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MR3002B. Design and Implementation of Mechatronic Systems

Final Project

Micro-Scaled Concrete 3D Printer Design and Implementation: SHAP3

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Micro-Scaled Concrete 3D Printer Design and Implementation

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***Abstract*—The following project report gives an overview on current concrete 3D Printing techniques, applications and market competitors; to later introduce the design, prototype and implementation of a 2m X 2m X 2m concrete 3D printing system parting from existent mechanical components, recycled electronic components from a CNC machine, and other proposed purchased materials. The system is meant to be developed at a relative low-cost budget to be replicated on educative institutions; tests on the system were carried out achieving to supporting 65 Kg or higher dynamical weight, a lower to 1cm error, multi-axis simultaneous movement and a 54,000.00 MXN approximated cost.**

***Index Terms*—3D Printer, Concrete Printer, Cartesian Robot, CNC to 3D Printer, 3D Printer Design and Implementation.**

I. Introduction

The following report aims to describe the carried out development and implementation processes that took place during the design and construction of a 3D concrete micro-scaled printer with maximum dimensions of (2m x 2m x 2m), as shown in *Figure 1*. The proposed 3D printing system is meant to be capable to manufacture concrete prototype structures . The system is mainly developed, in regards to its own electrical and electronic components, from existing components from a CNC system adapted for the previously established purpose.
The printing system will be supported by a steel structure with four bottom plates to enhance stability, this structure would be supported and integrated through 3D printed Poly-Lactic Acid pieces, designed through Computer Assisted Drawing software.
In terms of functionality, the system must be able to slice CADs and following their corresponding G-Code routines to achieve tri-dimensional tangible representations. Whereas the feeding concrete system is ignored by the purposes of this project, the design and implementation of this sub-system will be carried out within parallel projects.

Fig. 1. Ilustrative 3D Concrete Printing Mechanism. [1]

A. Technological Relevance

According to CEMEX (2023), multiple benefits can be remarked from the utilization of 3D printing technologies within the construction and real estate industries, those are enlisted as follows [8]:

- The controlled usage of precise amounts of required material to be used in a structure, leads to an up to 60 percent reduction of waste material on construction sites.
- The utilization of this technologies tends to reduce up to 70 percent of the required building time; becoming construction project achievable in a few days or even hours, depending on the complexity of the project.
- The United States Occupational Safety and Health Administration (OSHA) reports that 1 out of 10 construction workers are injured each year; 3D printing may avoid this issue.

B. Project Scope and Aim

This project results of significant relevance as it brings cutting edge technologies closer to college students, particularly to those studying civil engineering and related degrees. Thus, by engaging directly with this innovative machinery, students not only gain hands-on experience but may also become familiar with a technology that has far-reaching implications across various societal domains and the future challenges of modern society; such as housing solutions, and the development of SMART sustainable cities.
The final presented prototype in regards to the results presented on this report will include the deliverables defined as follows:

1) System Documentation.
   a) Electrical, Mechanical and of processes.
2) System CAD representation.
3) Physical assembly of structural elements in a 1:1 scale.
4) Functional and calibrated X (horizontal) and Y (vertical) axes, connected with an easy-to-use platform (Match 3).
5) X and Y axes design physical testing (trajectory tracking).
6) Z-Axis design (CAD) of a proposed mechanism.

C. Considered Design and Engineering Details Topics

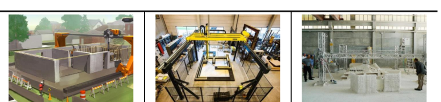
The following report considers a general introduction to the actual state of art and technique of functional concrete 3D printers, followed by a detailed description on carried out design processes, operational tasks, manufacturing methods, assembly steps, electrical-electronic and mechanical design; complimented by their corresponding applied supporting tools. Afterwards, obtained results (mainly on system precision and stability) will be presented to allow further discussions and recommendations; which will then converge into a general conclusion summarizing the developed knowledge, possible project implication, and recommendations for future related developments.

II. Current Research and Development State

The 3D concrete printing technologies emerge as a disruptive innovation in the construction industry, offering new opportunities for efficiency and safety in the creation of structures. The ability to manufacture three-dimensional concrete objects layer by layer presents significant potential to accelerate construction times and improve precision in the production of prefabricated elements and complex structures. Studies such as those by Zhang et al. (2019) and Liu et al. (2022) highlight the importance of optimizing the properties of 3D printed concrete to enhance its flow-ability and strength, while Bos et al. (2022) point out practical challenges and the need for regulatory frameworks for effective implementation [9] [10][11]. These trends suggest a promising direction for future research on how 3D concrete printing technology can revolutionize the construction industry.

A. Existing Concrete 3D Printing Methods

According to Zhang et al. (2019), as the application of concrete 3D printing has boomed highly popular in recent years, as shown in figure 2; different printing methods have been developed by researchers and engineers all around the world [9]. The main existing 3D Printing (3DP) techniques for concrete include *Contour Crafting* (CC), *Concrete Printing* and *D-Shape*; CC refers to concrete deposition after its extrusion through a nozzle (allowing then the usage of different building materials, but requiring a pumping system), Concrete Printing refers to a likewise system that those used in CC technique with the difference of printing entire geometry layers at once rather than their edges and considering a premixing mechanism (higher speed and lower resolution), D-Shape refers to powder concrete deposition aided by bonding solids and binding chemical agents (resulting in a higher environmental impact) [9]. The reported system refers to a Concrete Printing mechanism.



