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State-of-the-Art Review on 3D Printing Technology Applications in Construction

THESIS

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MASTER OF SCIENCE

By

Andrew Truong

Thesis Committee:

Professor: Ayman Mosallam, Chair

Assistant Professor: Mohammad Javad A. Qomi

Assistant Professor: Joel Lanning

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DEDICATION

To

my parents and friends

in recognition of their kindness

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ABSTRACT OF THE THESIS

STATE-OF-THE-ART REVIEW ON 3D PRINTING TECHNOLOGY APPLICATIONS IN CONSTRUCTION
By

Andrew Wesley Truong

Master of Science in Civil and Environmental Engineering

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Professor Ayman Mosallam, Chair

This thesis presents a state-of-the-art review on the 3D printing technology and its applications in construction. This technology is the computer aided design and manufacturing of objects. It is a new way of manufacturing products by layer to layer adhesion. The material can include thermoplastics, photopolymers, concrete and many other materials. The major benefit of 3D printing applications in construction is the ability to 3D print concrete without the use of formwork. The use of concrete 3D printing allows for the construction of concrete structures that are cost and time efficient. Construction of concrete 3D printing deviates from typical methods of concrete construction and therefore requires structural analysis and novel engineering design to maintain structural integrity. A review of concrete 3D printed structures that are currently being printed and how 3D printing works are presented in this thesis to allow for informed design decisions when 3D print structures. The overview of the 3D printing will also include the feasibility of 3D printing structures on planet Mars. Due to the autonomous nature of 3D printed construction, structure can be constructed on the desolate planet before astronauts arrive to Mars. The use of 3D printing has a variety of applications and can increase the efficiency of structural engineering design and construction.

CHAPTER 1

INTRODUCTION

1.1 GENERAL

In this chapter, thesis content is introduced, and a review of related works is presented. The 3D printing technology and its broad range of applications in the construction industry is discussed in this chapter. In addition, the current state-of-the-technology of 3D printing related to construction applications is discussed. A brief description of each chapter of this thesis is presented herein. Also, each chapter in the thesis is describes in the introduction to understand the layout of the thesis.

1.2 THESIS ORGANIZATION

This thesis (i) reviews leading and pioneering contributions of some of the companies and universities that have made developments in recent years, (ii) explains the 3D printing technology, (iii) describes the applications for 3D printed construction, and (iv) provides sample work of a 3D printing prototype.

Chapter 1 introduces 3D printing and its applications in the construction industry. Chapter 2 provides an overview of 3D printing technology, the main components used in 3D printing, the materials used in 3D printing, the strength properties of 3D printed parts, and modifications to the 3D printing machine.

In Chapter 3, the use of 3D printing in the construction industry is discussed. For reference purpose, information on commercial companies that are currently using 3D printing concrete and building houses are presented in this chapter. An overview of 3D printing technology being used on planet Mars is presented in Chapter 4. Chapter 5 presents suggested modification of a commercially produced 3D printing machine to extend its capability for printing with cementitious mortar. Based on the information presented and analyzed throughout this thesis, conclusions and recommendations for future research work are presented in Chapter 6.

1.3 HISTORY OF THREE-DIMENSIONAL (3D) PRINTING TECHNOLOGY

1.3.1 The First 3D Printing Patent

In May 1980, Dr. Hideo Kodama describes a rapid prototyping technique that is like stereolithography 3D printing. Dr. Hideo Kodama is from the Nagoya Municipal Industrial Research Institute. The patent is like stereolithography, because it uses a laser to harden photopolymers in a vat. The laser builds up an object layer by layer like how stereolithography 3D printing is done today. Unfortunately, Dr. Kodama could not commercialize the invention, because the non-provisional patent was not filed within a year of the provisional patent. A provisional patent is a patent that describes the invention and gives the inventor one year to create the invention so that a non-provisional patent can be created. [1]

1.3.2 Stereolithography

In 1986, Chuck Hull [2] invents the process of 3D printing known as stereolithography. Stereolithography (SLA) is the process of 3D printing where photopolymers are solidified from a liquid form in the presence of ultra-violet light. The Ultraviolet (UV) light hardens the photopolymers by crosslinking the photopolymers with radiative light. The 3D object is created in a vat of photopolymer resin and UV light shines on a build platform that selectively solidifies the photopolymer. Chuck Hull uses this method of stereolithography to 3D print the first object with the 3D printer, the SLA-1(See Figure 1.1). Hull then acquires a patent for stereolithography and creates 3D Systems Corporation with the aim of selling 3D printers to aerospace, automobile, and manufacturing. The 3D printers would be used as rapid prototyping methods to create an efficient method of design and production [3].

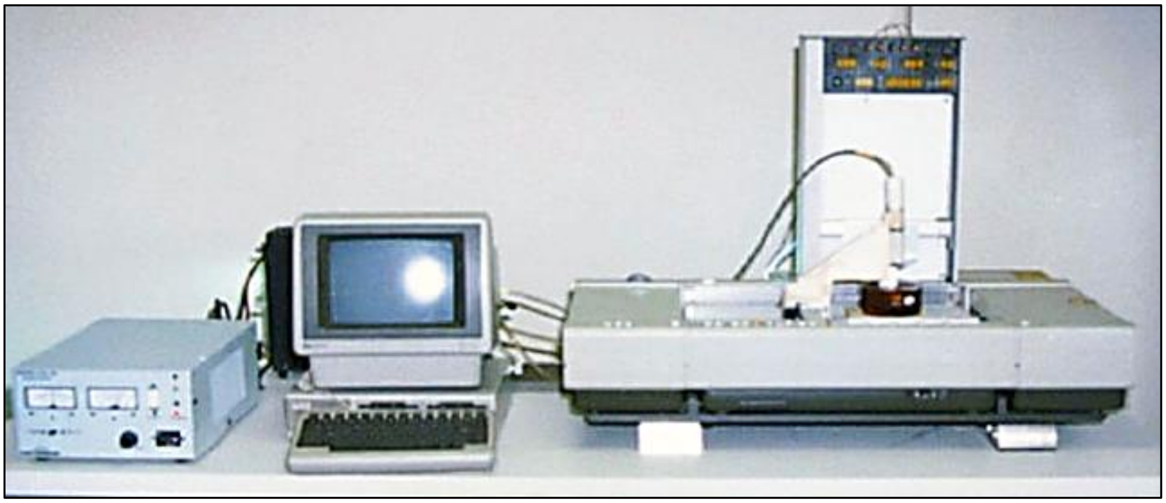


Figure 1.1: The SLA-1 [3]

1.3.3 Selective Laser Sintering (SLS)

In 1987, Carl Deckard at the University of Texas, created a selective laser sintering (SLS) printer (refer to Figure 1.2). The broader definition of sintering or frittage *is the progressive transition process occurred prior to melting that involves compacting and forming s material solid mass using heat or pressure. Under the effect of heat, the grains are welded together forming cohesion between particles. The application of compacting pressure provides the ability to control both powder grains size material density. Controlling grain size and density can alternatively be achieved by using of special binders that are added.* For 3D printing, selective laser sintering is a way of 3D printing objects by sintering a bed of powder together with a laser. The 3D printing method uses a bed of powder that can act as support material for overhanging objects. A selective laser sintering machine uses two containers to move the powder back forth. Once the powder is sintered to the build plate, a sweeper moves a layer of sintering powder onto the adjacent container (see Figure 1.3). The laser then sinters the next layer and the process continues until the 3D printed object is created. Selective laser sintering can be used with plastics and metals [4].

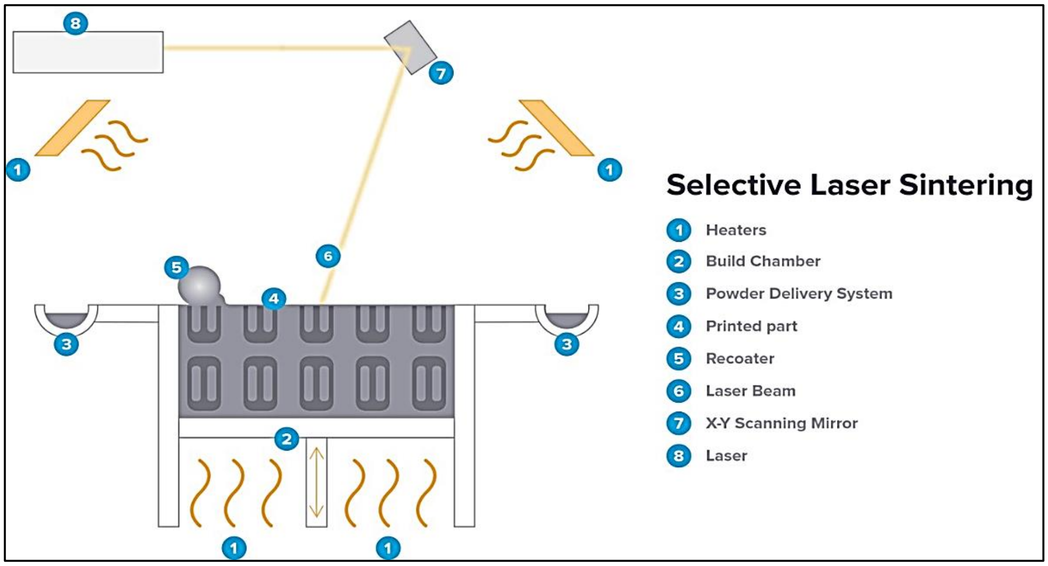


Figure 1.2: SLS Process [Source: https://formlabs.com/blog/what-is-selective-laser-sintering/]

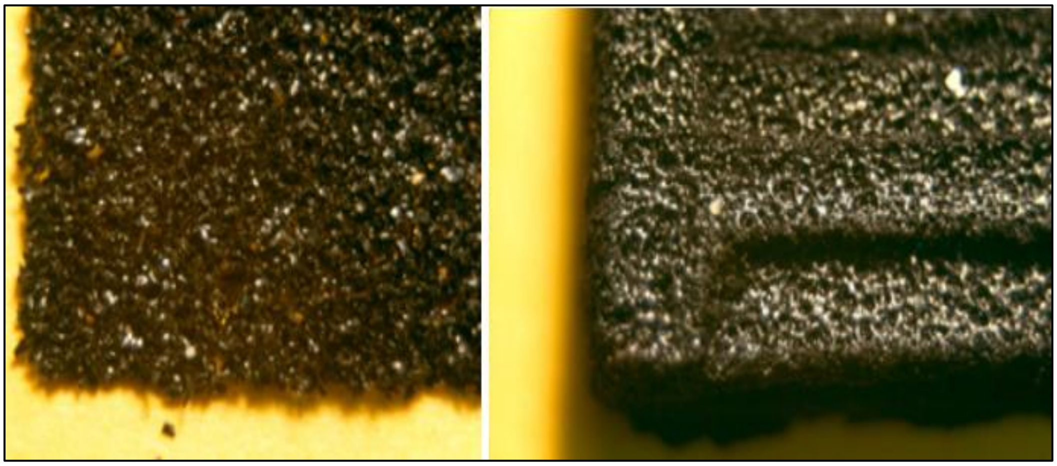


Figure 1.3: Close ups of the first plastic powder Deckard used in his SLS project before (top) and after (bottom) sintering process. [76]

1.3.4 Fused Deposition Modeling

In 1989, S. Scott Crump and Lisa Crump invent fused deposition modeling. They used thermoplastics to deposit material onto the build platform to 3D print an object. This technique is commonly used today and synonymous with 3D printing. Fused deposition modeling uses a spool of thermoplastic filament that is feed into a heated nozzle extruder. The heated plastic is transiently converted into a malleable plastic, while it is placed onto the 3D printed object where it solidifies and fuses to the rest of the 3D printed object. Since fused deposition modeling uses a filament made of thermoplastics, a variety of materials can be added to the thermoplastics mixture to create composite materials. Some fused deposition modeling materials include carbon fiber, timber, and metals. Crump received the patent for *fused deposition modeling* in 1982. [5] Crump then founded the company Stratasys in 1989. Stratasys was founded with the goal to market to the medical industry [6]. 3D printing is a way a rapidly prototyping parts which is cheaper than injection molding prototypes. However, 3D printing does not offer economies of scale. It has a linear production curve meaning that printing 50 objects will take 50 times as long to complete. [7]

1.3.5 3D Printing in Medical Applications

In 1999, the first 3D printed organ was transplanted into a human patient. The organ was a lab grown bladder made from a biodegradable scaffold. This technology was developed at the

Figure 1.4: Examples of 3D Printing Medical Applications [8]

Wake Forest Institute for Regenerative Medicine. Human organs are made by first 3D printing a scaffold, and then inoculating the scaffold with cells from the patient's body or stem cells. Other human parts such as kidneys, legs, and blood vessels are also being developed. (see figure 1.4) [8]

1.3.6 RepRap Open Source Printing

In 2004, the open source initiative was founded by Adrian Bowyer. An open source concept for a 3D printer became widely available for the mass public to use. Open source technology is a way of democratizing advancements in technology by making new developments available to the

