the print head, so the print lines do not coincide. In Figure 6.3(b), the arc radius is less than the print head diameter, and the print lines are overlapping, which will affect the actual size compared to the 3D drawing, and also affect the next layer. Figure 6.3(c) is the shape of a wall, the movement of the wall and the support will not intersect. Because the material used is concrete, different from conventional 3D printing materials such as PLA, ABS,... Along with a print head size of 28mm instead of 0.4mm like plastic 3D printers. To avoid overlapping materials on the same layer, 3D drawing needs to be tight, limiting circular arcs to small radii.

The drawing process determines the shape and texture of the resulting product. First, drawings will be sketched and drawn on specialized 3D software such as SolidWorks, AutoCAD, Inventor,... The finished drawing will be converted to STL format for easy processing later.

6.2 Print file processing

A wall usually concerns only one side and connects to other parts of the house through the upper and lower sides and terminals. And the core of the wall can increase the resistance of the environment to the interior of the house. Therefore, it can be said that the wall has an impact on users but little attention is paid to the solidity of the whole building undertaken by the pillar.

This research aspires to produce good quality 3DCP surfaces without the need to use retreatment methods such as plastering or planing. For such feedback, the best direction for the print direction is vertical and should be continued without interruption. Defects will appear when the printing process is interrupted due to uneven crystallization of the material. Process continuity is a prerequisite of the system. Starting or stopping requires synchronization between the system's XYZ motion control software and the feeding pump control.

In this step, the team uses Cura tomography software to create the path for the printer as shown in Figure 6.4. The software cuts the model file into layers and generates a detailed G-code for the printer. However, the software is designed to be used by most small printers that use plastic materials. Due to the small size of the machine, the inertia of the machine is also small, resulting in negligible acceleration and deceleration. Therefore, there is no need to care about the orientation of the print head. And the direction of movement is chosen randomly.

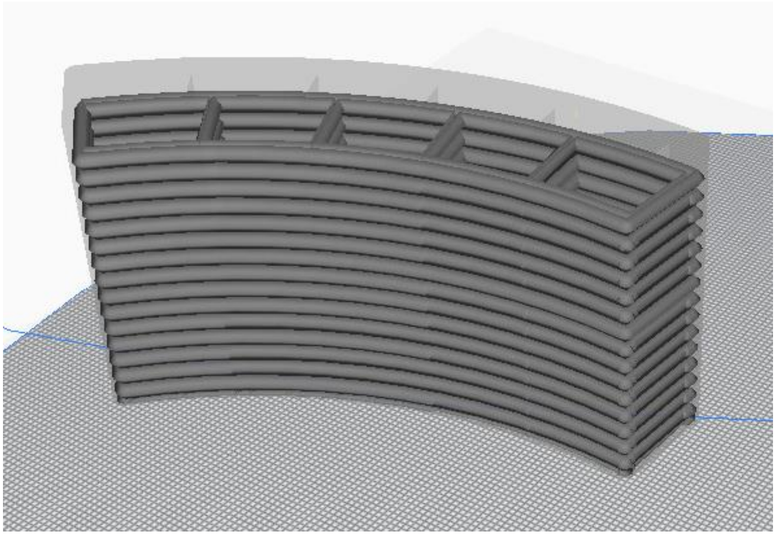


Figure 6-3 Tomography using Cura software.

However, for the research product of the group with large size, moderate movement speed, the shape of the printed product is not too complicated. But the large size, large inertia, acceleration and deceleration speed of the machine have a great influence on the quality of printed products. As a result, the direction of movement of the print head is focused, limiting sudden changes in direction that cause unwanted instability.

Turning on or off the speed of the extruder will interrupt the material flow. Even if the loading shaft in the working head has stopped, the material flow may not stop completely due to the effect of gravity. XY transfer is very important to bring the material to the desired location. User-defined print speed indicates the volume of material sent per unit area [52]. The thickness of the printed layer can be determined, assuming the flow of material is always continuous without interruption.

Path processing is considered the most important step, arranging the order of movement of the print head to avoid unnecessary movements, and eliminating sudden changes in direction. Careful handling can shorten the travel distance, thus reducing the whole process time. To edit visual paths and group details, use CIMCO software.