	Contour Crafting	Concrete Printing	D-Shape
Process	Extrusion	Extrusion	3D Printing
Use of mould	Yes (Become a part of component)	No	No
Binder	None	None	Chorine-based liquid
Pros	- Smooth surface by trowel	- High strength - Minimum printing process	- High strength

Fig. 2. Concrete 3D Printing Methods [2]

B. Current Applications

Further than applying Concrete 3DP as a feasible solution for housing within populations with high growth rates, and as an affordable solution for housing within financially marginalized communities, plus the previously mentioned benefits; concrete 3DP presents multiple potential applications as those presented as follows [9]:

- Ultra-high performance concrete structures with complex geometries, today only achievable trough either mouldable materials or complex and time-consuming construction techniques.
- Eased construction in vacuum ambience, developing further applications for concrete 3DP for space colonization; for example in the moon or mars.
  - Using an specific type of loose soil called *regolith* as raw material.
- Concrete structures restoration by developing specific moulds of damaged regions through scanning technologies such as LiDAR, this scanned cloud points will be converted to a 3D model that will then allow the development of adapted patches that could be installed in situ, for example, through a robotic arm.

It is also pointed out by Zhang et al. (2019), that according to Weistein et al. (2015) that concrete 3DP may present an annual 15 percent market growth rate , surpassing the market value of 56.4 million dollars by 2021, as shown in figure 3 [9].

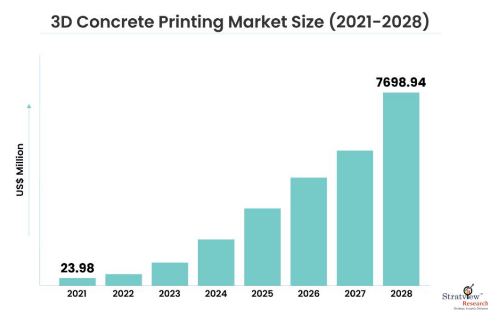


Fig. 3. Concrete 3D Printing Market Growth Rate [3]

C. Likewise Projects

A 3D concrete printer was developed by Jo et al. (2020), as shown in figure 4; pointing out the main considerations for this category of mechanisms, this printer is meant to build prototype industrial scale models for performance tests within a cubic meter tri-dimensional area [[4]]. The noted considerations are listed below [[4]]:

- Optimized motion precision through control systems and mechanical elements.
- Printing material mechanical and chemical properties.
- Adequate, steady and constant concrete dispensing mechanism.

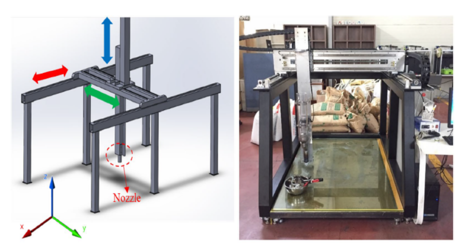


Fig. 4. Existent Concrete 3D Printer Prototype [4]

III. The Ongoing Concrete 3DP Industry

While yet, multiple patents on inventions related to concrete 3D printing have been and are developed nowadays, this industry has presented a proportional market growth rate, leading to the institution of enterprises focused on this topic, the two main bench markers within this industry will be detailed as follows.

A. COBOD -BOD 2

The BOD2 printer, as shown in figure 5, represents the culmination of extensive iterative improvements and refinements, positioning it as the most widely adopted 3D construction printer globally [5]. Its distinctive modular architecture addresses a broad spectrum of 3D printing applications within the construction sector. This printer benefits from comprehensive field research and extensive global deployment, ensuring a high level of reliability and performance. The BOD2, with over 50 units delivered in the past three years, stands as a fully validated and operational system rather than a prototype [5]. Each component is constructed from high-quality materials and engineered to meet the stringent requirements of the construction industry, particularly in terms of operational speed, structural stability, and durability [5].

Fig. 5. BOD 2 Design Simulator [5]

B. Apis Cor

Apis Cor, a leading Russian 3D printing company founded by Nikita Chen-yun-tai, achieved a milestone in early 2017 by printing a 38 m² house in Stupino in under a day for $10,000. The house includes advanced features such as noise protection, freeze resistance, and integrated security and climate control systems [12].
The innovative 3D printer, shown in figure 6, used is compact and mobile, allowing construction from both the interior and exterior. This contrasts with traditional, larger "gantry-type" printers that require complex setup. The Apis Cor printer, which simplifies the construction process with its small size and integrated systems, is capable of creating unique designs and operates with minimal waste. The nearly fully automated process reduces human error and facilitates efficient, versatile construction[12].

Fig. 6. APIS COR 3D Concrete Printer [6]

IV. Experimental Set Up and Methodologies

Once established the relevance, theoretical background and directives of this project, emphasis will be done on the developed strategies, applied materials and techniques, experimental set up, and data collection for analysis. Afterwards, results analysis and discussions will take place to develop general conclusions.

A. General Methodology

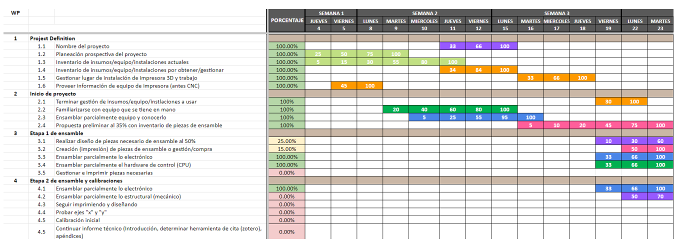
To carry out the desired tasks, a previously established methodology will be determined for the development of the project. The project will begin by developing an analysis on project scope and requirements to lately develop a WBS structured plan to schedule through a Gantt Diagram; afterwards, an inventory on existing materials and lacking resources will be carried out to then allow their purchase. A CAD model would be design through *Solid Works* software to emulate the general structure and axes mechanisms, in compliment, supporting structures (including their technical drawings) will be also designed and printed through slicing software such as *CURA* or *Bamboo Labs*.

In respect to the electric-electronic design, given components functionality will be tested to then develop an electric diagram. Once designed the structures and having access to the required materials, a 1:1 scale physical prototype will be developed to then test its precision, controlability and robustness to several experiments such as repetitiveness on achieving a desired coordinate, precision to arrive to a desired coordinate (desirable 5mm error or lower according to construction industry standards), and being able to carry a 50 kilograms or higher weight after assembly. This data collection and analysis processes will be presented on the results section.