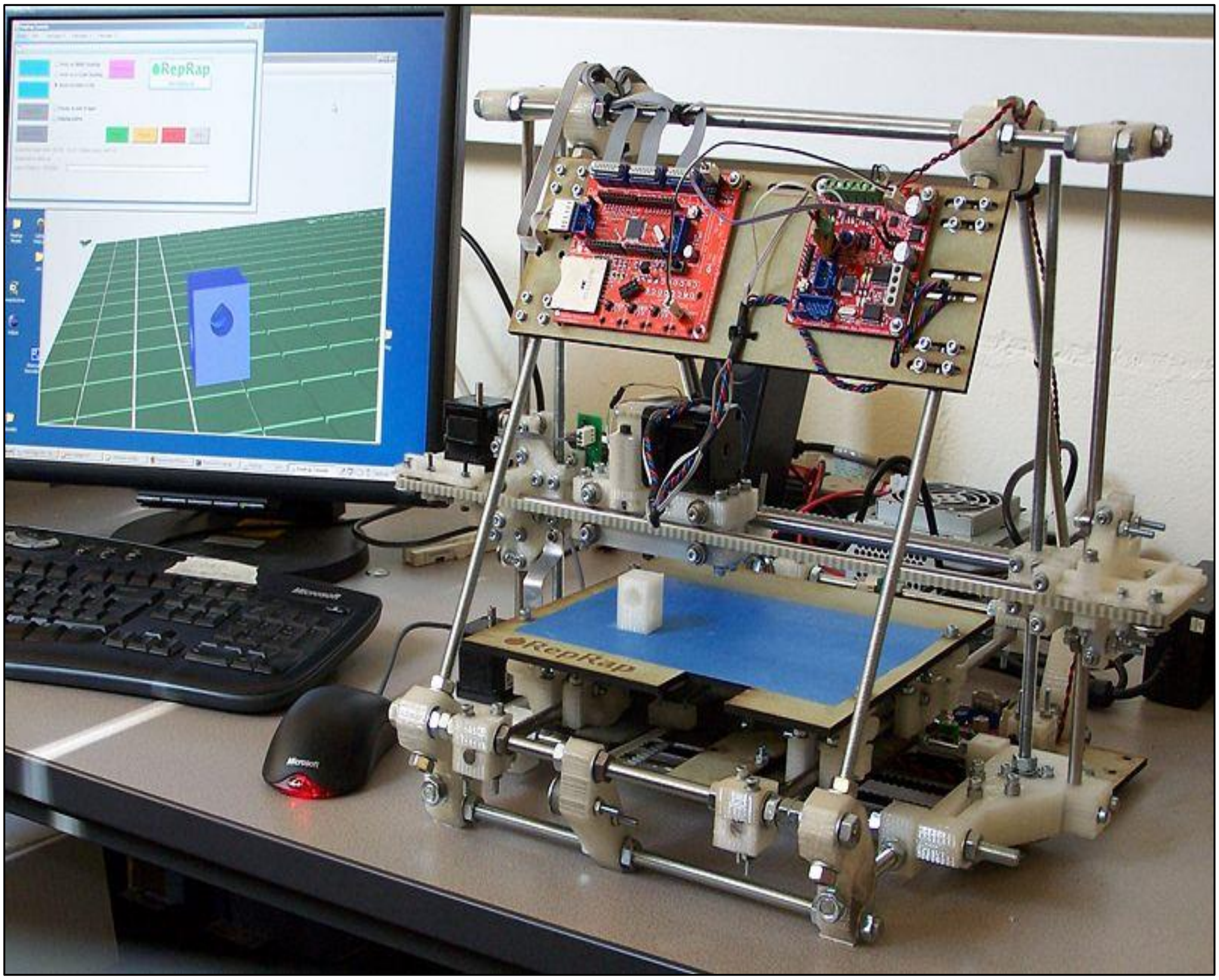


Figure 1.5: The first version of RepRap design (Mendel) [Source: https://reprap.org/wiki/Build_A_RepRap]

public. Therefore, technological research in the field of 3D printing is more easily accessible [6]. Figure (1.5) shows the first operational version of RepRap called Mendel. This version is fully functional but is relatively complex as compared to later versions.

Figure 1.6: First Fuel-Efficient 3D Printed Car is Back on the Map [9]

1.3.7 MakerBot

In 2009, Crump [4] fused deposition modeling patent expired. Therefore, MakerBot commercialized the technology and produced 3D printers that could be used at home. MakerBot also created Thingiverse.com; a database for 3D printed objects that are shared freely. MakerBot was sold to Stratasys in 2013 for $400 million [1]. Open source files can be downloaded from thingiverse.com. These files can be used and modified in SketchUp for 3D printing. The files on thingiverse.com are .stl files. These .stl files can be imported into SketchUp to be modified. Once the .stl file has been modified, the .stl file is imported to the slicing software. The slicing software controls the 3D printing parameters and slices the file for printing [7].

1.3.8 Present 3D Technology

Currently, 3D printing has impacted a variety of industries. In 2010, the first 3D printed car was made by Urbee (refer to Figure 1.6) [9]. For food applications, Cornell built the first food 3D printer in 2011 (see Figure 1.7) [10]. In 2012, the first 3D printed jaw was implanted for dental applications. In 2015, Cellink prints cartilage from nanocellulose. In 2016, Daniel Kelly's lab printed bone [4].

Figure 1.7: 3D Food Printing [10]

1.4 HISTORY OF CONCRETE 3D PRINTING

Concrete 3D printing is a way of building concrete structures without the use of formwork. The 3D printer builds a component layer by layer with a mix design that uses accelerators and concrete additives to meet design requirements. Several advancements have occurred since the beginning of concrete 3D printing [11].

1.4.1 Contour Crafting

In 2003, Behrokh Khoshnevis created contour crafting. Contour Crafting is the first documented invention of a concrete 3D printer [12]. The concrete 3D printing process was founded by Behrokh Khoshnevis. Contour Crafting uses a layering technique to build up concrete without the use of form work. The company intends to use concrete 3D printing to construct houses and civil structures on earth and on the moon [13] . In Figure 1.8, contour crafting is shown 3D printing a wall.

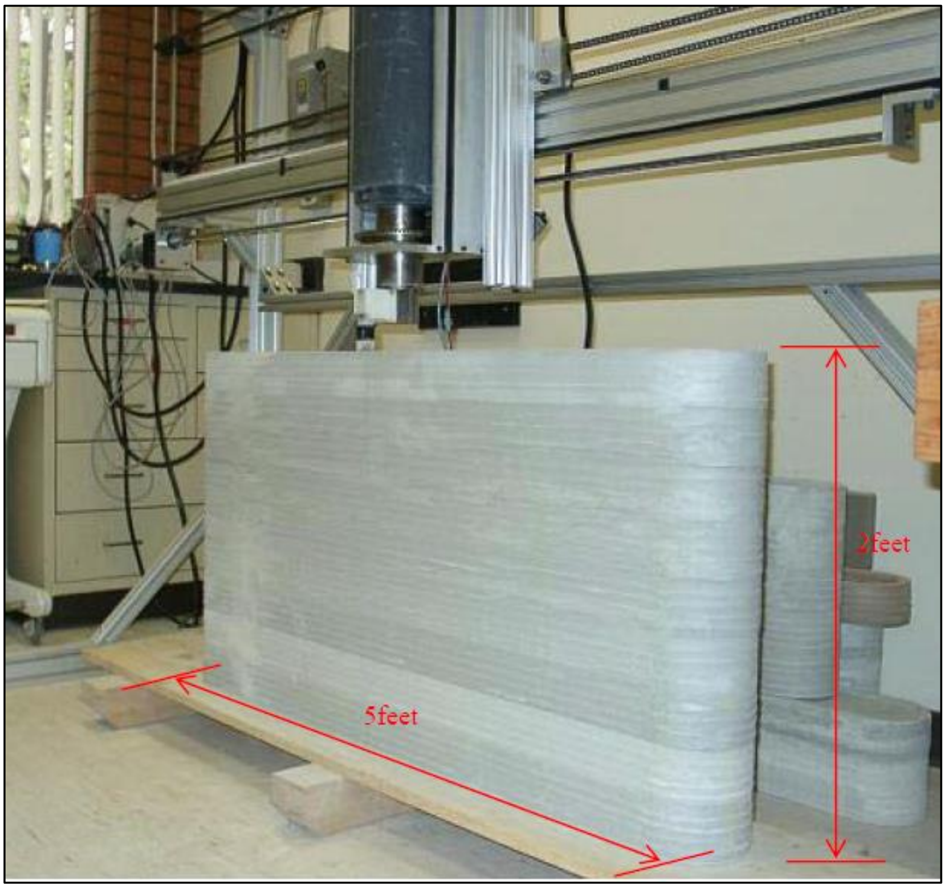


Figure 1.8: A concrete form of desired span and height fabricated by the CC machine [12]

1.4.2 Loughborough University

In 2008, Loughborough University creates a freeform construction method using a layering technique as well as a powdered sintering technique. The goal of the university is to print highly customizable building components [14]. Figure 1.9 displays a custom 3D printed bench.

Figure 1.9: The printed Wonder Bench [14]

1.4.3 WinSun™

In 2015, Winsun prints ten houses in 24 hours to demonstrate concrete 3D printings ability. Winsun also 3D printed a six-story building to display the architectural flexibility concrete 3D printing has. The company prints the civil structures within a warehouse. The 3D printed components are then pieced together on the construction site [15].

1.4.4 XtreeE™

In 2017, XtreeE™ prints a 3D printed wall with integrated windows. The wall was built with robotic arms that can simultaneously work together. Robotic arms can print walls and placing window frames. This multitask construction sequence is a technological development in automated construction [16]. Figure 1.10 presents two industrial robots working together to print a window and wall system.

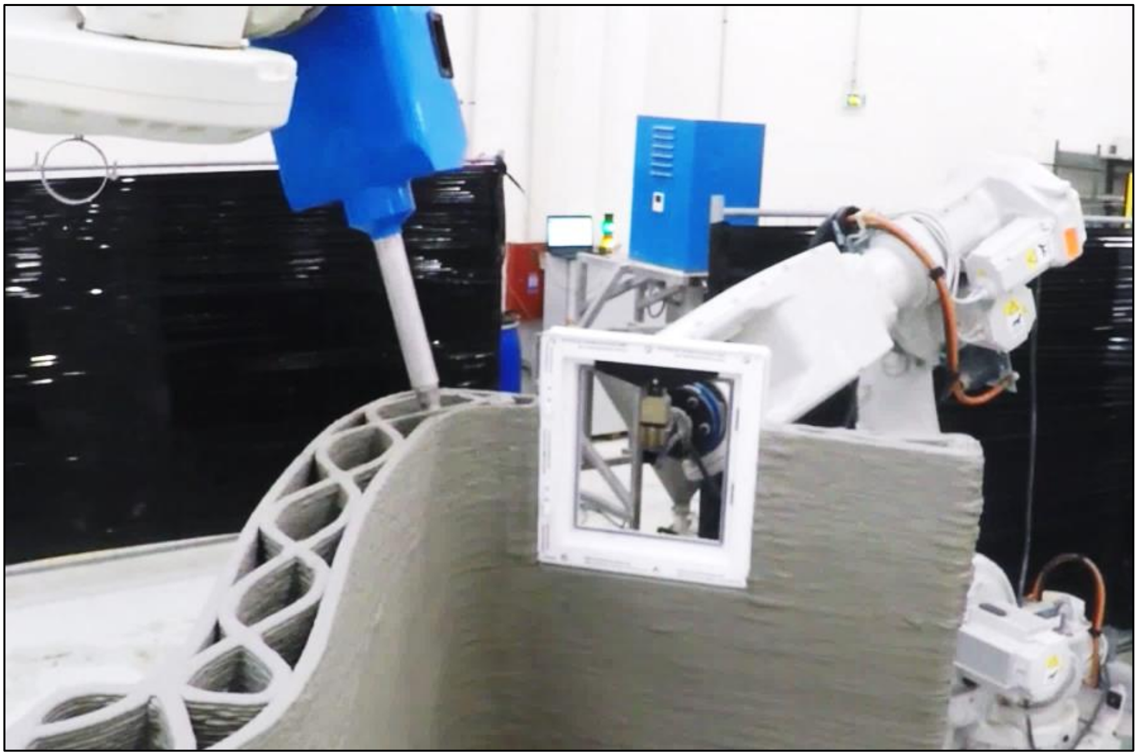


Figure 1.10: XtreeE™ - 3D Printed wall with integrated window frame [16]

1.4.5 TU Eindhoven

In 2017, TU Eindhoven 3D printed the first bridge that was building code approved in Eindhoven. The 3D printer is in a warehouse facility and the bridge was printed in three pieces. The pieces of the bridge were grouted together and pretensioned so that no reinforcement had to be used. The design of the bridge was done through the testing of a smaller scale 3D printed bridge. The structural testing of the scaled model provided stress and strain data for the construction and implementation of the actual bridge. [17]

1.4.6 ICON™ Build

In 2018, ICON™ 3D printed the first building code approved house in the United States. The 3D printed house is a one family single story house with a timber roof. The 3D printed house was printed in Texas. The 3D printer is a mobile gantry printer that can be transported to the construction site. ICON aims to print affordable housing and has many upcoming projects. [18] Figure 1.11 shows the concrete equipment next to the 3D printed house.

Figure 1.11: ICON Build 3D Printed House [18]

1.5 SUMMARY

Global development of 3D printing construction occurred within the last few years making 3D printed houses that are a proven concept and possibly an industry standard in years to come. Collaboration efforts across the building industry have led to the approval of 3D printing as a safe, affordable, and artistic advancement in the field of construction and civil engineering. The 3D Printing construction makes construction more efficient due to the automation of construction tasks when building structures such as houses and bridges [19]. This technique is considered to be an environmentally sustainable building method due to zero waste additive manufacturing process employed in 3D printing [20]. Therefore, 3D printing construction is a solution to alleviate deficits in the global housing economy.