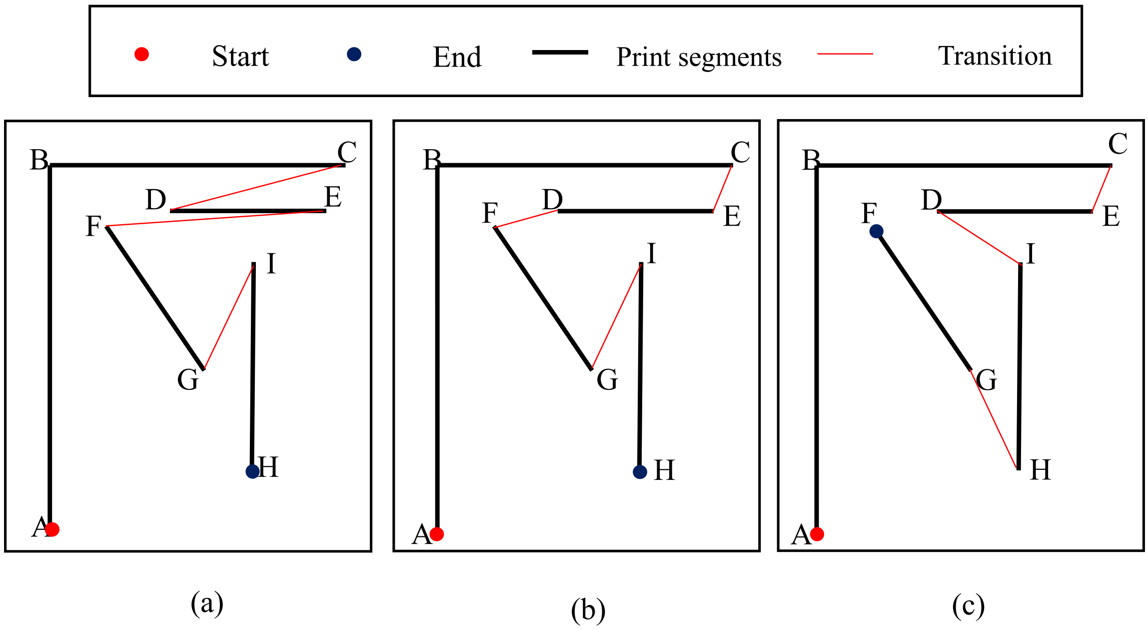


Figure 6-4 Select the optimal path.

As can be seen, the line stretched in Figure (a) tends from left to right, but it leads to a large change in the direction of movement, creating a large inertia, which in turn affects the stability of the structure, not only that, but also optimizes the path.

To edit visual paths and group details, use CIMCO software.

6.3 Orbit and interpolation

From the forward kinematics problem, it is possible to determine the position of the robot based on matching variables. And from the kinetic inverse problem, suitable variables can be determined based on the position and direction of the end extruder. The control of speed and acceleration at each joint creates the path and trajectory of the robot moving from one position to another using a given algorithm. Create trajectories that move between pre-divided segments, straight line orbits, or sequential trajectories. Requires the use of both kinetic and kinematic problems of robots.

The same starting and ending points but with different speeds and accelerations will create the same path but completely different trajectories. So, for precise control, we will choose the solution to the orbital problem with functions of position, velocity and acceleration according to the time variable.

Interpolation generates position data to shift axes from data blocks generated by the interpreter. An important part reflects the accuracy of the control system. The data from the interpolator should match the shape of the path of movement of the working head. The interpolator is limited to n speed depending on the architecture of the processing computer and the response speed of the motor. Limit accumulated errors during interpolation.

In this topic, the most important issue is to control the speed of the working head so that the robot can move smoothly and accurately. There are 3 commonly used interpolation methods: straight line interpolation, circular arc interpolation, and spline curve interpolation to perform basic robot movements.

6.3.1 Linear Interpolation

In a straight motion sequence, the coordinates of the end point of a straight segment become the starting point of the next segment. Line interpolation requires 3 parameters: starting point coordinates, destination point coordinates, displacement speed. In 2-axis line interpolation, the interpolator calculates the speed for the X and Y axes in a way that ensures the rate ratio between the X and Y axes is equal to the ratio of the incremental interval required dx/dy. With 3-axis line interpolation, the interpolator calculates the increments dx, dy, dz along the X, Y, and Z axes from start to end.

6.3.2 Round arc interpolation

In arc interpolation, chords are divided into small straight segments. The interpolator calculates the velocity components along the V-x and V-y axes and creates a pulse for each axis of motion. The sum of the pulses determines the position of the shaft and the frequency of the pulses determines the velocity of the shaft. Circular arc interpolation helps create arcs with a few simple program instructions. It is necessary to have the coordinates of the starting point, the coordinates of the end point and the radius of the arc, and the direction of the arc.

6.3.3 Interpolation of Block Splines

The most common and most effective method of interpolation for complex profiles is the alternative to straight line and circular interpolation. In higher-order polynomial interpolation, such as 3 and 5, only a single formula, given by a polynomial, is used to compute all data points. The idea of Splines interpolation is to use multiple formulas, each of which goes through a certain number of data points, and the end point of one polynomial is the beginning of the next polynomial.

CHAPTER 7: APPLICATIONS OF THE 3D CONCRETE PRINTER

The automation of constructions by 3d concrete printer is a magical tool witch can produce a lot of products in different fields that mean it is a multi usage machine.

This chapter shows the applications of 3dcp in different filed.