B. Work Breakdown Structure

The planning structure of the current project has been developed within a maximum delivery period of 9 weeks and 2 days, excluding weekends as working days. For detailed engineering and as shown in figure 7, the first 4 weeks have been proposed for project planning, quotation of required

materials, inventory of initially handled materials, task division (EDT), and electrical-electronic assembly and system instrumentation [see sections “General Connection Scheme of Electrical, Electronic, and Monitoring Systems” and “Project Cost Analysis”].
Weeks 5 and 6 have been allocated for the receipt of purchased supplies; these weeks were also dedicated to refining the mechanical design of the final product outlined in the previous section, through CAD design of the structure, printed joints, machine elements, and general assembly visualization [see section “Definition of Mechanical and Structural Elements”].
The final 3 weeks considered for the realization of this project focus on the assembly of the final product, the manufacturing or, if necessary, the PLA printing of designed elements, functional testing, calibration, software configuration refinement, documentation, and determination of the general functional procedure diagram [see sections “Definition of Mechanical and Structural Elements” and “Flowchart and Procedural Operational Details”]. Access is given to GANTT WEEKS 1-6 and GANTT WEEKS 7-9.



WP			PORCENTAJE	SEMANA 1		SEMANA 2					SEMANA 3						
				JUEVES 4	VIERNES 5	LUNES 8	MARTES 9	MIERCOLES 10	JUEVES 11	VIERNES 12	LUNES 15	MARTES 16	MIERCOLES 17	JUEVES 18	VIERNES 19	LUNES 22	MARTES 23
1	Project Definition																
	1.1	Nombre del proyecto	100.00%						33	66	100						
	1.2	Planeación prospectiva del proyecto	100.00%	25	50	75	100										
	1.3	Inventario de insumos/equipo/instalaciones actuales	100.00%	5	15	30	55	80	100								
	1.4	Inventario de insumos/equipo/instalaciones por obtener/gestionar	100.00%						34	84	100						
	1.5	Gestionar lugar de instalación de impresora 3D y trabajo	100.00%									33	66	100			
	1.6	Proveer información de equipo de impresora (antes CNC)	100.00%		45	100											
2	Inicio de proyecto																
	2.1	Terminar gestión de insumos/equipo/instlaciones a usar	100%												30	100	
	2.2	Familiarizarse con equipo que se tiene en mano	100%				20	40	60	80	100						
	2.3	Ensamblar parcialmente equipo y conocerlo	100%					5	25	55	95	100					
	2.4	Propuesta preliminar al 35% con inventario de piezas de ensamble	100%									5	10	20	45	75	100
3	Etapa 1 de ensamble																
	3.1	Realizar diseño de piezas necesario de ensamble al 50%	25.00%												10	30	60
	3.2	Creación (impresión) de piezas de ensamble o gestión/compra	15.00%													50	100
	3.3	Ensamblar parcialmente lo electrónico	100.00%												33	66	100
	3.4	Ensamblar parcialmente el hardware de control (CPU)	100.00%												33	66	100
	3.5	Gestionar e imprimir piezas necesarias	0.00%														
4	Etapa 2 de ensamble y calibraciones																
	4.1	Ensamblar parcialmente lo electrónico	100.00%												33	66	100
	4.2	Ensamblar parcialmente lo estructural (mecánico)	0.00%													50	70
	4.3	Seguir imprimiendo y diseñando	0.00%														
	4.4	Probar ejes "x" y "y"	0.00%														
	4.5	Calibración inicial	0.00%														
	4.5	Continuar informe técnico (Introducción, determinar herramienta de cita (zotero), apéndices)	0.00%														

Fig. 7. Gantt Diagram Schedule

In general terms, global responsibilities have been assigned to each member of the development team as listed below:

- **Mechanical and Structural Design:** Lilian Scarlett Díaz Romero.
- **Electronic and Software Design:** Luis Enrique Camaños Rebollo.
- **Electrical and Functional Logic Design:** Israel Lezama López.
- **Administrative and Financial Control:** PhD. José Guadalupe Rangel Ramírez.

C. Electrical-Electronic System Materials and Software

It should be noted that no purchases of supplies were required for the electrical and electronic implementation of the system, as it was based on the materials initially provided by the advisor in charge of this project, as shown in figure 8. Access is given to GENERAL MATERIALS INVENTORY.

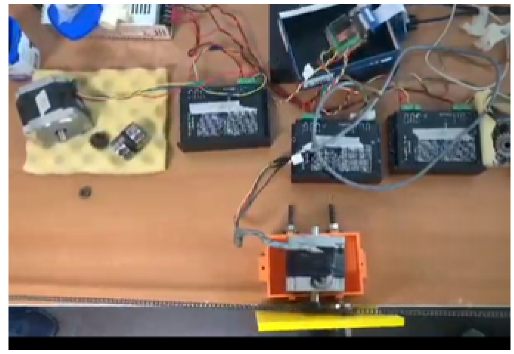


Fig. 8. Electrical Equipment Testing

In respect to the usage of software, the open source design program *CADe Simu* was deployed for the development of electrical diagrams. In respect to control and slicing software, *MATCH 3* and its corresponding 3D Printer Add-On were selected, as shown in figure 9.