In the recent years, 3D printing technology became an industry trend that has affected various fields such as manufacturing, healthcare, construction and others. In the construction industry, 3D printing is used to manufacture structures with nearly zero waste, minimum costs, and faster building time. Within days, depending on the complexity and size of building, a new structure can be built that can be customized for each building iteration. Houses built using 3D printing technology can be achieved by a variety of ways and each method of construction has its advantage and disadvantages. In the following chapter, some of the recent advancements in 3D printing construction applications are discussed.

CHAPTER 2

THREE-DIMENSIONAL (3D) PRINTING TECHNOLOGY

2.1 GENERAL

This chapter describes the 3D printing technology and how it relates to the construction industry with a special emphasis of the use of concrete in 3D printing. In this chapter, a summary of the 3D printing process is presented, where the overall 3D printing mechanism is described for different types of 3D printers. The main mechanical parts of a typical 3D printers are presented and explained in this chapter. Materials that are commonly and potentially used in this technology and their respective strengths are presented including plastic, composites, mortar and concrete. A strength comparison between typical plastic concrete 3D printing materials is discussed. Accordingly, modifications to the 3D printer to be able to achieve concrete 3D printing is described.

2.2 SUMMARY OF 3D PRINTING PROCESS

The development of 3D printing has been built upon previous research and development in additive manufacturing. The 3D printing process uses a computer design that specifies spatial coordinates of the house. This computer design can be created in design software and can customize the house in an infinite amount of ways. This process of design a house or structure is called computer-aided design (CAD). This computer design is then sent to a slicing software to prepare the design for 3D printing. The house design is sliced into layers which the 3D printer interprets as machine code coordinates to trace out. The tracing of the coordinate system can be mechanically achieved through a variety of mechanisms such as gantries, robotic arms, and construction cranes. The 3D printer has a nozzle with the 3D printing material attached to the end effector to be able to extrude material. Since the computer design has the spatial coordinates of the house, the machine can turn on and off the extrusion of print material placing material exactly in the specified locations. Different materials that can be for the 3D printing methods includes thermoplastics, timber, carbon and glass fibers composites, concrete, polyurethane, metal weld, and other hybrid materials. This process of building is called computer-aided manufacturing (CAM). The start to finish CAD/CAM procedure streamlines the manufacturing process through a reduction in intermediary steps leading to 3D printing technology's efficiency.

2.3 MAIN COMPONENTS OF A TYPICAL 3D PRINTING MACHINE

The main components used in 3D printing thermoplastics and concrete are the coordinate controls and the extruder than dispenses the material. The coordinate system machinery can be comprised of various components in order to reach the desired coordinates. For example, a gantry crane mechanism can be used, or a robotic arm can reach to the locations where the 3D print extrudes materials [21]. The gantry system and the robotic arm use rotary motors to create linear and rotational movement [22]. The machine system moves the end effector or extruder to the desired coordinate to be able to 3D print concrete. The end effector is the location on the printer that is associated with the coordinate point on the computer aided design model. The computerized manufacturing of the model moves the end effector/nozzle to the coordinate points to 3D print objects by creating a nozzle path that 3D prints objects layer by layer. The computer model is sliced into various layers and the nozzle stacked concrete on top of the previously sliced layer. To stack concrete, the concrete mixture must have no slump and high early strength when leaving the nozzle [23]. An example of the 3D concrete printer in operation is shown in Figure 2.1.

Figure 2.1: 3D concrete printer in operation. No-slump concrete leaves the nozzle as a relatively stiff continuous filament. [23]

In figure 2.2, a gantry system uses rotary motors to make linearized movements in the three-dimensional coordinate axis space. Each of its motors is responsible for a coordinate frame, therefore, there are three motors and axes. A robotic arm that 3D prints also uses three rotary motors to achieve three degrees of freedom to 3D print. The coordinate system is based on cylindrical coordinates rather than cartesian coordinates. Robotic arms with more than three degrees of freedom can be used to 3D print objects. The use of a robotic arm that has more than three degrees of freedom is used to develop wrist motion to 3D print at angles in hard to reach areas as shown in Table (2.1) [24]. The components of a 3D printing machine are shown in Figure 2.2.

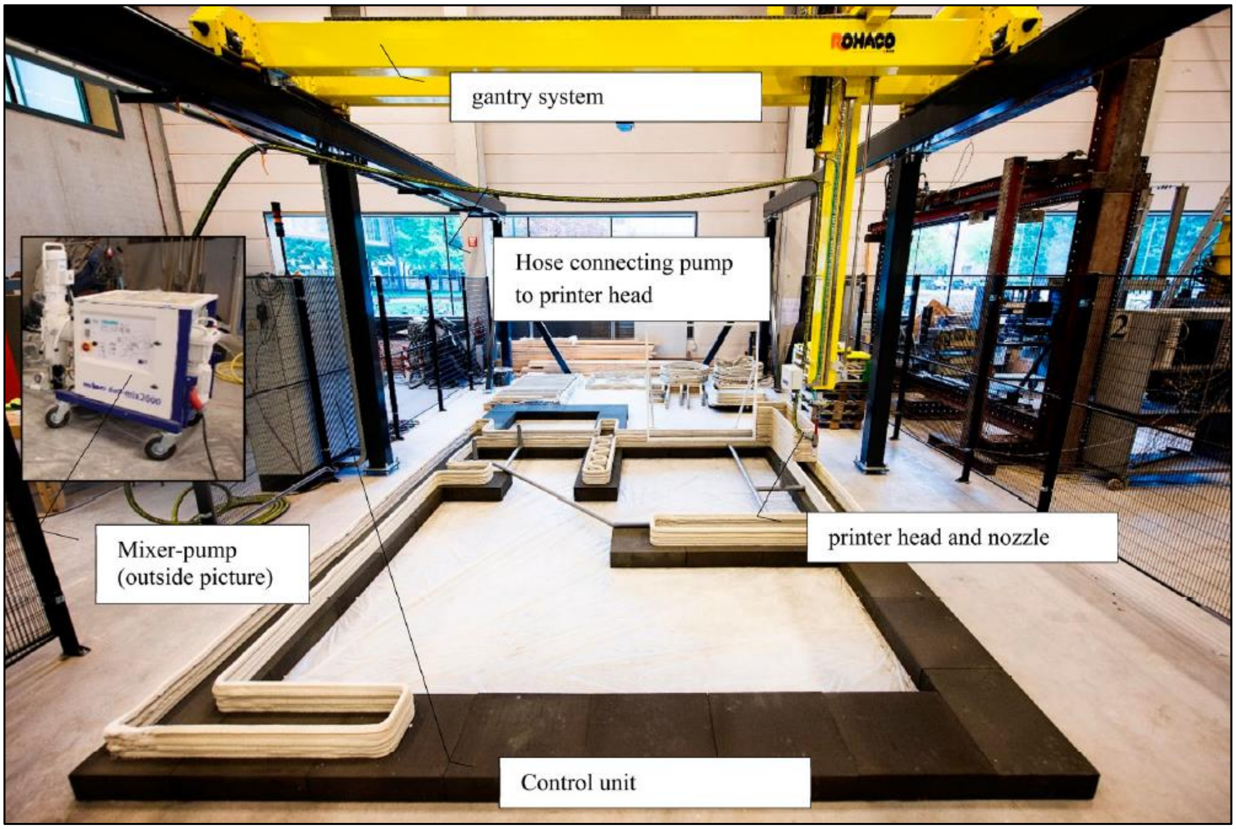


Figure 2.2: 3DCP facility at the TU Eindhoven, with some examples of printed objects [23]

Table 2.1: Gantry robot motion parameters [23]

DOF	v_{max}	a_{max}
x-axis Translation	1.8 m/s	1.0 m/s^2
y-axis Translation	1.8 m/s	1.0 m/s^2
z-axis Translation	1.8 m/s	2.0 m/s^2
z-axis Rotation	3.0 m/s	6.0 m/s^2

Once the machine is at the coordinate where the extruder should dispense material, the extruder mechanism will actuate to lay down material. The extruder is also comprised of a rotary motor that rotates whenever the coordinate mechanism is at a desired coordinate for printing. The extruder is different for a thermoplastic printer than a concrete 3D printer. A thermoplastic printer consists of a filament spool and a rotary motor. The motor attaches to the filament and moves the filament through a heated nozzle. The heated nozzle then changes the solid thermoplastic to a liquid state until it is dispensed onto the 3D print where it then solidifies. The concrete 3D printer extruder works by placing a grout pump onto a 3D printing mechanism. The pump and concrete hopper then dispense concrete that sets after being placed in the coordinate locations [25].

The nozzle of the 3D printer can be modified to properly lay down the concrete while adjusting the nozzle orientation (see Figure 2.3). The direction of the nozzle must always be rotated so that the extrusion is laid down properly. This nozzle design shown in Figure 4 depicts a layer by layer extrusion that is used for fine resolution printing. The high resolution of the printing makes it able to print thin layers that are refined to have a finish exterior on the print. This nozzle houses the extrusion screw auger motor that pumps out the concrete before it is place on the 3D print. The printer then moves in the direction and orientation of the printer to accurately 3D print the object. Therefore, the extrusion system has two motors. One motor is used to dispense the concrete out of the nozzle. The other motor is used to orient the nozzle in the correct direction. The shape of this nozzle creates a fine layer instead of a glob bead. The fine layer creates way for the 3D printer to have fine resolution prints in the same way a thermoplastic 3D printer works with a different print material and nozzle extruder [26].

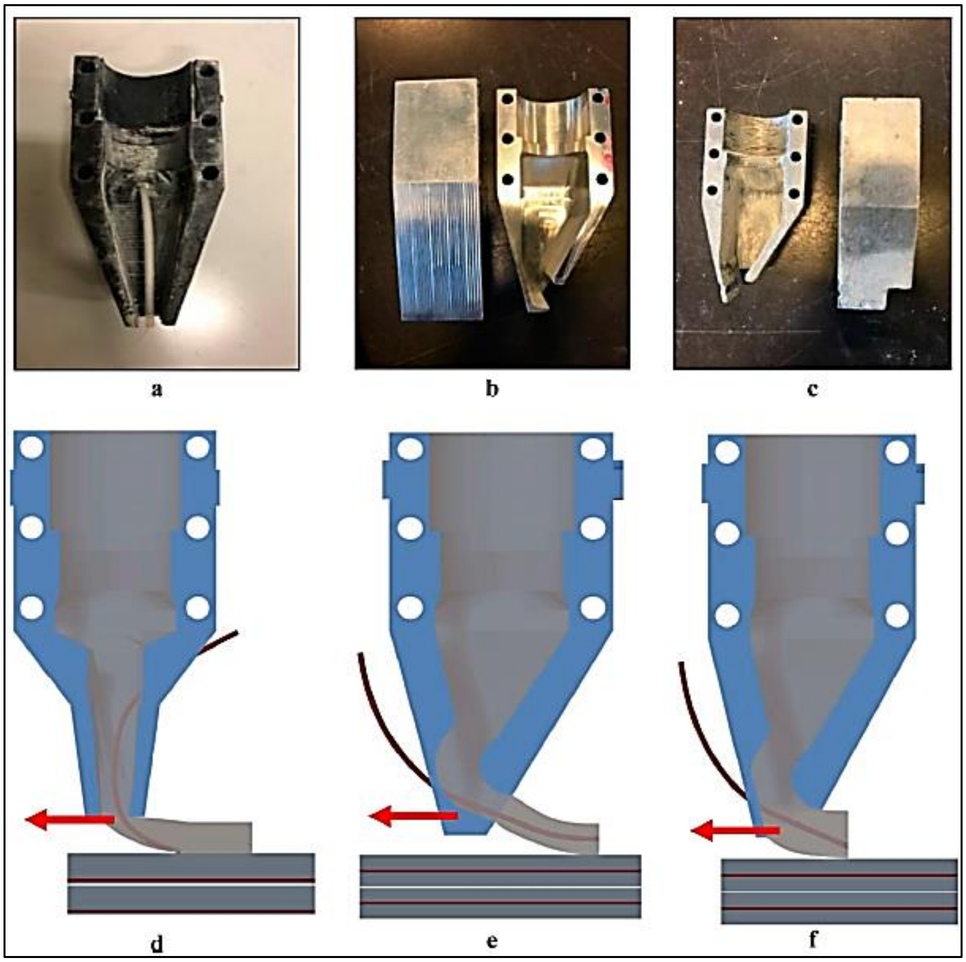
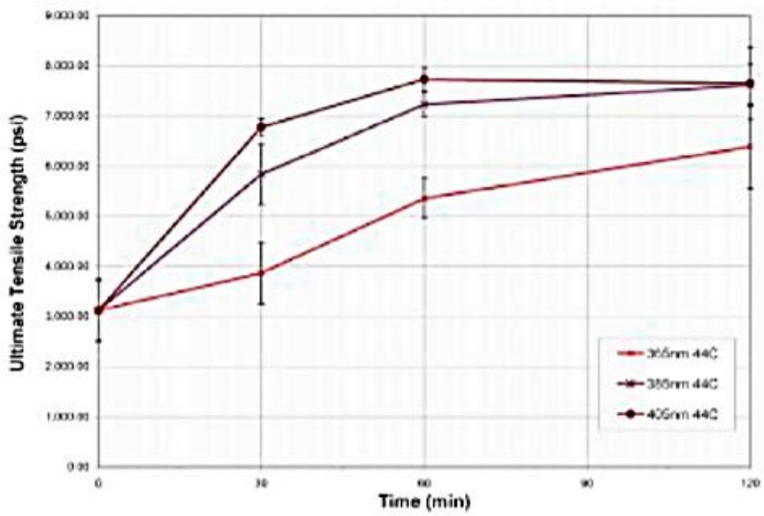