7.1 Residential units

The 3dcp can build many residential units with many different size and shape as houses and villas and chalets.

7.1.1 Houses

Figure 7-1 3d concrete printed house in ksa [53]

7.1.2 Villas

Figure 7-2 3d Concrete Printed Villa in UAE[54].

7.1.3 Chalets

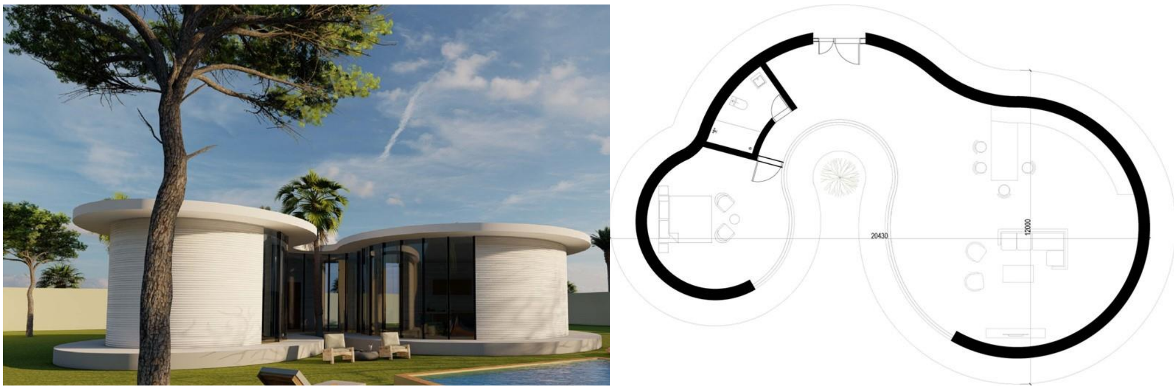


Figure 7-3 3dcp chalet design

Figure 7-4 3dcp chalet bulid in guatemala [55]

7.1.4 3d printed community

Figure 7-5 multiple residential units[56]

Figure 7-6 the 3d printed communities that will house the homeless [57]

7.2 Commercial and industrial facilities

Such as commercial company offices, shops and stores , factory warehouses , storage depots and others.

7.2.1 Offices and meeting rooms

3d printed meeting rooms made by cybe company.

Figure 7-7 Turbines Factory Meeting Room [58].

7.2.2 Office

As a solution for the companies is rent office with low cost and can make a lot of points for customs services.

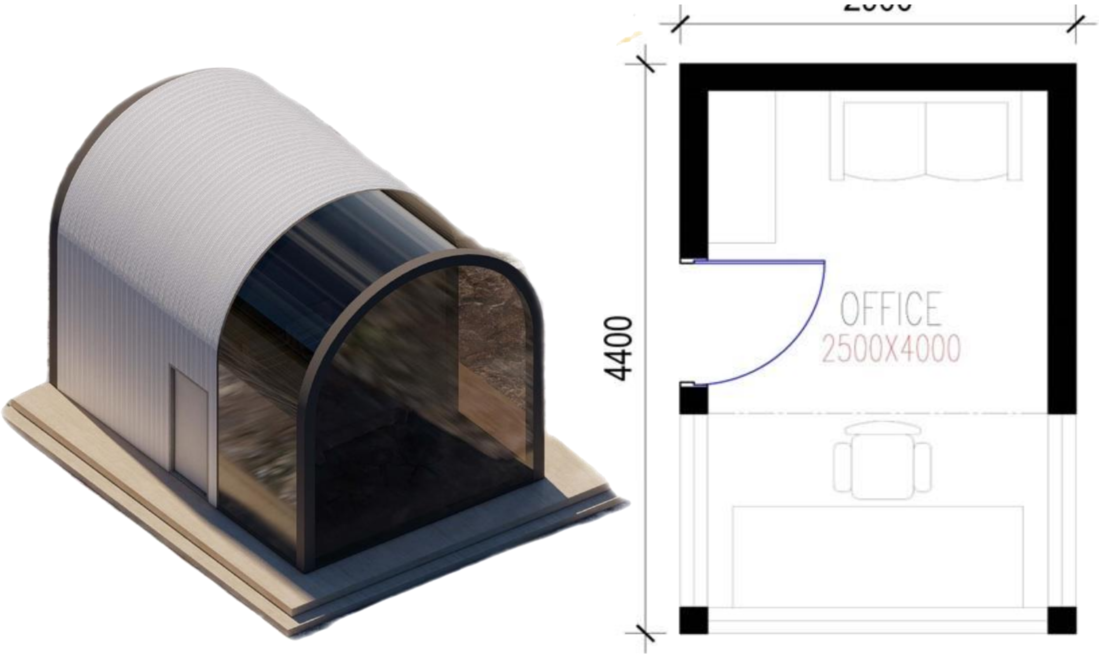


Figure 7-8 design of modern 3d printed office.