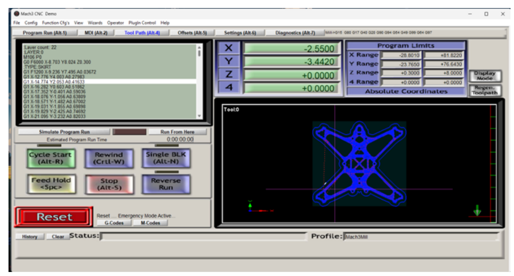


Fig. 9. MATCH 3 Software and 3D Printing Add-On

D. Mechanical System Materials and Software

The general structure has been defined as the construction of a cube using steel structures coated with electrostatic paint and fixed together using standardized elements readily available and printed parts in PLA (with tolerances considered to be 0.25 mm, according to printing standards), which will be further detailed in future sub-sections. Additionally, the structural elements and mechanisms that will allow the operation and movement of the X, and Y, and Z axes have been designed; these designs are respectively led by *Luis Enrique Camaños Rebollo*, *Israel Lezama López*, and *Lilian Scarlett Díaz Romero*.

1) Prefabricated Components: Before delving into the development and explanation of the designed parts for the operation of the established system, it is worth mentioning the mechanical and structural elements that are already available or can be acquired for the project's development.

PERIMETER STRUCTURE DJ OF 2 MTS 30 X 30 FOR ILLUMINATION
This will be used as a structural element, consisting of 4 galvanized steel structures placed vertically as pillars, and they will be joined with 4 more structures positioned horizontally, which will be connected using structural elements designed in

CAD software and printed in PLA. Access to PERIMETRAL DJ STRUCTURES is given.

ALUMINUM BOSCH PROFILE 90 X 90 MM AND UNION ACCESSORIES

The X-Axis structure, which will be moved by the X-axis of the proposed system and will also serve as support for the Y and Z axes, will be built from extruded aluminum Bosch profiles selected based on considerations of moment of inertia, maximum deflection (standardized to 2 mm in construction contexts), and normal bending stress. The information used for the calculations shown was consulted with 3 different suppliers, and the purchase was made with RexRoth, a Bosch Company.

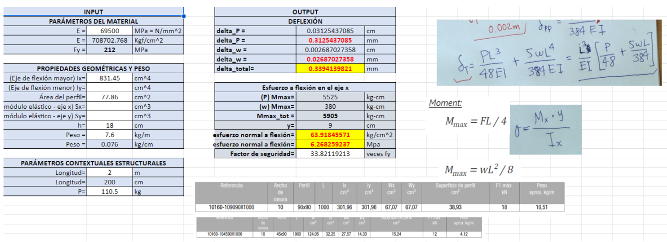


Fig. 10. Structural Calculi Format

As shown in figure 10, 90X90 mm light Bosch profiles were elected, achieving a 0.34 mm deflection being 2 mm the maximum secure standard structural deflection; considering a 110 Kg charge, the selected structure presents a security factor against bending of 33.82 times the permissible limit. Together with the purchase of these profiles, the purchase of joining elements such as 90 X 45 MM brackets, T-nuts, and screws was considered. Design is shown in figure 11.

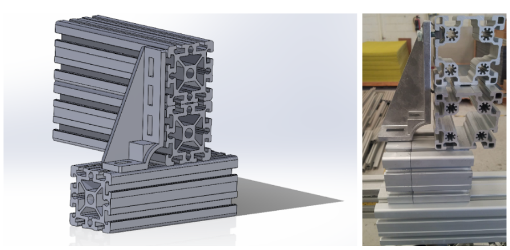


Fig. 11. X (bottom profile) and Y (on top profiles) Axes Structural Proposal

VEVOR RAILS WITH LINEAR GUIDE BEARINGS 1700 MM

The use of 7 structural elements of this type is considered as a means to allow the movement of the X-axis of the device; supporting both bases of the Bosch profile with 2 rails per side for a 4 rails total. The displacement of the Y-axis is also aided and directed by 2 rails on top and 1 rail at the perpendicular to the stepper-supporting moving plate. It is of worthy mention, that the selected elements significantly exceed the load requirements developed with a safety factor greater than 2. Access to purchased LINEAR GUIDE RAILS is given.

2) Available Mechanical Components and CAD Software: Comparable to the previous inventory of electronic elements, the inventory also includes a list of numerous mechanical elements, among which couplings, worm screws or spindles, bearings, toothed bearings, transmission chains, sprockets, screws, and fastening elements stand out. Access is given to GENERAL MATERIALS INVENTORY.

In respect to software, the previously mentioned pieces to be designed an printed through the usage of PLA were developed within the CAD software *SolidWorks 2023* , as well of the technical drawing of each designed piece. As well, to aid CAD slicing and 3D printing two software tools were deployed, being this *CURA* and *Bamboo Labs Printer Software*.

V. Proposed System Design

Once elected the construction means of the desired concrete 3D printer, the realistic and viable design of a concrete 3D printer is carried out taking into account mechanical, electrical-electronic and control considerations.

A. Operational Design

The diagram shown in figure 12 outlines the general operational logic of the system discussed in previous sections, aimed at fulfilling the objectives of this project. Access is given to the mentioned OPERATIONAL LOGIC DIAGRAM.

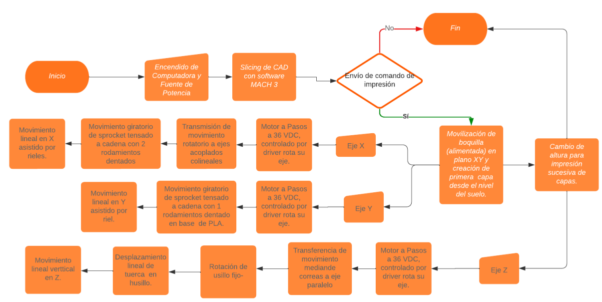


Fig. 12. Operational Logic Scheme

B. Electrical and Electronic Design

The system relies on the use of three NEMA 34 stepper motors, powered by 36 VDC, to control each axis of the Cartesian robot. A power supply, intended to be connected to 127 VAC 60 Hz, provides three 36 VDC outputs. The system also includes a two-position toggle switch to enable or disable electrical power consumption.