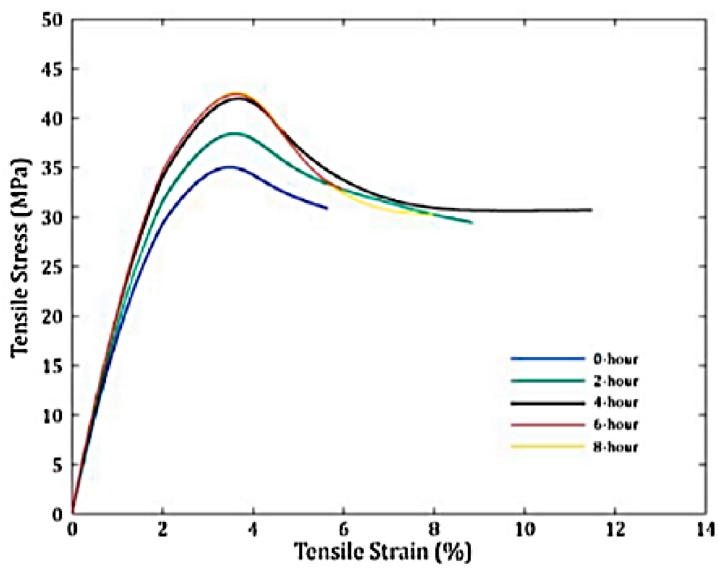
Figure 2.3: Printer head and nozzle. [23]

2.4 MATERIALS COMMONLY USED FOR 3D PRINTING

Some of the common materials that are used in 3D printing include thermoplastics, photopolymers, and concrete (and mortar). The thermoplastics used in 3D printing include poly lactic acid (PLA) and acrylonitrile butadiene styrene (ABS). The PLA is a plant-based plastic that can be printed for rapid prototyping. The ABS is printed at a higher temperature and can be used for engineering applications. The strength properties of the plastic printer are depicted in the table. The strength properties of thermoplastic are weaker and used for rapid prototyping [27]. The ABS thermoplastic is used for some engineering applications. The tensile stress/time and stress/strain curves presented in Figure (2.4) compare the various types of 3D printing with the strength tests do in the direction perpendicular to the manufacturing direction. The strength curves, therefore, exhibit linear yielding and plastic failure. Since the thermoplastics have plastic strain capabilities, the thermoplastics show extreme elongation until the failure point [28].



(a)



(b)

Figure 2.4: (a) Effect of Post-Cure wavelength on the tensile strength of a commercially available resin by Formlabs [126]; (b) Stress-strain curves of specimens post-cured at various period [29]

The orientation of the 3D print dictates the strength properties of the 3D print. 3D prints stress in the direction of manufacturing will show weakness and fail at the points of adhesion between the layers of the 3D print (see Figure 2.5). Therefore, the 3D prints must always be loaded in the direction perpendicular to the layer grains to achieve maximum loading capacity (refer to Figure 2.6) [29]. Table 2.2 presents the tensile strengths of various 3D printing materials.

Table 2.2: Overview of 3D printing materials. Mechanical characterization of 3D-printed polymers [29].

Supplier/Process	**Material**	**Density (g/cm^3)**	**Tensile Strength (MPa)**	**Tensile Modulus (GPa)**	**Elongation to Failure (%)**	**HDT (°C at 0.45 MPa)**
3D systems/SLA	Polypropylene-like, Visijet Flex	1.19	38	1.6	16	61
3D systems/SLA	ABS-like, Visijet Impact	1.18	48	2.6	14	47
3D systems/SLA	Polycarbonate-like, Visijet Clear	1.17	52	2.6	6	51
3D systems/SLA	High temp, Visijet High Temp	1.23	66	3.4	6	130
EOS/SLS	General purpose nylon, PA2200	0.93	48	1.7	24	163
EOS/SLS	Biocompatible nylon, PA2221	0.93	44	1.6	10	157
EOS/SLS	Glass bead filled nylon, PA3200GF	1.22	51	3.2	9	166
EOS/SLS	Aluminum filled nylon, Alumide	1.36	48	3.8	4	169
EOS/SLS	Polyaryletherketone, PEEK HP3	1.32	90	4.2	2.8	165
Stratasys/FDM	ABS, M30	1.09	26	2.2	2	96
Stratasys/FDM	PC-ABS	1.11	28	1.7	5	110
Stratasys/FDM	PC-ABS	1.14	30	2	2.5	138
Stratasys/FDM	PPSF/PPSU	1.33	55	2.1	3	188
Stratasys/FDM	PEI, Ultem 9065	1.21	33	2.3	2.2	153
Stratasys/Polyjet	Tangoblack FLX973	1.14	2	0.1	50	45
Stratasys/Polyjet	Durus RGD430	1.16	25	1	40	40
Stratasys/Polyjet	Veroclear RGD810	1.18	50	2.2	10	45
Stratasys/Polyjet	DABS RGD5160	1.17	55	2.6	25	58
Stratasys/Polyjet	High Temp RGD525	1.18	70	3.2	10	63

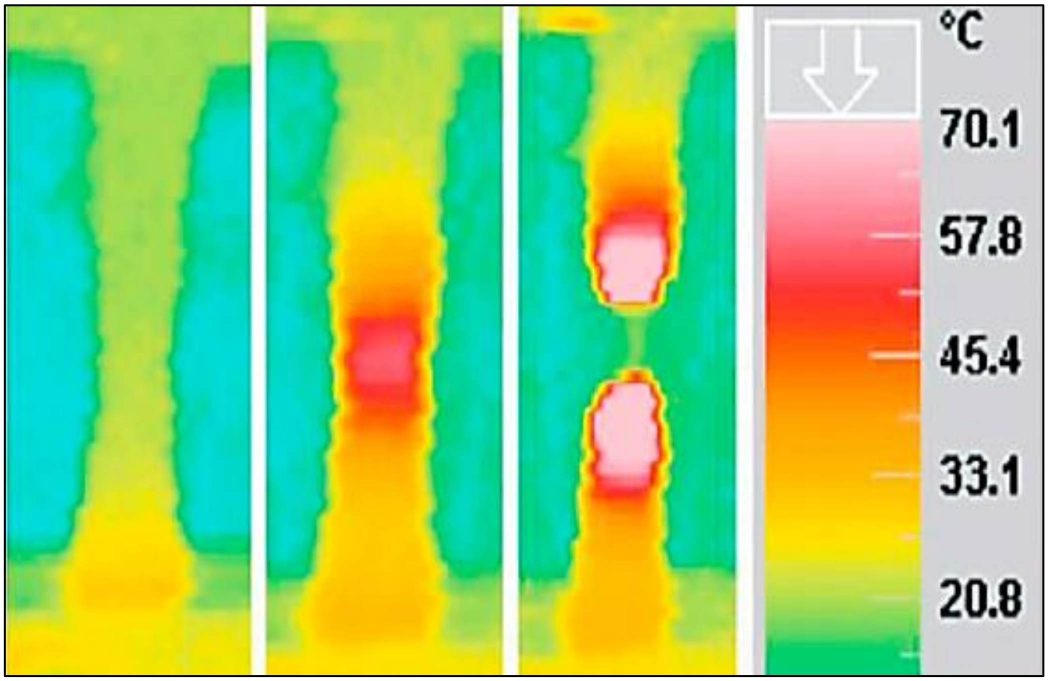
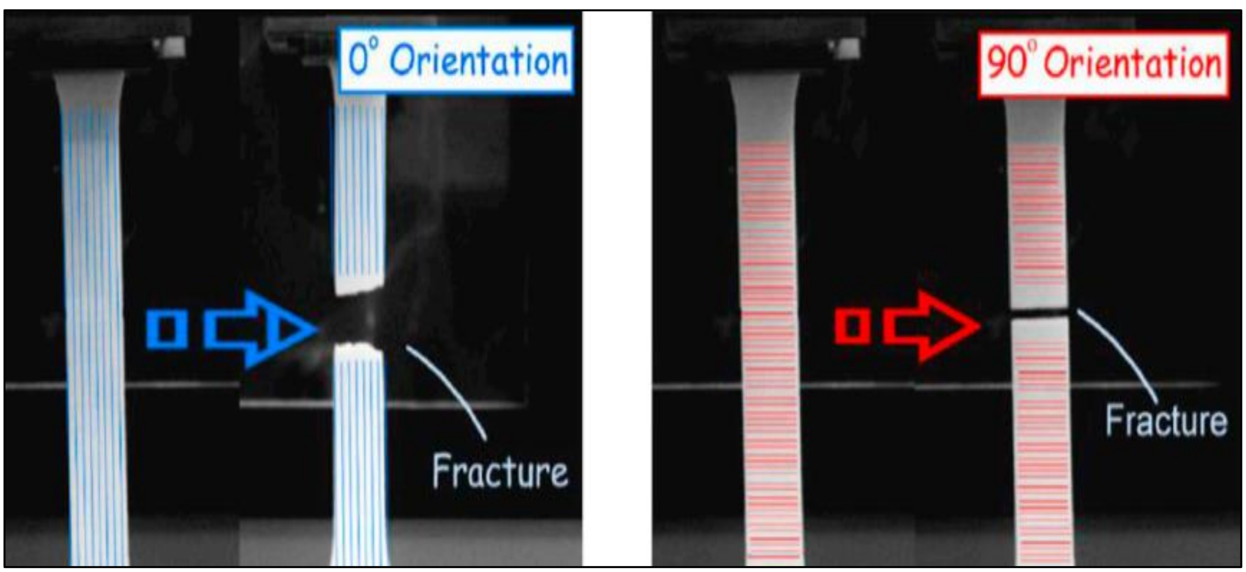


Figure 2.5: IR-camera temperature measurements during fatigue testing. [29]

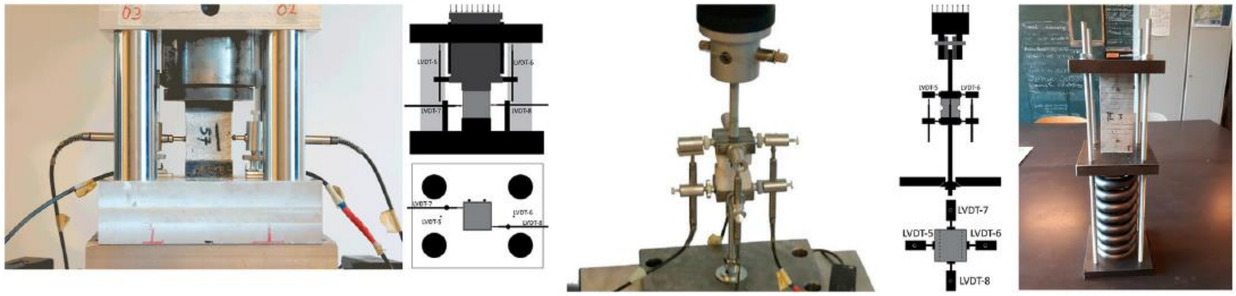


(a) *(b)*

Figure 2.6: (a) Actual fracture of a 0◦oriented test specimen; (b) Actual fracture of a 90˚oriented test specimen. [29]

2.5 STRENGTH PROPERTIES OF CONCRETE 3D PRINTING

As for any concrete application, strength properties of concrete 3D printing are dictated by the mix design. A mix design should consider the demand of the structure. Concrete 3D printing can be used as formwork and as structural members. If the concrete is used as a structural member the strength of the 3D printed concrete must be tested. Since 3D printed concrete is manufactured layer by layer, the strength of the adhesion of the layer must be structurally tested [30]. Pre-tensioning methods can be used to improve the strength between layers [31]. In Figure (2.8), 3D printed concrete is tested using a compression failure axial strength test. Prestressing concrete is a method used to improve to structural efficiency of the structural member. Since concrete is strong in compression and weak in tension, prestressing concrete will improve the concretes overall capacity by eliminating tension stress. The pretensioned 3D printed concrete will experience no tension as the entire structural member will be under continuous compression. The compression will serve to strengthen the structural member when loaded in beam bending. Tensile shear tests are also performed in order to characterize the 3D printed member in shear [32]. The strength properties of 3D printed concrete are shown in Table 2.3. The table lists properties such as the modulus of elasticity, average compressive strength, average tensile strength, creep factor, and shrinkage. The values were obtained through testing methods with equipment shown in Figure 2.7.



(a) *(b)* *(c)*

Figure 2.7: Test set-up of a compression test (a), a direct tensile test (b) and a creep/shrinkage test (c) used to determine structural properties of the print mortar. [17]

Table 2.3: Structural properties of Weber 3D 115-1 print mortar, as used in the structural design of the bridge [17].

Property	Direction	Age	Symbol	Value
Density		28 days	*P*	2,000 kg/m3
Modulus of elasticity		28 days	*E*	19,000 MPa
Average compressive strength	u	28 days	$f_{ck,u}$	23.2 MPa
	v	28 days	$f_{ck,v}$	21.5 MPa
	w	28 days	$f_{ck,w}$	21.0 MP
Average tensile strength (also used for flexural tension)	u	28 days	$f_{ck,u}$	1.9 MPa
	v	28 days	$f_{ck,v}$	1.6 MPa
	w	28 days	$f_{ck,w}$	1.3 MPa
Creep Factor		7 days	$\Phi 7$	1.0
		14 days	Φ 14	2.5
		56 days	Φ 56	3.0
Shrinkage		7 days	ε_7	0.6
		14 days	ε_{14}	1.2
		56 days	ε_{56}	1.5

Unlike concrete that are used in conventional parameter, other parameters, in addition to target compressive strength, dictates the design mix that is related to the demand of the 3D machinery. Concrete used in 3D printing, it must be viscous, yet firm enough to go through the hopper and concrete pump. Also, concrete used in 3D printing should also have a short curing (set) time so that, concrete can withstand buildable printed layers without collapse. For this reason, most of the 3D printing concrete uses special additives for viscosity and fast curing requirements. As an exception, these additives may affect the concrete strength and their effect must be considered when specifying 3D printing concrete or mortar [33].