7.2.3 Stores

design stores with the style design of the company product.

Figure 7-9 3d printed stores for dior company

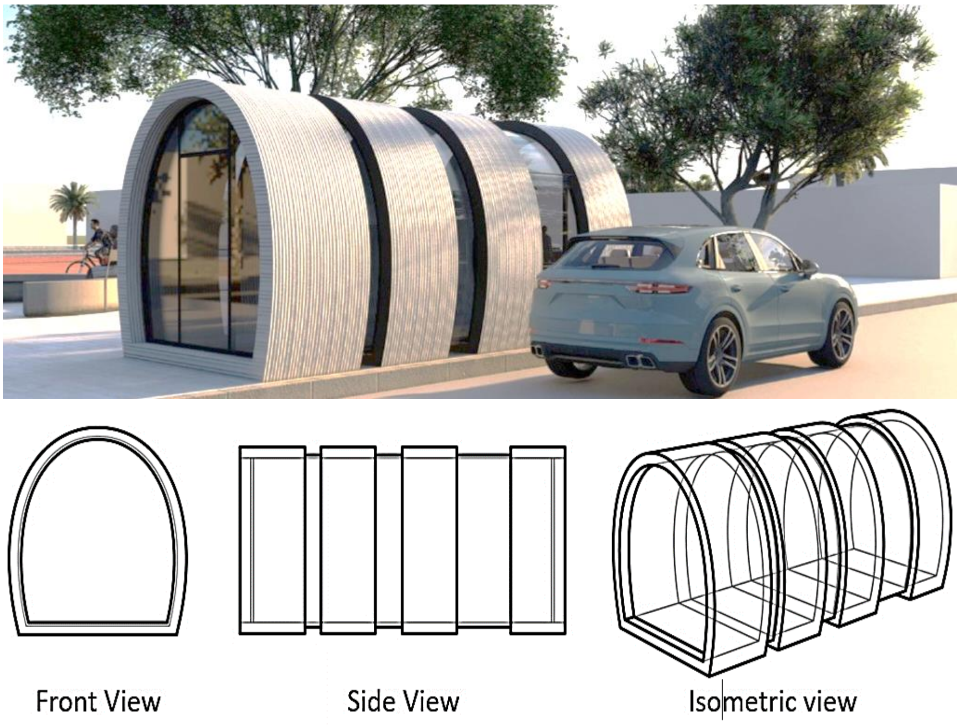


Figure 7-10 Design for 3d-printed coffee shop

7.2.4 Warehouse

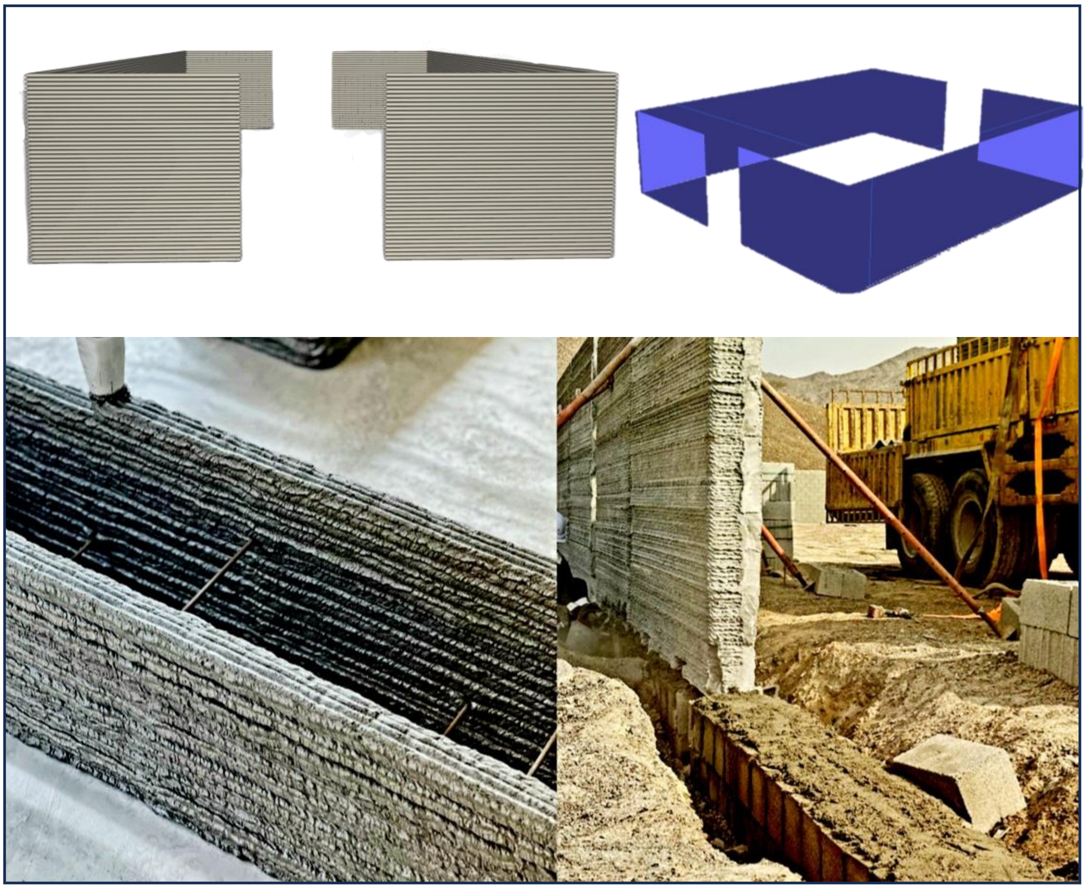


Figure 7-11 Pre-Fab walls for bulid warehouse

7.3 Infrastructure

7.3.1 Bridges

build bridges for many applications.

Figure 7-12 World's largest 3d printed concrete bridage in china [60]

7.3.2 Sewerage

Figure 7-13 3d print drainage[61].

Figure 7-14 3d printed manholes[62]

7.3.3 Huge Water Tanks

Figure 7-15 3D-Printed Water Tanks for Kuwait United Poultry Company[63].

7.3.4 Waterways

Figure 7-16 3d printed waterways [64]

Figure 7-17 3d printed waterways [65].

7.3.5 Energy infrastructure

Figure 7-18 3D-Printed Energy Infrastructure With Lower Material Consumption[66]

7.3.6 Stairs

Figure 7-19 Concrete Stairs From 3d Printer[67].

7.4 Public Facilities

7.4.1 Schools

As an application of 3d concrete printing is the classrooms in villages where the life is difficult .

Figure 7-20 3d printed classroom in africa

7.4.2 Medical center

Figure 7-21 first 3d printed medical in ukrain

7.4.3 Public parks

Create a new design of public parks with low cost and high quality.

Figure 7-22 3d printed public parks

7.4.4 Street furniture (urban furniture):