The stepper motors are connected to the 36 VDC outputs of the power supply via three CW8060 drivers, one for each motor. According to the ELECTRICAL COMPONENTS DOCUMENTATION, the drivers are connected to a *Build Your CNC* control board. This control board requires a 5 VDC power supply and is connected to a computer or processing unit through a 25-pin flat cable, allowing system control via

MACH3 software, which is native to the control board being used.

Limit switches were added to X and Y axes, connected in parallel at their Normally Opened terminal to pin 12 and GND; activating stop signals, once configured in *MATCH 3* software, through the pull-up resistance existing in this pin. The figure 13 illustrates an electrical diagram with the described connections. Access to ELECTRICAL DIAGRAM is therefore given.

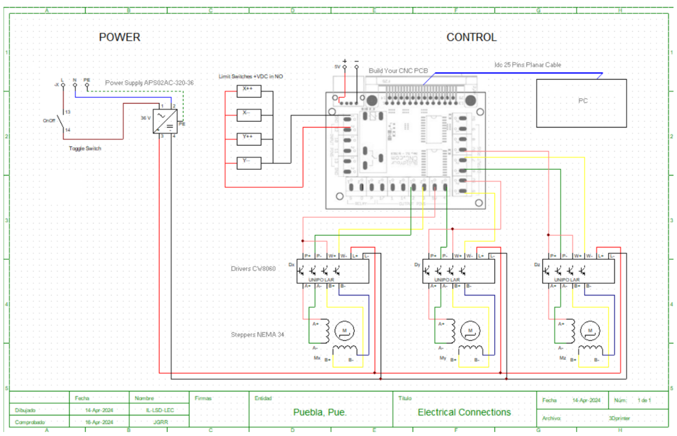


Fig. 13. Power and Control Electric Diagram

C. Mechanical Design

The aforementioned structure has been modeled in CAD, as shown in figure 14, to provide a better visualization of the proposal. In this section, the structural elements designed for the connection of perimeter structures and Bosch profiles are enlisted and displayed. Access is given to CADs and TECHNICAL DRAWINGS.

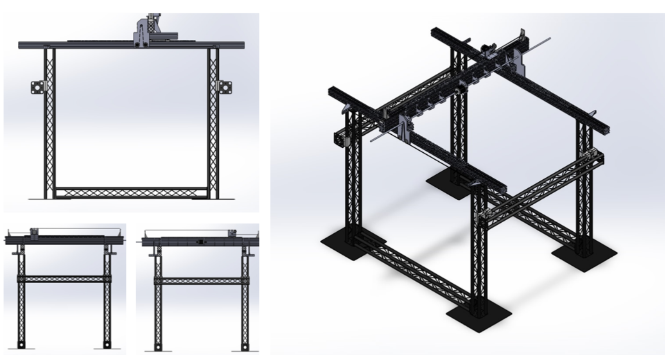


Fig. 14. Concrete 3D Printer Proposed Design

In regards to the general structure, perimetral columns where assembled together with no structural resistance means, but to increase the robustness of this machine by maintaining a strictly regular printing area shape and dimensions. The mentioned columns where joined by 4 horizontal columns; the bottom structures where drilled and bolted to achieve an over-floor-level height, two more mutually parallel structures where added in the perpendicular walls to the previously described columns; this last structures are supported by specially designed PLA couples at their vertical center to avoid columns inclination, as shown in figure 15.

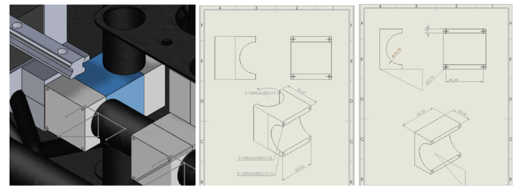


Fig. 15. General Structure Couples

1) X Axis: The X-axis, as shown in figure 16, consists of a dual-axis stepper motor coupled to longer shafts, both supported by pieces designed at the back of the proposed Bosch profile structure. This system is attached to a set of toothed bearings secured to a tensioned chain to guide the axis movement. To facilitate this dynamic, the Bosch profile structure will be fastened to the rails with the previously proposed bearings using M8 screws.

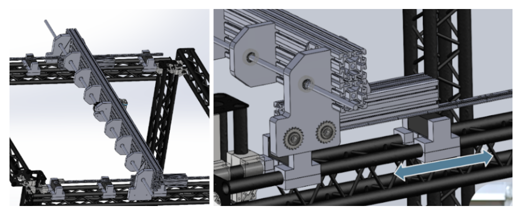


Fig. 16. X Axis Design Proposal

As previously mentioned, specialized supports were developed to sustain the stepper, the extended shafts, and the toothed bearings, this are shown as follows in figure 17, 18 and 19.

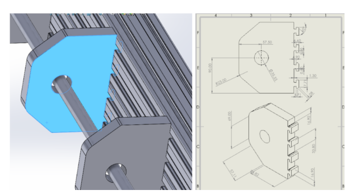


Fig. 17. Shafts Support

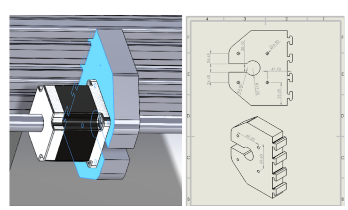


Fig. 18. X Axis Stepper Support

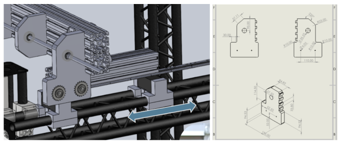


Fig. 19. Bearings and Sprocket Supporting Structure

2) Y Axis: The Y-axis, as shown in figure 20, consists of a base attached to two slides of the proposed rails, allowing linear displacement of the axis through a fixed chain system, which is driven by rotary motion from the stepper motor. The chain will be secured to structures printed in PLA on the edges of the profile, using screwable staples.