The strength properties of 3D printed concrete were tested in the design of a 3D printed bridge at TU Eindhoven (refer to Figure 2.8). The 3D printed bridge was 3D printed with the strength design properties shown in Table 2.3. The design of the 3D printed bridge is shown in Figure 2.8. It is meant to function as a bike bridge of cyclists. The design of the 3D printed bridge is a concrete truss system that has been prestressed with cables and plates at the ends of the bridge. The bridge is simply supported across the span. The bridge is also a lightweight concrete design because of the 3D printed truss network shown. The 3D printed bridge is printed with three continuous extrusions of concrete material to achieve an overall span of 6.5 meters [17].

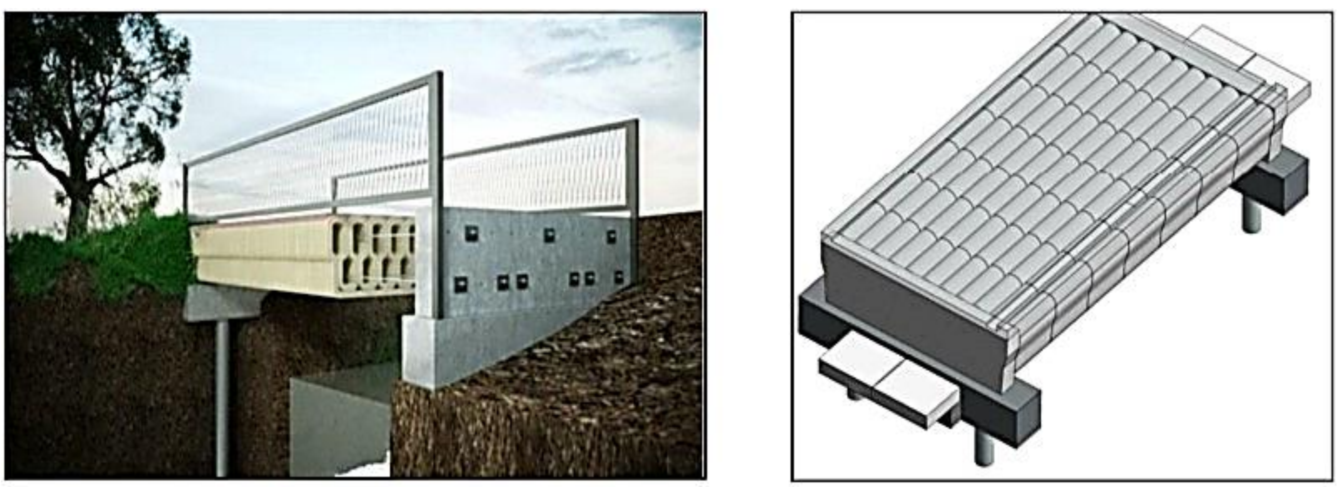


Figure 2.8: 3DCP bicycle bridge conceptual design (illustration by BAM) [17].

To test the strength capacity of the concrete 3D printed bridge, a scaled model was created and loaded to failure. The print path of the 3D printed bridge is shown in Figure 2.9. The bridge that was loaded to failure was a scaled 1:2 model of the bridge. The scaled model of the bridge was 3D printed with repeating layers as shown in Figure 2.9. The entire model was printed with curved tops and bottom to take care of bending moment. The bottom section of the bridge is designed to resist shear force [17].

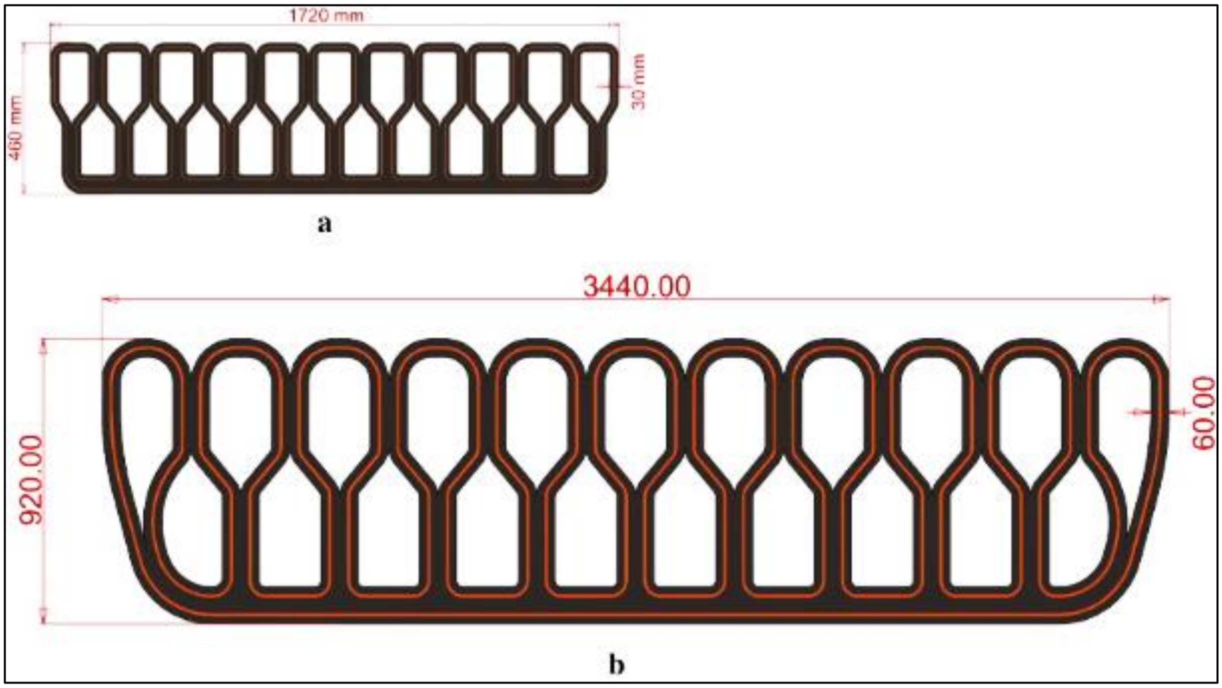


Figure 2.9: Print paths of the 1:2 scale model for testing (a) and the actual bridge section (b). The optimized pattern of the latter with regard to the former saves 4% of print path length [17]

The test setup is shown in Figure 2.10. The test set up is a four-point bending test with two support reactions and two applied loads. The bridge was loaded and unloaded in 30 kN increments to determine the fatigue strength of the bridge. The force- displacement curve is shown in Figure 2.11. The curve displays the loading and unloading. This fatigue test is used to determine at which stress does the bridge exhibit permanent deformation. In each loading and unloading sequence, the bridge was inspected for cracks that would contribute to failure. As shown in Figure 2.11, permanent deformation did not occur until 240.0 kN of force was applied to the bridge [17].

Figure 2.11: Scale-down model tested in a 4-point bending protocol [17].

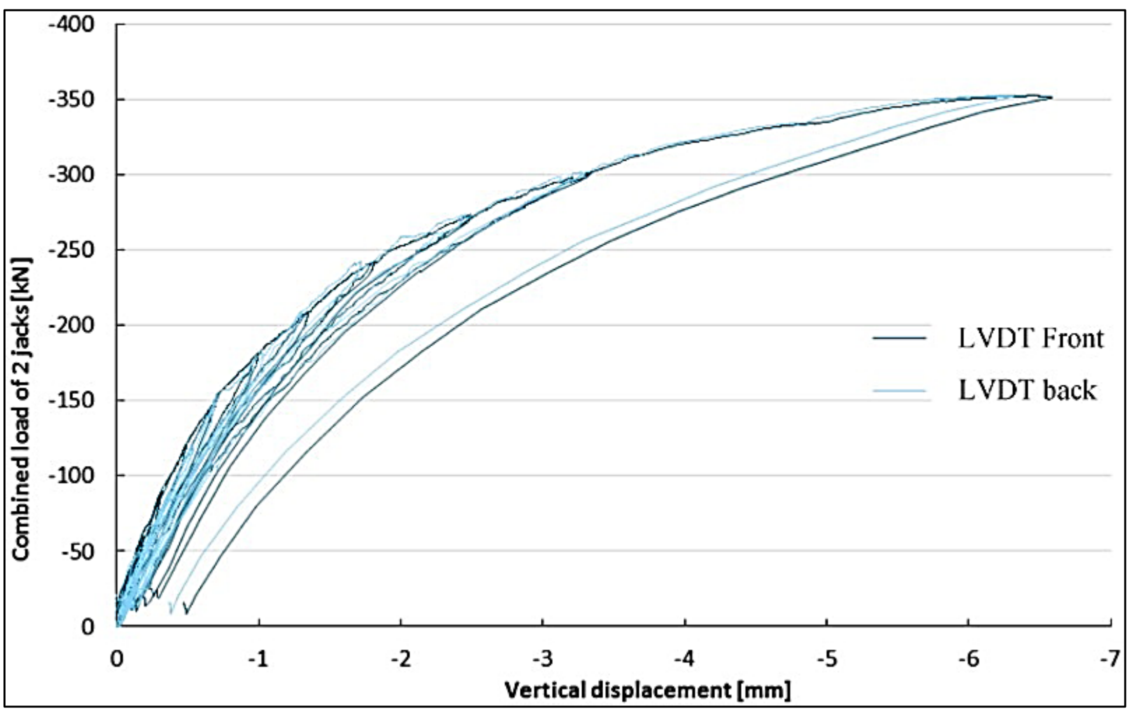


Figure 2.10: Load-displacement curve of the 4-point bending test on 1:2 scale model, measured through linear variable differential transformers (LVDTs) [17]

2.6 MODIFICATIONS OF 3D PRINTING MACHINE FOR CONSTRUCTION APPLICATIONS

3D printing can be used to construct various structures such as houses and bridges. When building a 3D printed house, the walls are 3D printed and traditional construction tasks are then performed. 3D printing the walls of concrete require reinforcement that is placed in between layers depending on the structural demand [34]. However, no formwork is needed to construct the structures, so houses are built at a faster rate. Doors and windows are built by placing a beam across the overhead gap while 3D printing or modular piece by piece construction is used [35]. After the house walls are 3D printed, the roof is then built to complete the structure. Mechanical, electrical, and plumbing can then be surface mounted to the structure. The exterior design of the house can be a layering pattern due to 3D printing or finish grout can be applied to create a smooth surface indistinguishable from traditional concrete building methods.

In order to modify the 3D printers to be used for construction the 3D printer is retrofitted with a concrete pump and concrete dispenser. The concrete pump and hopper take the concrete from the truck to the 3D printer. The concrete then fills the 3D printer extruder. The extruder then dispenses the concrete from a nozzle through an auger screw driven dispenser [36]. The concrete that goes through the extrusion system is then layered in a way that creates the 3D printed object. The layered concrete must have zero slump and yet viscous enough to be go through the extrusion system. The extrusion system then creates concrete objects that can be used in the construction industry. Examples of 3D printed concrete applications include bridges, walls, and foundations [37]. The concrete that is used acts as formwork. Since there is no formwork being used in concrete 3D printing, the 3D printed concrete is more cost effective. The 3D printed concrete is also zero waste. Therefore, 3D printed concrete can achieve strength results similar to traditionally built concrete members in an environmentally efficient way.

CHAPTER 3
APPLICATION OF 3D PRINTING TECHNOLOGY IN CONSTRUCTION

3.0 GENERAL

Chapter 3 provides details of the various application of 3D printing in the construction industry. The construction industry has commercialized 3D printing and the technology is being used in for real world applications. The way that companies use the technology differs to meet a specific market need. Different types of 3D printers are also presented and the method of 3D printing a structure is also compared in this chapter.

3.1 CyBe® CONSTRUCTION

This company uses a robotic arm that operates on a mobile cart. The advantages of using a robotic arm on a cart are variable square footage, a robotic wrist to print at angles, and mobility of on-site construction. Having a variable square footage building is useful when printing multiple structures and building products at multiple points on a construction site. The robotic wrist for angled 3D printing is useful when printing edge corners near adjacent structures. Finally, the mobility of the 3D printer reduces transportation costs associated with prefab construction. CyBe® Construction builds houses with sectioned concrete walls and anchors the walls together to create a structure. This method of construction can lead to gaps in the structure decreasing thermal insulation [38]. Figure 3.1 displays the industrial robot that is printing a wall with concrete.

3.2 ICON® 3D PRINTED HOUSE

In Austin, Texas, a 3D printing company called ICON® have printed a house that is building code approved in the United States (refer to Figure 3.2). This was an initial challenge in construction 3D printing leading to the business viability of selling houses. Since a 3D printing construction company could now be economically self-sufficient, business sector incentives could now proliferate the research and development of 3D printing technology [18].

ICON® used a gantry printer that can be moved to the construction site with a build area of 2000 square feet. Houses are printed as an entire piece leading to higher thermal insulation and structural distribution of stresses caused by earthquakes and hurricanes.

Figure 3.1: CyBe® Robotic Arm [38]

Houses can be printed in a single print due to nozzle control of concrete flow. Even though a gantry printer is limited in its building size, a gantry mechanism allows for heavier objects to be picked up and placed. This is considered as a potential solution for future development of automated roof and floor beams constructing.