Figure 7-24 3d printed stop chairs

Figure 7-23 3d printed fountain

Figure 7-25 3d printed street chair

Figure 7-26 3d printed outdoor tables

Figure 7-27 3d printed benchs

CHAPTER 8

RESULTS OF EXPERIMENTS

For a research topic, empirical results are considered important content, helping to evaluate whether the research and experimental content are relevant, complete and accurate. From there, the research team will make conclusions, solutions to overcome them, and future development orientations. Below is the empirical content and evaluation of the contents that the team has studied.

8.1 Mechanical parts and structures

Mechanical parts and details after being designed and machined by the team as shown below.

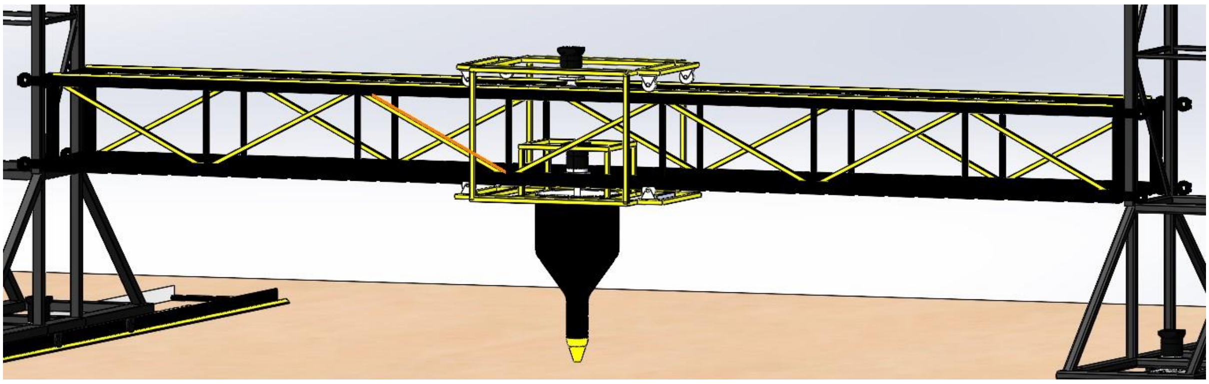


Figure 8-1 X-axis horizontal beam and extrusion unit on design.

Figure 8-2 . X-axis horizontal beam and actual extrusion unit.

The x-axis horizontal beam and the extruder unit are considered important parts, bearing the entire load of the extruder containing moving materials on it. After fabrication, the part was the same as the original design, and in the experiment, the extruder moved smoothly, without vibration, and the displacement accuracy was less than 0.5 mm.

Figure 8-3 The body pillar assembly of the machine, (a) By design, (b) In fact.