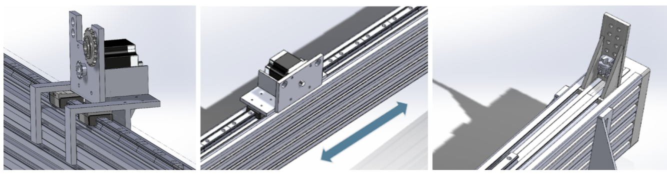


Fig. 20. Y Axis Design Proposal

As it has been yet mentioned, specialized supports were developed to sustain the stepper, and to fix the tensed chain, this are shown as follows in figure 21 and 22.

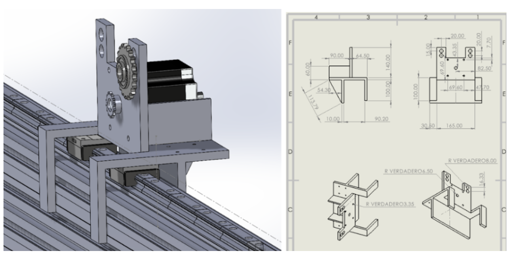


Fig. 21. Y Axis Stepper Supporting Plate

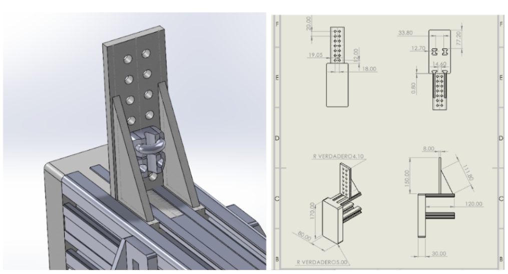


Fig. 22. Y Axis Chain Fixing Structures

3) Z Axis (Only Theoretical): The Z-axis, as shown in figure 23, comprises a linear actuator transmitting motion to a spindle with a nut-screw system to enable vertical displacement; the proposed system is developed based on the mechanism presented by Safarabadi, M. (2023) [7]. This axis will not be physically implemented due to time limitations.

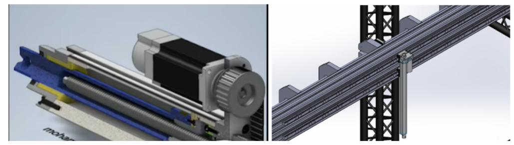


Fig. 23. Z Axis Design Proposal [7]

VI. System Implementation and Obtained Results

After establishing the final mechanical, electrical and electronic design of the final concrete 3D printing structure prototype, and once defined the control software to operate it; the implementation stage of this project was executed according to the developed CAD guides and electric diagram. The final results of this implementation are shown on figure 24.

Fig. 24. Physical Prototype General View

A. Mechanisms Implementation

The CAD developed structures and planned mechanisms where also deployed within this prototype structure; it must be added that some of the designed structures were not 3D printed on PLA due to time limitations (X Axis Supports) however, the correct implementation of the originally presented idea shall increase the stability of the system. The implementation of structural couples, axes mechanisms and limit switches will be detailed in the following sequence of figures.

Fig. 25. Structural Coupling Mechanisms Implementation

Fig. 26. X Axis Mechanism Implementation

Fig. 27. Y Axis Mechanism Implementation

Fig. 28. Limit Switches Fixation

The mentioned not-3D-printed pieces, as shown on previous figure 26, were fixed using bolts, nuts and rubber stoppers; this pieces were manufactured through a laser cutting machine and by overlaying and fixing 3 layers of 3mm width MDF, for a total 9mm width structure. After assembling and connecting the machine given the previously developed designs, testing conditions were established; as mounted on top of the structure de Y and X axis (around 2 meters apart from floor level), a green 3 kilometer range laser light was positioned on top of the axes emulating the Z axis and allowing an eased measurement of the precision of the concrete 3D printer. This measurement technique can be illustrated through figure 29.

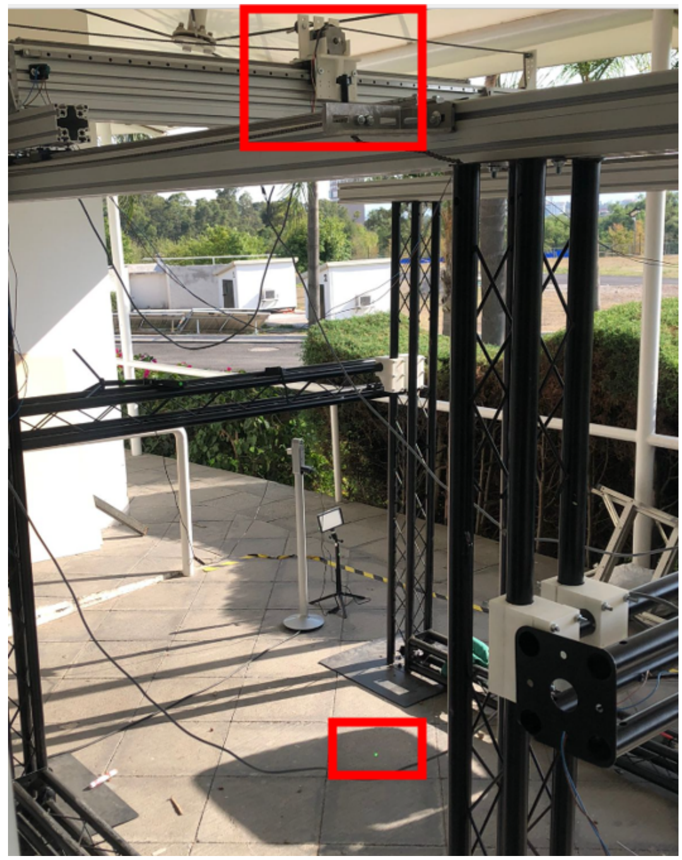


Fig. 29. Laser Measurement Technique Proposal

B. Configuration, Calibration and Testing

As previously mentioned, MATCH 3 software was selected as the main control interface for the deployment of the concrete 3D printing system; thus, steppers configuration and system calibration will take place through this interface. Interface is shown on figure 30.