Figure 3.2: ICON® 3D Printed House [18]

3.3 WinSun® BUILDING TECHNIQUE

The Chinese company WinSun® is a leader in the 3D printing concrete market, because of its list of building products and developments worldwide. The company has prefabbed concrete 3D printing products that range from architectural and landscaping products to multistory apartments in countries such as the United Arab Emirates and Dubai. Figure 3.3 shows a multistory building that was 3D printed.

The 3D printer is stationed in China so building products must be shipped to the construction site. However, this allows for finished products to be sold to builders globally. The multistory building is made from prefabricated concrete pieces with a metal deck and I-beam to support the floors and overcome the overhang effect [15].

Figure 3.3: WinSun® Multistory Construction [15]

3.4 TOTAL KUSTOM®

Total Kustom® is one of the first 3D printing house companies that can print houses with a gantry crane set up. The houses were constructed in the Philippines and adhere to the local building code. Shown in the picture, spiral columns and a door frame are designed to meet engineering code. The column is a non-typical spiral shape form work that can be simplified into the inscribed circular cross section during design (see Figure 3.5).

The spiral columns are form work and can be infilled with concrete and steel to gain enough structural strength. The door frame requires the print of an overhang. Overhangs cannot be directly printed because there is no support material to hold the 3D printing material in place (refer to

Figure 3.4). Therefore, the door frame is printed with a wood beam to bridge the gap between the two walls and to be used as support for the concrete formwork above the door level [39].

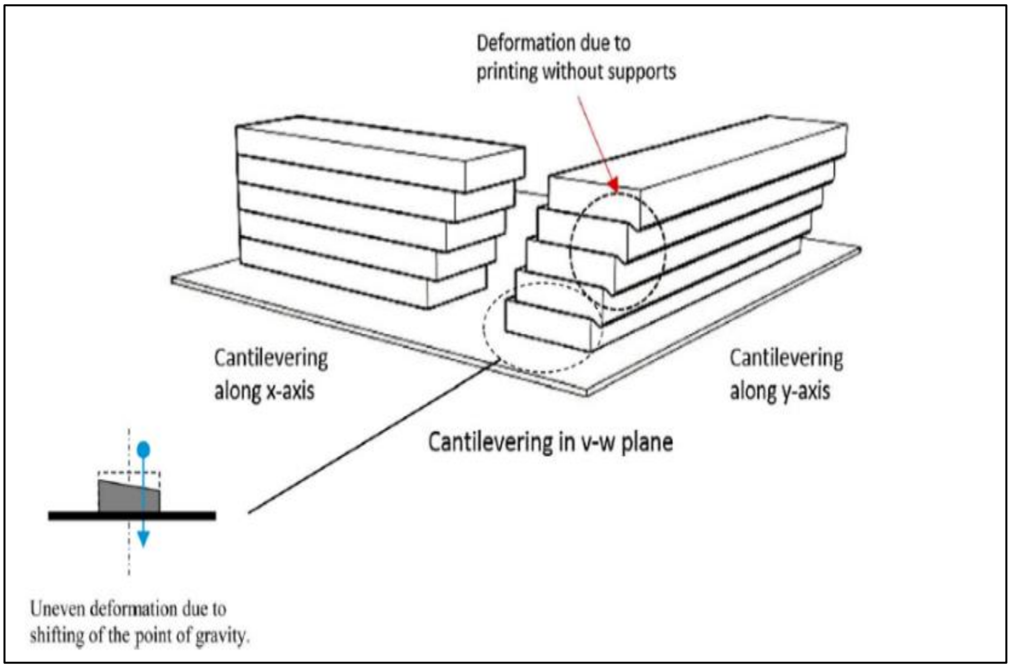


Figure 3.5: Cantilevering layers of filament in the v,w- and u,w-plane [23]

Figure 3.4: Total Kustom® Spiral Columns and Door Frame [39]

3.5 APIS COR®

This 3D printer works on a cylindrical coordinate system that reduces the printer size while increasing the build area of 3D prints. The mechanism of 3D printing causes more precision when 3D printing circular structures, which are structurally efficient in earthquakes and hurricanes. Apis Cor® has also developed an environmental geo-polymer that reduces the use of industrial additives used in concrete 3D printing. The 3D printer is compact and lightweight so that it can be transported around the construction site and to various locations for construction. The 3D printer is a mobile crane design that is connected to a grout pump. The 3D printer can print circular structures with ease due to its cylindrical shape and design (see Figure 3.6). The company also uses environmentally friendly geo polymers which are used to increase the strength and reliability of the structure [40].

Figure 3.6: Apis Cor Crane Printer. [40]

3.6 WASP™

WASP™ uses a delta printer with an end effector supported by three rails. The printer uses earth material to maximize the sustainability of the house. The 3D print design emphasizes the architectural capabilities of 3D printing in the construction industry. WASP™ has a variety of products including 3D printers and the architectural structures that it prints. WASP also does research into plastic hopper printing for large scale 3D plastic printing and 3D printed beams for construction [41]. WASP™ uses a 3D printed geo polymer that is environmentally sustainable. The 3D printed house is shown in Figure 3.7.

Figure 3.7: WASP 3D Printed Geo House [41]

3.7 TU EINDHOVEN UNIVERSITY

In the academic sector, developments in 3D printing structures also occur. TU Eindhoven uses a stationary gantry 3D printer with a unique nozzle for printing concrete. The nozzle extrudes a thin layer of concrete to decrease the 3D printing layer height to increase the finish resolution of 3D prints. This allows for a decrease in construction finish work such as drywall or grouting. TU Eindhoven is set to 3D print an entire neighborhood with custom design for each house to display the architectural capabilities of 3D printing technology [42]. TU Eindhoven aims to 3D print a functioning neighborhood that will used by homeowners. The project is the first of its kind and depicted in Figure 3.8.

Figure 3.8: TU Eindhoven 3D Printed Concept. [42]

3.8 University of Nantes

In France, polyurethane 3D printing is used to construct houses at a faster rate than 3D printing concrete. The printer is a robotic arm on a mobile cart with a polyurethane nozzle. This decreases the time spent 3D printing but increases the time spent on finish work construction. The advantage of using polyurethane is its thermal insulation properties. The University of Nantes has constructed a fully functional house that will house a family. The university uses a polyurethane mold which is then infilled with concrete to achieve structural strength and insulation. This method is like preform blocks that use Styrofoam piece as formwork. The thermal insulation is thus improved, and the construction time is reduced due to polyurethane 3D printing [43] (refer to Figure 3.9).

Figure 3.9: University of Nantes Polyurethane Printing [43]

CHAPTER 4

POTENTIAL USE OF 3D PRINTING ON PLANET MARS

4.1 GENERAL

The use of 3D printing on Mars is presented in this chapter. 3D printing on Mars and why it is useful to 3D print on Mars is first introduced. The concrete 3D printing regolith design and its feasibility study is then presented. The 3D printing regolith design has several components. The components of regolith 3D printing are the geological resources on Mars that can be obtained to be able to 3D print structures on Mars. The methods for obtaining regolith that can be converted into 3D printing material is presented, and the design considerations of 3D printing on Mars is shown.

4.2 WHY 3D PRINT ON MARS

3D printing on Mars allows for construction to take place before astronauts arrive to Mars. 3D printing robots will be able to create a livable habitat for astronauts, so that human construction does not occur when the planet is inhospitable. The Mars atmosphere is 96% carbon dioxide and 100 times thinner than Earth's. The average temperature is -81 degrees Fahrenheit with a range of -284 to 86 degrees Fahrenheit [44]. The constructed habitat will have to protect astronauts from the solar radiation and maintain atmospheric conditions like Earth's. 3D printing construction will allow for an enclosed structure that can be pressurized and sealed from the Mars environment. Since 3D printing creates structures that are monolithic, the building can be sealed and pressurized. The contours made by 3D printing will distribute the stress of the dust storm pressures on Mars [45]. 3D Printing also allows for construction autonomy without the reliance of resources from Earth. 3D Printing saves materials launched from Earth by 60% [46].

4.3 3D PRINTED HABITAT

The living environment on Mars will require a multitude of building materials and construction solutions to be able to create a habitable civilization. NASA hosted a centennial challenge to encourage housing solutions for the first structures on Mars. The competition is called the 3D Printed Habitat Challenge. Several citizens inventors teams have joined the competition to 3D print a functioning sheltering. The goal is to create a shelter that can house four astronauts for a year with considerations to the mechanical, electrical, and plumbing systems. The shelter also takes into account functionality for spacesuits and rovers on Mars. The challenge aims to advance construction technology in regard to housing and shelter on Earth while developing technology for a Mars habitat [47].

Zopherus

This team has a special consideration to the construction process on Mars where 3D printing could be disturbed by winds and temperature changes. The team's solution is to create a spaceship that can house and protect the 3D printer while the printer is constructing the shelter. The spaceship would then move lift itself above the 3D printed house and then construct the next shelter. The spaceship also acts as an emergency pressure vessel. The shelter that the spaceship creates consist of two layers, an HDPE layer and a Mars concrete layer. The multiple layers protect the shelter from temperature changes and radiation. Since the housing system is module, the community can expand [48].

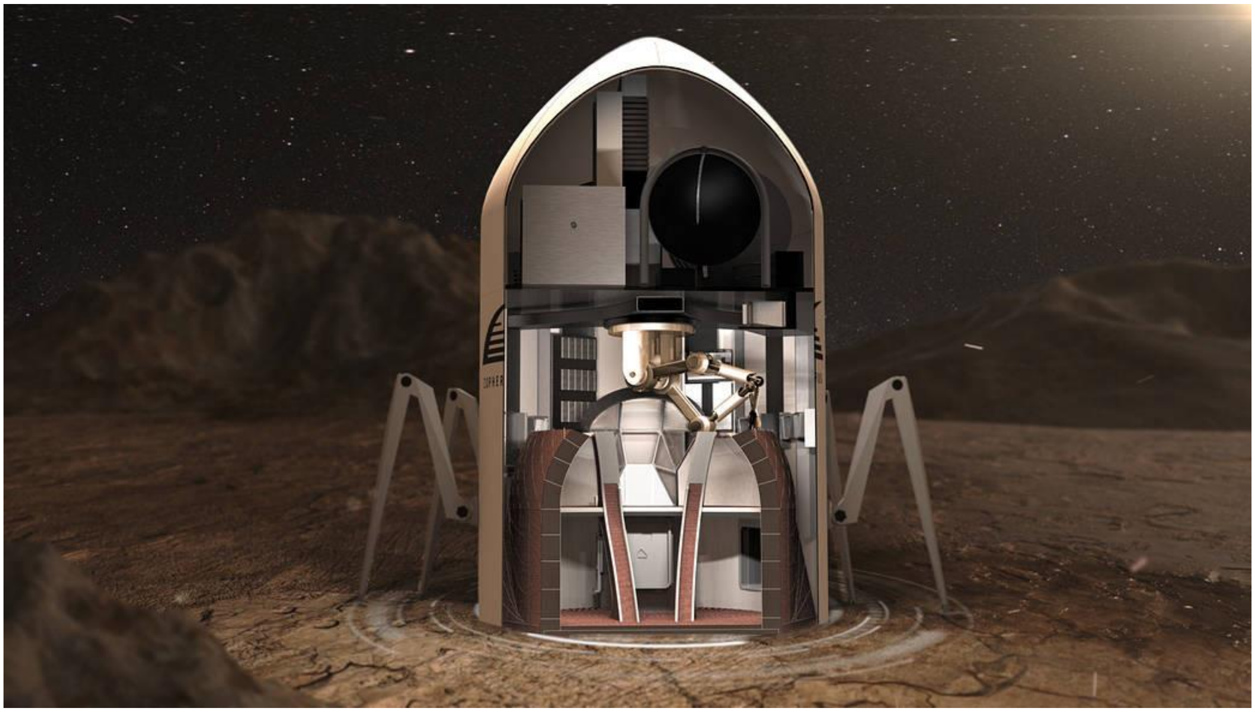


Figure 4.1 Team Zopherus from Rogers, Arkansas, is the first-place winner of Phase 3: Level 1 of NASA's 3D-Printed Habitat Challenge. The team's design includes using a moving printer that deploys rovers to retrieve local materials. [48]

Ai Spacefactory

The design of this Mars shelter is based on a cylindrical egg shape and uses basalt reinforced polymer 3D printing. The cylindrical egg shape of the structure helps mitigate the overhanging effect when 3D printing while reducing structural stress and increasing livable area per surface area of printed material. The use of basalt polymer 3D printing helps save water on Mars. The material can also be recycled and reused for future use. The shelter also has multiple floor levels to allocate various livable functions. Since the structure is tall and slender, the structure is anchored to the ground and sits on movable plates the handle lateral loads [49].

Figure 4.2 Team AI. SpaceFactory of New York is the second-place winner in NASA's 3D-Printed Habitat Challenge, Phase 3: Level 1 competition. [49]

Kahn-Yates

The 3D printed shelter made by Kahn-Yates is unique in that it lets in natural light to grow plants to sustain life in the house. The structure is built around the spaceship, and the spaceship is used as a prefabricated shelter. The exterior layer is then printed around the spaceship shelter so that there are multiple functioning units of the living habitat. The space between the spaceship shelter and the exterior 3D printed house is a garden for a sustainable food supply. The 3D printed shell is made of HDPE and concrete made from in-situ materials on Mars [50].