The body of the machine when designing and after production are compatible with each other. The cylindrical body assembly is the part that moves along the y-axis while carrying the x-axis horizontal beam moving along the z-axis. During the experiment, the unit ensured that the team's technical requirements such as the movement of the wheels on the rails ensured the evenness of the wheels and smooth movement.

After assembling the parts form a complete 3DCP as shown in Figure 8.4. With this design, 3DCP has a rectangular box operating space with dimensions of 4x4x3m respectively, suitable for the set goals.

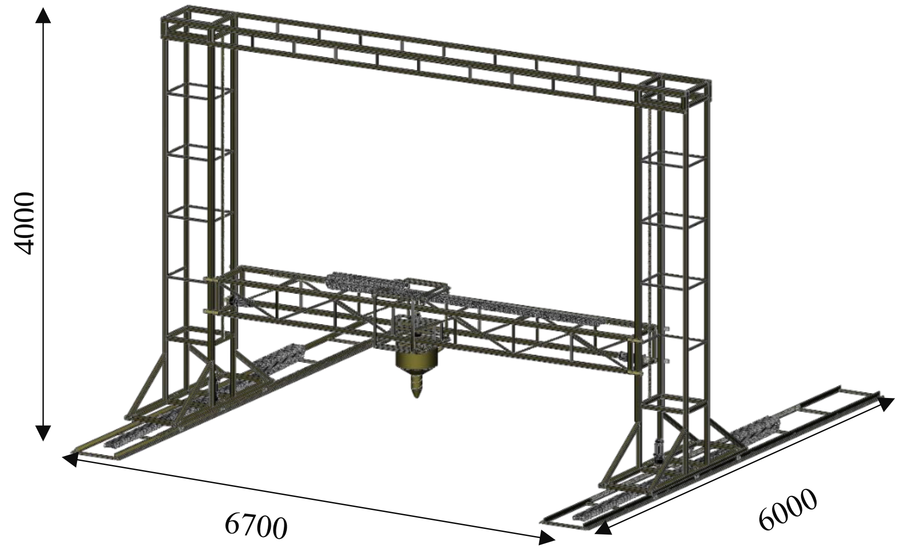


Figure 8-4 The overall design of 3DCP.

8.2 Pumping System

The mixer is designed with a volume of 0.45m3 that has met the requirements of the project as shown in Figure 8.5. The components of the mixture are well mixed for 10 minutes. This type of machine limits the adhesion of concrete during mixing.

Figure 8-5Concrete mixer in practice.

The concrete before reaching the pump is stored in the intermediate tank thanks to the discharge process at the bottom of the mixing drum. Here the stirring mechanism works effectively to avoid material stratification as shown in Figure 8.6.

Figure 8-6Concrete is turned continuously to avoid material stratification.

The mixed concrete is pumped with suction peristalsis into the inlet. The mixer is connected to the pump by a specialized concrete conduit as shown in **Figure 8.7**. During the test, the pump with a capacity of 2m3/h met the capacity of the extruder. The extruder works most stably with a travel speed of 80mm/s. During operation, the flow of the pump is controlled synchronously with the speed of the extruder, so the project has realized the requirement to automate the supply of raw materials. The maximum height during test concrete printing is 3.5m. The pump met this height to deliver the concrete to the extruder. The concrete piping from pump to extruder is installed as **shown in Figure 8.7**. This type of specialized concrete conduit has a diameter of.$\emptyset 35mm$.

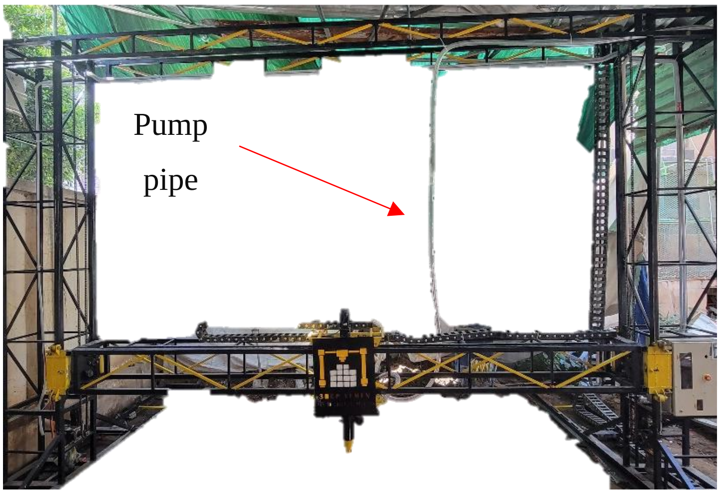


Figure 8-7 Concrete piping system.