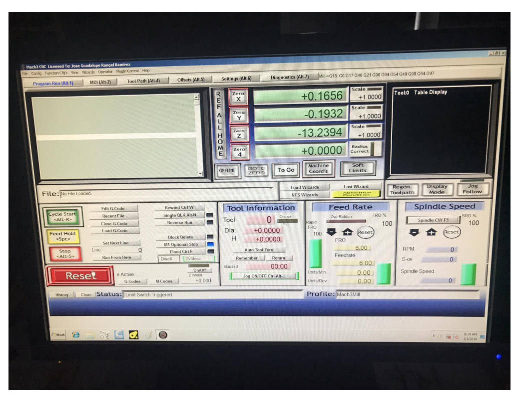


Fig. 30. MATCH3 Interface

1) Calibration: The first elemental task to develop refers to the establishment of the required steps per inches, velocity and acceleration to control the steppers that may actuate to provoke the movement of axes. While velocity and acceleration can be arbitrarily fixed according to the properties of the printing material, desired vibration level, and total printing time; steps per inches must be calculated either theoretically or trough the usage of MATCH 3 software. The software method refers to the direct calibration of the concrete 3D printer by the usage of the *set steps per unit* option in the *Settings* sub-menu, shown in figure 31 ; there an axis to calibrate will be selected to then define an N distance to advance, then the software will require as input the actual displacement of the axis, afterwards user must accept the restoring process of current steps per unit. This process can be indefinitely repeated until achieving the desired precision.

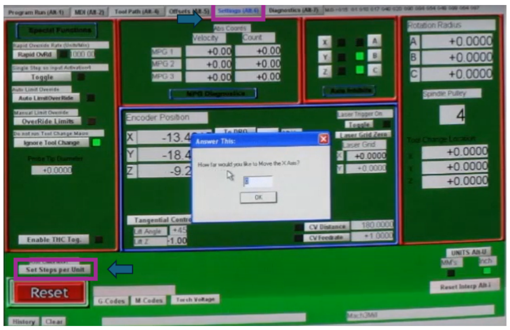


Fig. 31. Calibration Interface

Theoretically, steps per inches can be calculated according to the specifications of the used stepper and according to the used sprocket to transmit rotational movement to linear through a chain; this is achieved by multiplying the steps per revolution of the stepper by the desired micro stepping factor (1/16 is recommended), and then multiplying this value by the result of dividing the number of teeth in the sprocket by its radius in inches. The first option (via software) was preferred as resulting much more accurate during experimentation. The final Motor Tunning selected parameters for each of the axis is shown in figure 32.

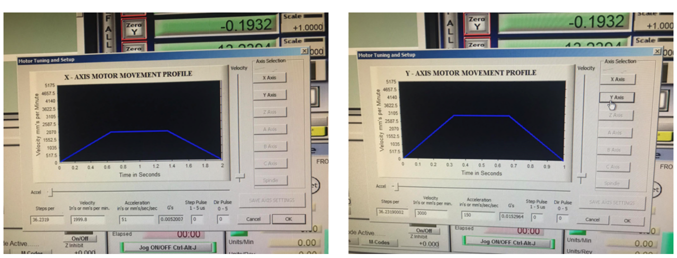


Fig. 32. Axes Configuration Parameters

2) Port Configuration: An essential step for the correct monitoring and control of the system an the limit switches refers to ports configuration; whether this wiring system has been previously defined, the port configuration of pins for axes and limit switches results relevant for an optimal deployment. The final port configuration in MATCH 3 software is shown in figure 33. It must be added that soft limits shall be established on the system to avoid the constant activation of limit switches, which may cause the system to emergency stop and thus requiring to either restart it or *manually overriding* this limits in the *Settings* sub-menu.

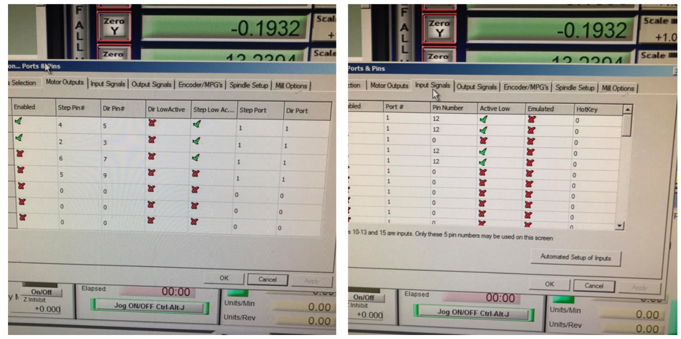


Fig. 33. Ports Configuration in MATCH 3

3) Testing: Four different tests were carried out to determine the effectiveness of the system; robustness and resistance to dynamical weight holding, precision, path tracking in two simultaneous directions, and costs analysis.

Robustness and Resistance to Dynamical Weight
After assembled, a 65 kilogram weight charge was added in the moving axis line of Y axis; supported by the X axis and thus the entire structure, as shown on figure 34. This dynamical charge was displaced 3 times at different arbitrary speeds to determine absence of vibrations and to detect structural failures by naked eye.

Fig. 34. Dynamical Charge Resistance Experiment

After this experiment, null structural damages were detected. The system presents a safe robustness at low acceleration rates (around or lower 150 mm/s), a desirable speed for printing tasks; approving the system this test.

Precision Test

A spot was marked with tape for this experiment and selected as coordinate (0,0), the system was asked to displace 1 meter apart from this spot in both directions at different repetitions. The experiment was carried out and repeated 5 times per axis, results were recorded on chart 1.