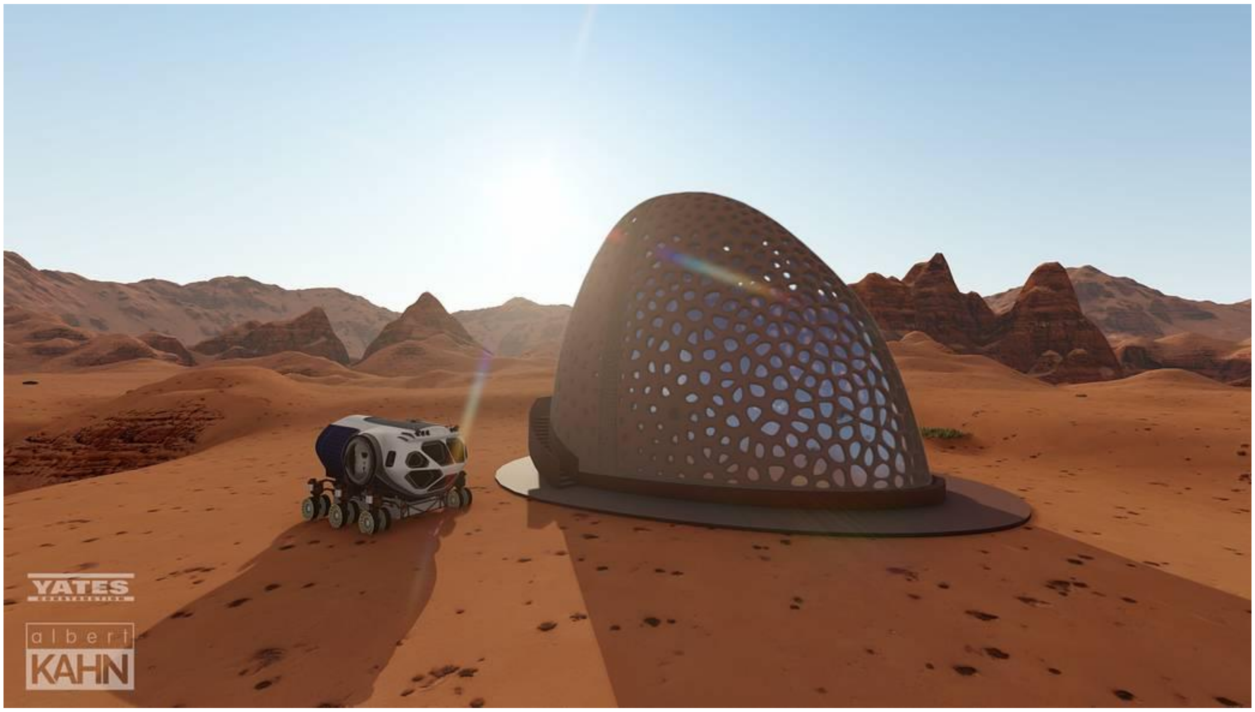


Figure 4.3 Team Kahn-Yates from Jackson, Mississippi, won third place in Phase 3: Level 1 of NASA's 3D-Printed Habitat Challenge. The team virtually designed a Mars habitat specifically suited to withstand dust storms and harsh climates on the red planet. [50]

SEArch + Apis Cor

This design is a hyperboloid cross hatching reinforcement structure. It features a mechanical core that supplies water, heating, and cooling to the sheltered habitat. The structure is a multi-level floor structure that is reinforced with basalt fibers, regolith concrete and polyurethane. The reinforced concrete is made from in-situ regolith materials which physically protects the astronauts from radiation [51].

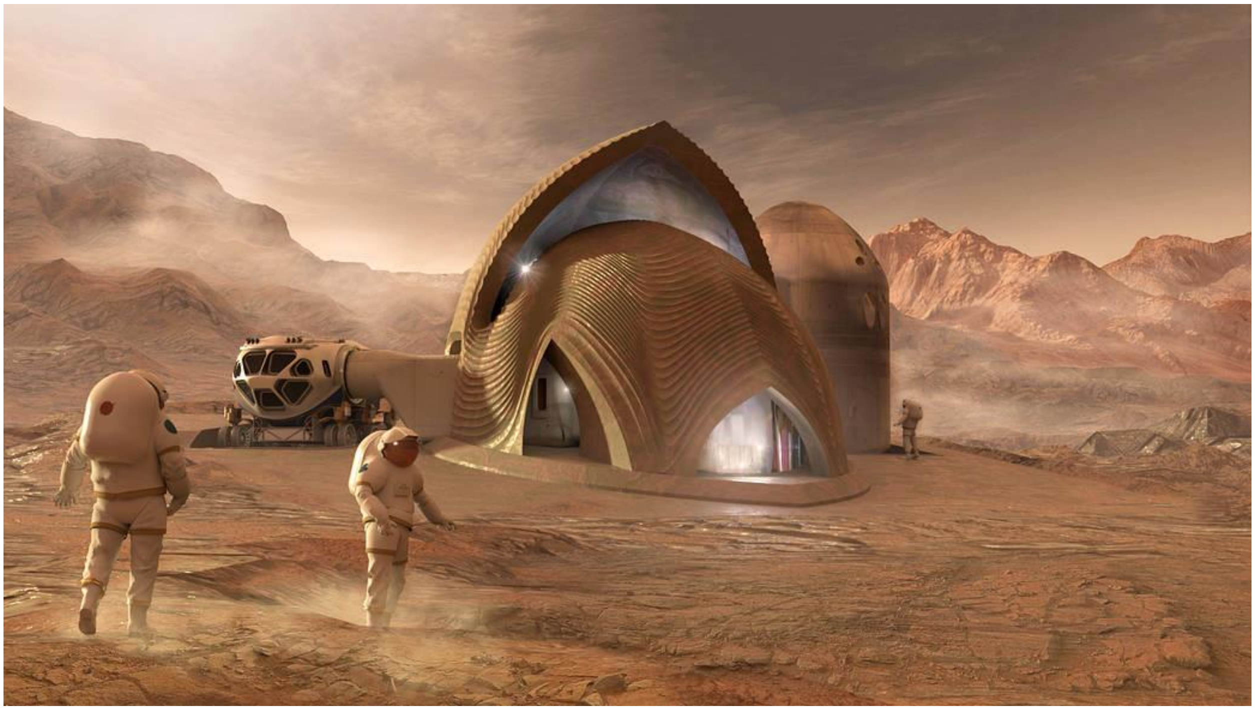


Figure 4.4: SEArch+/Apis Cor of New York won fourth place in Phase 3: Level 1 in NASA's 3D-Printed Habitat Challenge. This team focuses on regolith construction to provide radiation shielding and physical protection. [51]

Northwestern University

The shelter is made of two layers. The inner layer is made of a pressure vessel that supports the 3D printed concrete outer layer. The shape of the structure is a spherical dome with overhead cross beams. The cross beams are 3D printed with the rest of the structure and support the overhead weight of the structurer similar to beam and slab construction. The shelter protects the astronauts from radiation and temperature changes. The unit is module and is able to connect to other modules to form a community [52].

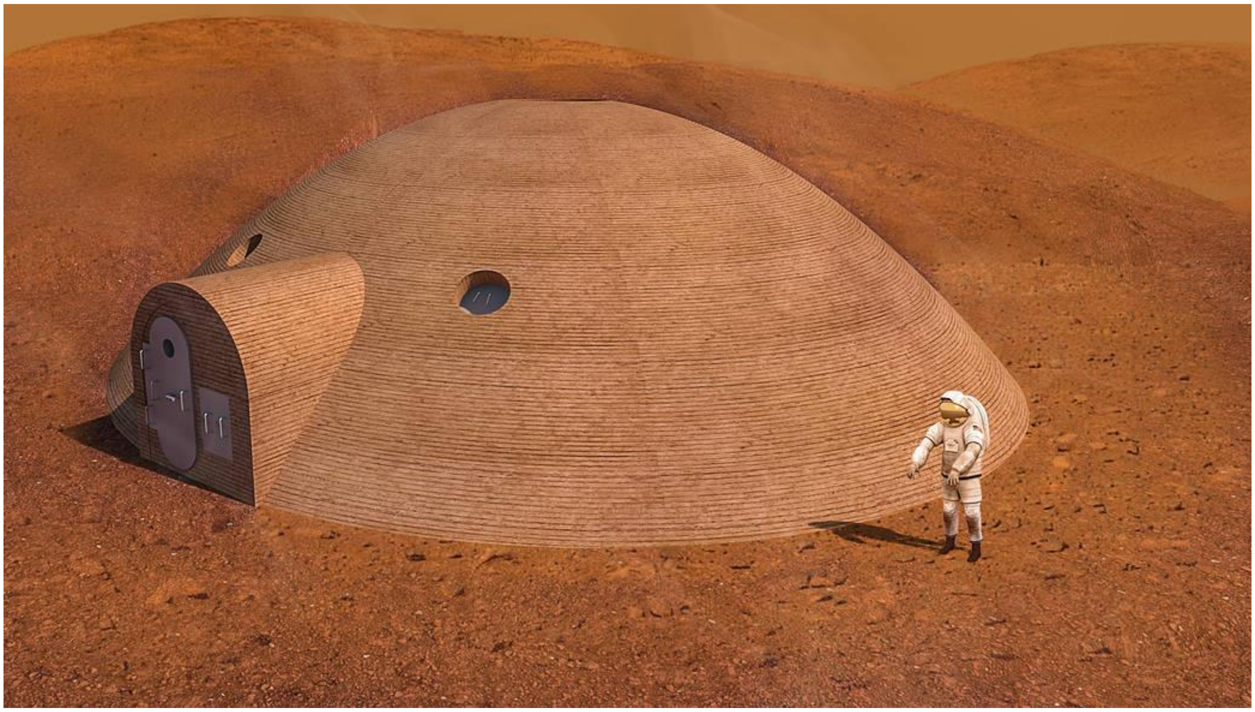


Figure 4.5 Northwestern University from Evanston, Illinois, won fifth place in Phase 3: Level 1 of NASA's 3D-Printed Habitat Challenge. The team's design features a unique spherical shell and outer parabolic dome. [52]

4.4 BASALT REINFORCED POLYMER 3D PRINTING

Water on Mars is a scarce resource, and therefore must be limited in the construction of infrastructure on Mars. Basalt is an abundant resource that can be used to reinforce poly lactic acid (PLA) when 3D printing habitats. Even though PLA will have to be shipped to Mars, the construction of PLA houses will not use any of the scarce amounts of water on Mars. The advantages of PLA 3D printing are the thermoplastics properties. The material can be reheated for recycling and reuse. The use of basalt in thermoplastic 3D printing can improve the flexural and tensile strength of the materials. Since basalt is readily found on Mars, manufacturing of such material can be done on Mars without increasing shipping costs from Earth. The increase in tensile strength from adding basalt fibers to acrylonitrile butadiene styrene is 40% [53].

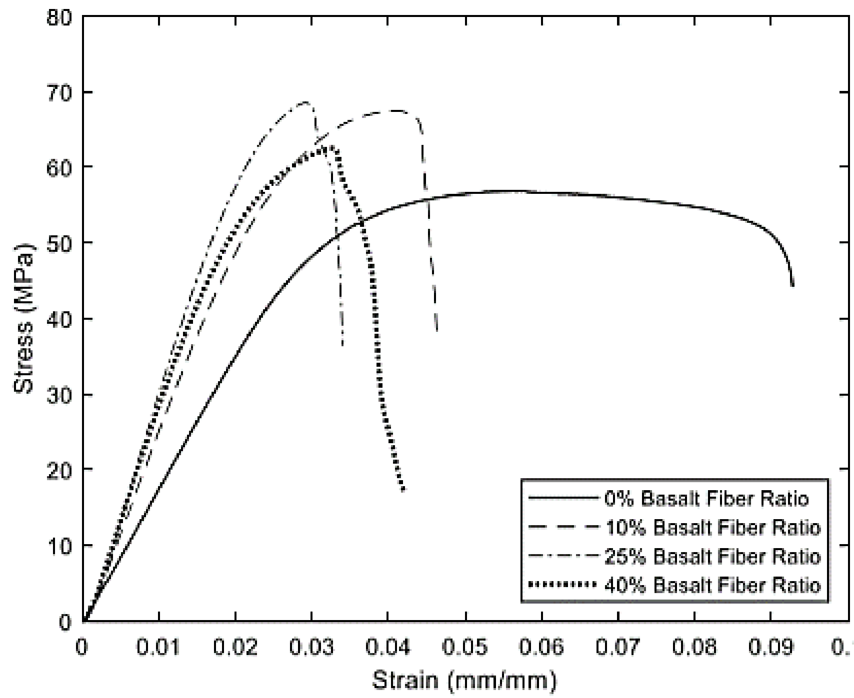


Figure 4.6 Representative flexural stress/strain results for each fiber ratio [53]

4.5 CONCRETE REGOLITH MIX DESIGN

Building a civil infrastructure on Mars can be achieved through the technological advancements in 3D printing manufacturing. Since Mars is covered with a regolith that can be used for in-situ construction, building on Mars is also economically feasible [54]. 3D printing is an emerging field in construction that builds concrete formwork layer by layer without the use of molds nor forms. The feedstock used in 3D printing concrete requires a mix design that uses fine particles, because the feedstock must have a viscosity and workability that is able to flow through an extrusion and dynamic pump system. The concrete mix will be 3D printable based on buildable layers, flowability through the system, and low gravitational out gassing [55]. The material properties of the mix design should also be structural enough to be used as radiation shielding and resilient to brittle cracking which induces a loss of cabin pressure in order be used in the Martian environment.