8.3 Material Evaluation

Materials play an important role in the project. Factors such as the flowability of concrete, the strength of each printed layer, the bonding between layers must be strictly controlled. Based on the experimental data in chapter 3, C5 mixture was used to mix concrete in the project. The C5 mixture uses PET resin and banana fiber as the mixing ingredient as shown in Figure 8.8. To evaluate the characteristics of the material blending formulation, test printing was performed. Through many test printings, the concrete layers all meet the requirements of the project. Each printed layer has a width of 40mm and a height of 20mm as shown in Figure 8.9. The height and width size error is approximately 1mm. The concrete layers after the printing process ensure formality. There are no signs of layering for test specimens.

Figure 8-8 Concrete is mixed according to the formula C5.

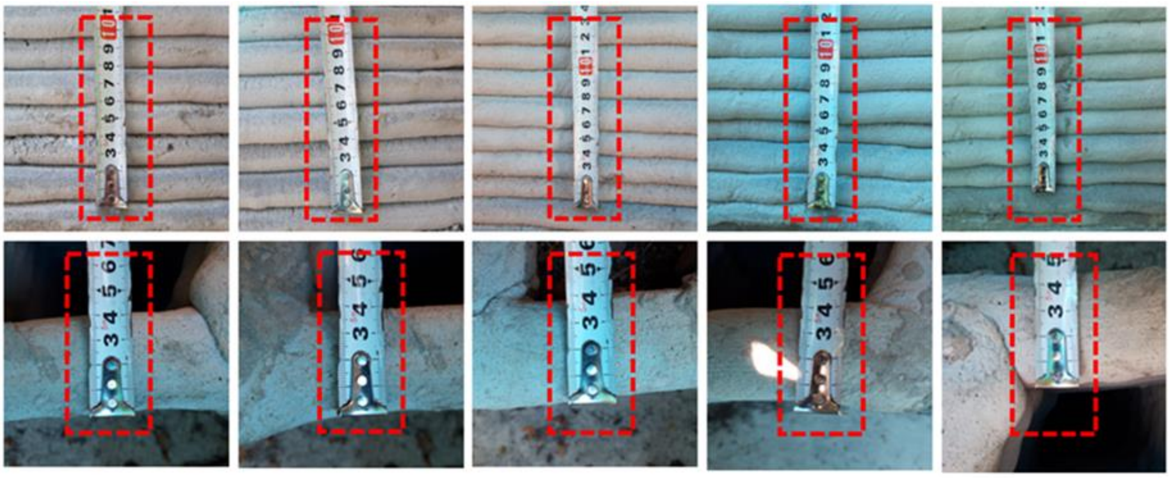


Figure 8-9 Concrete after curing.

8.4 Electrical System

The electrical system is designed and constructed to meet the requirements of the project. The electrical cabinet in the design is as shown in Figure 8.10(a) and the actual electrical cabinet is structured as in Figure 8.10(b). The control signal from the computer transmitted to the motor is guaranteed, without signal interference. Electrical equipment and control circuits are installed as shown in Figure 8.11.

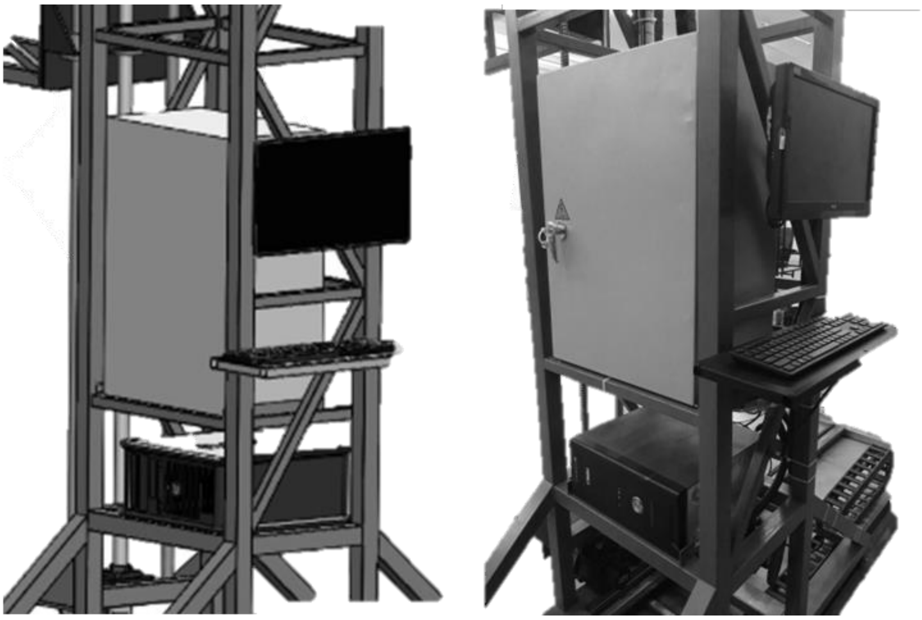


Figure 8-10 (a)Electrical cabinets according to design, (b) Actual electrical cabinets when completed.

Figure 8-11 Electrical equipment and control circuits in practice.