Axis	Exp. 1	Exp. 2	Exp.3	Exp.4	Exp.5	Avg
X	0.6	0.9	0.7	0.9	0.5	0.72
Y	0.5	0.2	0.3	0.3	0.9	0.44

TABLE I
PRECISION TEST RESULTS

A lower to 1 cm error was detected in this test; however, being 0.5 c the maximum standard acceptable error in the construction industry, new experiments with higher precision tools must be carried out as further work.

Precision Test

This test simply required the movement of both axes, simultaneously. The obtained results were favorable.

Cost Analysis

Once the materials, parts, machine elements, and electronics to be used for the development of this project were defined, quotations were obtained and phone inquiries were made to determine the approximate final cost of the project to be implemented. Quotation is shown on chart 2.

	Piece	Key	Extra	USD	Total USD	Total MXN
20	10 mm Flange Nut	3842345081	NA	0.25	5.00	85.35
20	M8 X 25 T-Bolt	3842528718	NA	0.97	97.00	1,655.92
8	90° Brackets 45/180 mm	3842551608	NA	22.79	182.38	3,113.46
2	90 X 90 mm Bosch Profile	3842553613	2 at 3m, 2 at 0.55 m	97.85	684.98	11,651.42
25	T- Nut M6	3842530285	NA	0.97	97.00	1,655.92
4	Guide VEVOR Rail	HSR 20	NA	107.40	429.60	7,159.34
8	2m 30X30 cm Perimeter Structure	NA	NA	NA	NA	18,240.00
4	Perimeter Structure Base	NA	NA	NA	NA	6,080.00
9	PLA Kg	NA	White	NA	NA	3,985.86

TABLE II
QUOTATION

TOTAL MXN: $53,627.27

VII. Discussion of Results

The testing phase of this project has encompassed four key areas: robustness and resistance to dynamic weight holding, precision, path tracking in two simultaneous directions, and cost analysis.

In assessing the robustness and resistance to dynamical weight, a 65-kilogram weight was employed on the moving Y-axis. This weight, supported by the X-axis and the overall structure, underwent displacement at varying speeds to evaluate the absence of vibrations and structural failures. Subsequent analysis revealed no structural damage, affirming the system's robustness particularly at low acceleration rates, deemed suitable for printing tasks. Even when the system was not tested with 110 Kg weight charges, it is known due to previously developed calculi that a security factor is considered on this test. The precision test involved marking a spot as the origin and instructing the system to move one meter away in both directions. Repeated five times per axis, the experiment resulted in an average error of less than 1 cm. However, given the maximum acceptable error in the construction industry is 0.5 cm, further experiments with higher precision tools are warranted. Additionally, simultaneous movement of both axes was executed successfully, and a comprehensive cost analysis was conducted to determine the project's approximate final cost, totaling 53,627.27 MXN; considerably lower to concrete 3D printers of this dimensions in the market. It must be remarked that design enhancement and robustness were affected by time limitations.

VIII. Further Work, Author Comments and General Conclusions

The main findings on this project are now established to deepen on the implications and further work surrounding this project and report paper. The main noticeable point of analysis on the project is to state that the construction of a relatively low-cost concrete printer within educative institutions, to bring undergraduates to a nearer connection to emerging technologies, is achievable.
In addition, the selected materials and designed mechanisms where enough to support robustness, precision, functionality, safety and cost requirements.
On the other hand, the project quality and deliverables were affected due to time limitations in two main ways; being the first reason the lack of time to physically prototype a Z-Axis mechanism, and the second the lack of time to print the required X-Axis pieces (stepper supports, shaft supports and bearing supports) that lead to lower precision and robustness in the system.
In regards to further work, the following points must be taken into account to develop new projects starting from the point at which this project report is now written:

- The modernization of the used hardware (PC, monitor and mouse).
- The exploration of open-source control software such as Linux CNC.
- The exchange of MDF pieces for the originally established PLA 3D printed pieces.
- The exploration of Z-Axis non-invasive movement mechanisms.
  - This task was not deepen due to time and environmental (spatial) limitations.
- The integration of high precision sensors for redundancy to determine position and other relevant variables.
- The integration of this system to a pre-mixing and a feeding system.
- The analysis of different concrete compositions to achieve optimal results.
- The distance-monitoring of the system on interfaces through tools such as MQTT protocol, Micro-controllers and Cloud Services.

No Appendix has been added to this paper, however, multiple complementary resources can be accessed through the existent clickable hyperlinks inserted on various sections of this document.

References

[1] "Impresora 3D de casas de hormigón," 2020.
[2] , "Optimizing 3D Printer Depending on 3D printing Concrete Property," *Semantic Scholar*, 2018.
[3] S. Research, "3D Concrete Printing Market Growth Analysis," *Stratview Research*, 2022.
[4] J. et al., "Development of a 3D Printer for Concrete Structures: Laboratory Testing of Cementitious Materials," in *International Journal of Concrete Structures and Materials*, 2020.
[5] COBOD, "BOD 2," 2024.
[6] RobotPlace, "APIS COR 3D PRINTING SYSTEM," 2024.
[7] M. Safarabadi, "Linear Actuator," 2023.
[8] I. Iribar, "Cómo funciona la impresión 3D en la industria de la construcción," *CEMEX Ventures*, 2023.
[9] J. e. a. Zhang, "A review of the current progress and application of 3D printed concrete," *ElSevier Composites Part A*, no. 105533, Jul. 2019.
[10] e. a. Liu, Huawei, "Hardened Properties of 3D Printed Concrete with Recycled Coarse Aggregate," *Cement and Concrete Research*, vol. 47, 2022.
[11] e. a. Bos F.P., "The Realities of Additively Manufactured Concrete Structures in Practice," *Cement and Concrete Research*, vol. 81, 2022.
[12] A. Valdés, "Panorama internacional de la impresión 3D en concreto," 2017.