8.5 3D Concrete Printing System

In this section, summarize the research contents in the previous chapters to form a concrete 3D printing system consisting of the following parts: feeding system, concrete 3D printer, electrical control system as shown in Fig. 8.13.

Figure 8-12 Overview Model of Concrete 3d Printing Project.

Table 8-1 3DCP Specifications.

STT	Specifications	
1	Number of degrees of freedom	3
2	Overall Dimensions	6000x6700x3800 mm
3	Maximum load	400 kg
4	Repeatability of position	0.5 mm
5	Workspace	4000x4000x3000 mm
6	Maximum Print Speed	0.1 m/s
7	Maximum Print Flow	0.9 m3/h
8	Minimum Print Thickness	10 mm
9	Supply voltage	200-230V 50-60 Hz
10	Rated Power.	1000 watts

After having an overview of the project, the team evaluated the results of the concrete 3D printing test, including word printing and tiny house printing. The steps are presented as diagrams as shown in Figure 8.14 and Figure 8.15.

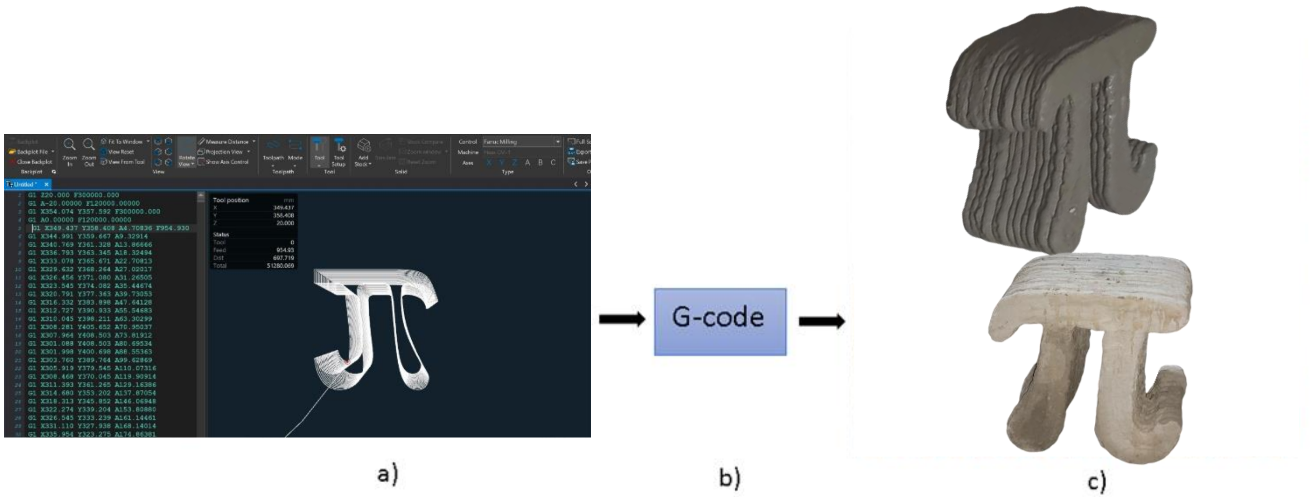


Figure 8-13 . Text printing process, a) Design and simulate the print line of the nozzle on the software; b) Export code g and edit it manually; c) Print the words.

The "π" pattern after printing is the size and shape as designed. The print layers ensure the alignment between the layers, ensuring the uniformity of the size of the print line. However, there is material sagging at the corners of the contour due to the extrusion velocity control not being fully synchronized.

CHAPTER 9 : CONCLUSION AND DEVELOPMENT DIRECTION

9.1 Conclude

The design of robots, as well as machines, must follow strict standards. The calculation and selection of equipment to complete the robot must follow the manufacturer's instructions.

During the production process, when working with machines, absolute safety must be ensured.

The process of testing materials consumes a lot of time, knowledge of concrete is still limited, so the material mixing formula is not the most optimal. However, the project was able to use PET plastic and banana fibers as raw materials for concrete 3D printing.

Working with the AC servo motor supplied with the motor controller requires reading and understanding the operating method in the manual that comes with the motor. Bring a lot of experience to the reading comprehension of the manual.

The serial configuration robot is considered to be a robot with a configuration suitable for the requirements of large operating space and high accuracy.

The pumping system is automated, but the extrusion speed is limited.

The electrical and control system design process provides an experience for the system's noise handling.

The interface is designed to be simple, easy to use, suitable for the construction field.

Due to the limited research time, it is not possible to come up with all the applications that the robot can perform. Currently, the project only uses robots to 3D print the wall structures of a house and complex decorative structures.

9.2 Development direction

In the future, if this project can continue, the team will add more degrees of freedom to the robot to create more flexible movements. Also, study more about the properties of concrete, recycled plastics, natural fibers for blending printing materials. This means protecting the environment. In addition, research the application of large-format 3D printing with other materials.

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