Concrete buildability properties are shown in Table 4.1. Martian regolith could be harvested and sieved to be used as an in-situ concrete 3D printing filament. This study will seek to design a 3D printability concrete mix which considers the Martian environment to create civil infrastructure that can be used by rovers and astronauts on Mars. The mix design iteration process is shown in Figure 4.1.

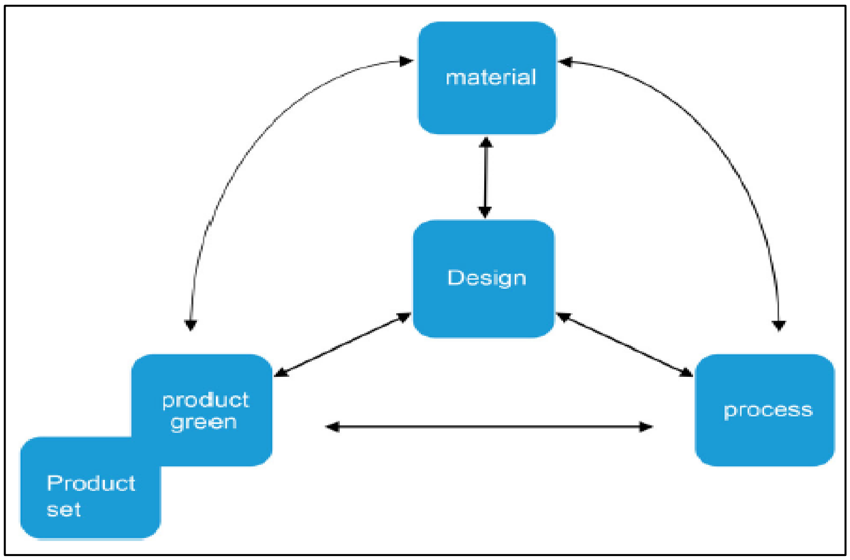


Figure 4.7: Interdependency of design, material, process, and product [23]

Potential NASA Commercial Application: The development of this technology will allow for in-situ construction of civil infrastructure for protection against radiation, thermal fluctuations, and dust storms on Mars. The use of robotics to construct habitable infrastructure before human exploration will improve astronaut safety by decreasing the amount of temporary construction work that needs to be performed. Having a human habitable structure before arriving to Mars will improve the success of manned missions to Mars by decreasing exposure to harmful environmental factors on Mars such as a non-breathable atmosphere and solar radiation [56]. 3D printing of concrete is mainly limited by the roof construction of monolithic structures.

Table 4.1: Reaction conditions and print process parameters [23]

Condition	Process Parameters
Concrete age (time between mixing and printing)	- The mixing process is not a continuous steady process, but rather a stepwise process in which the mixer fills a reservoir above the pump and mixes additional material once the reservoir level has fallen under a certain threshold. Thus, the age of the concrete in the system varies - Pressure in the system (varies, see below) - Non-continuous printing. Currently, the printer lays continuous filament. However, in order to achieve reasonable versatility, it is imperative the filament stream can be stopped and restarted, so that a printed line can be terminated and continued at another location. Since this introduces a waiting time in the system, this will influence the age of the filament upon leaving the nozzle head - Stagnation: in ordinary concrete construction setting is delayed by continuous mixing. However, this not possible in the current 3DCP system
Mix temperature	- Environmental conditions and start temperature of the system - Friction in the system, which depends on a range of sub-parameters such as the pump pressure, section dimensions of subsequent parts, hose length, and curves and angles in the system. Using a low slump concrete increases the sensitivity to this aspect - Heat conductivity of the system - Setting reaction itself (exothermal)
Mix internal pressure	- Parameters similar to friction: pump pressure, section dimensions of subsequent parts, hose length, and curves and angles in the system. The no-slump concrete requires a particularly high pump pressure to move through the system
Density of printed material	- Compaction - Pressure (see above) - Linear nozzle speed
Material mix	- Many variants possible
Water/cement ratio	- Machine setting in mixer-pump

Thus, robotic construction of roof trusses and polyurethane 3D printing provide a solution to creating monolithic structures that can efficiently maintain cabin pressure [57]. Technological applications include dust shields, equipment hangars, rover pathways, steel manufacturing facilities, and astronaut habits to prepare for a manned mission to Mars.

The potential applications on earth can range from expediated on-site building to increase the economic efficiency of construction. The automation of the construction industry on Earth will improve worker and building safety. Concrete 3D printing allows for cost effective construction of curved walls, which improve lateral strength during earthquakes and hurricanes. 3D printed construction has applications for custom built homes that have building geometries that are structurally stronger than stick framed construction [58]. Therefore, the cost, time, and labor of construction decreases to construct buildings that are safer, affordable, and customizable.

4.6 REGOLITH DERIVED FEEDSTOCK FOR 3D PRINTED CONSTRUCTION

In order to be able to 3D print structures on Mars, the regolith on Mars will be harvested and used as building material for the 3D printing rovers. Materials will be judged on its availability on Mars, 3D printability, and effective- ness as a building material. For In-Situ Resource Utilization (ISRU), soil binders derived from the regolith soil are more economically and feasible to extract and process than quarrying methods since regolith lies on the surface of Mars and utilization of regolith will mitigate dust storms by removing particulates from the atmosphere [59]. Using regolith as in-situ building material will also be more economical than shipping materials from Earth. Since the regolith soil has naturally occurring metal ions in it, the concrete mix can be structurally stronger than a comparable aggregate mix [60]. During the harvesting and sieving process, rust derived from the regolith can be sorted to reclaim iron to manufacture all- purpose steel. Martian environment factors such as radiation, thermal, and gravitational differences will be investigated to determine a relationship to variables such as setting time, adhesion of layers, and out gassing. [61]

Geological and material science research will be used to map the material availability and economic viability of the ore to set up a rover pathway and construction site. In 2014, the U.S. Geological Survey prepared the Geological Map of Mars, detailing stratigraphic relations and crater-density statistics. This geological map will provide information on regions with comparable soils with similar elemental compositions for harvesting and infrastructural foundation. Feasibility of extraction or processing cement and lime will build upon research conducted at the Japan Aerospace Exploration Agency for Particle-Size Sorting System of Lunar Regolith Using Electrostatic Traveling Wave in 2016. In this study, the use of the electrostatic waves for particle separation was successful for particle less than 20.0 m in diameter. This method would be useful for particle extraction because, elemental concentration rates are dependent on particle diameter. Limestone and basalt structures used in cement production are rocks and minerals that have been weathered on Mars into the regolith soil [62]. Therefore, cement could be manufactured on Mars without the use of environmentally and energy intensive quarrying and mining manufacturing methods, but rather using soil separating technology and sintering refining methods [63]. The materials properties and building material effectiveness will be based on strength, radiation shielding, and out gassing. Physical calculations such as the cracking moment of inertia and enough radiation shielding can be applied to design the outcome of feasible material structures.

The use of robotics for ISRU is necessary for the first steps to the colonization of Mars. Since robotics are limited in their ability to carry out large-scale mining and quarrying tasks, utilization of the elements found in Martian regolith will be essential. The regolith on Mars has been identified to contain precursor materials for cementation such as SiO2 and CaO. [64] Previous research has supported the extraction of elemental particles from the regolith soil and the 3D printing of concrete for civil infrastructures.

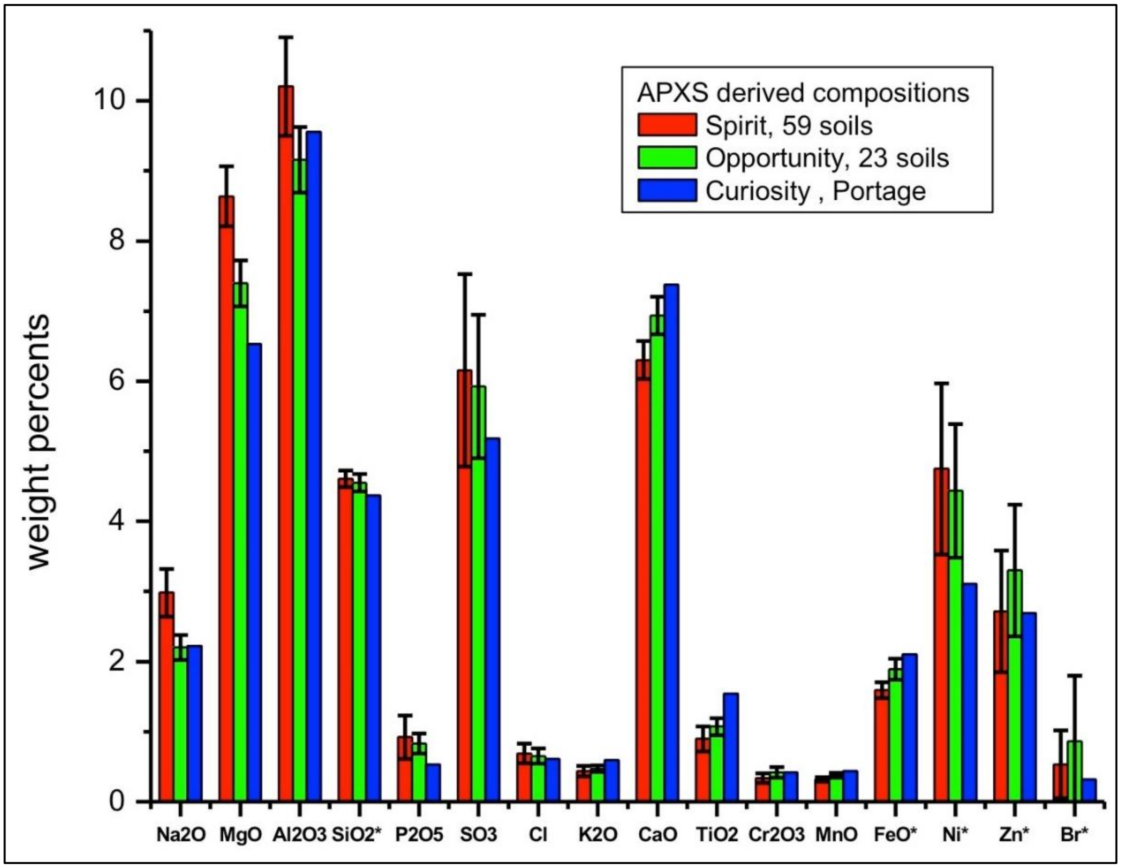


Figure 4.8: Quantification of the dry history of the Martian soil inferred from in situ microscopy. [64]

Mixtures will be judged on its availability on Mars as well as its economic viability and feasibility of extraction and processing. Insight into the materials properties as a building resource on Mars will also be considered. Figure 4.2 depicts the composition of Mars based on weight percentages. Geological composition and availability is done through X-ray spectroscopy on Mars rovers [65]. Material properties to include are strength, thermal, radiation, low gravity outgassing, and 3D printability.

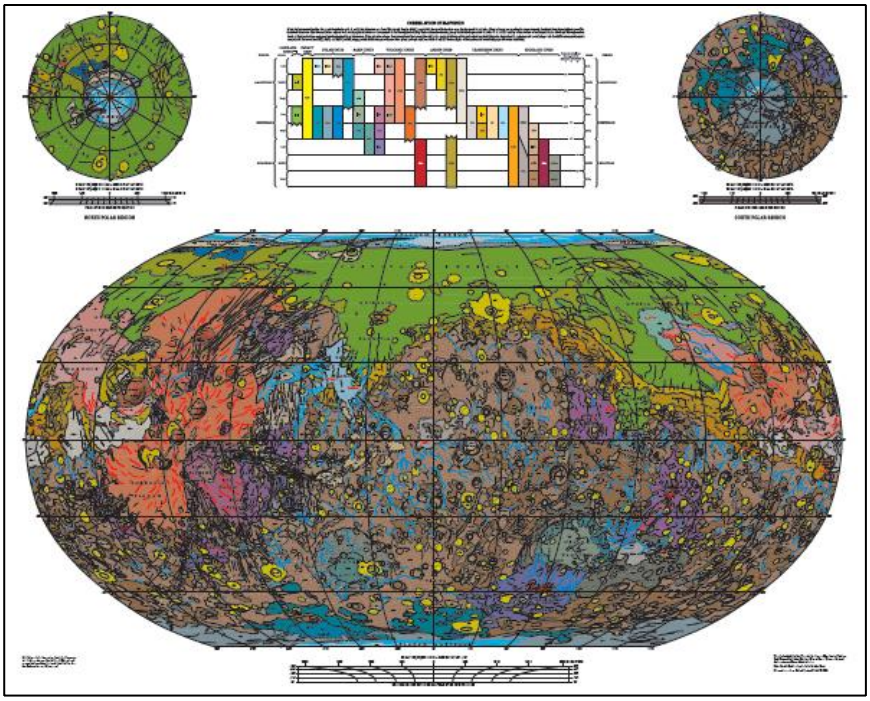


Figure 4.9: Geologic Map of Mars, Scientific Investigations Map [10]

Geological Resources on Mars The 3D printer will use a concrete mix that is mainly composed of regolith simulant soil, MMS- 2. Materials in the mix that require extraction, processing, and manufacturing on Mars are cement, water, and additives. The availability of precursor materials for cement, water, and additives on Mars can be used as building material [66]. After the identification of precursor materials has been conducted, probable extraction and processing methods will be determined to understand the economic viability of manufacturing these products on Mars. The geological map of Mars will be used to determine regolith soil samples that are comparable to the geological region to calculate the abundance of elemental compounds for in-situ concrete polymer constituents (see Figure 4.3). The materials will then be put into a 3D printing machine and mix system as shown in Figure 4.4

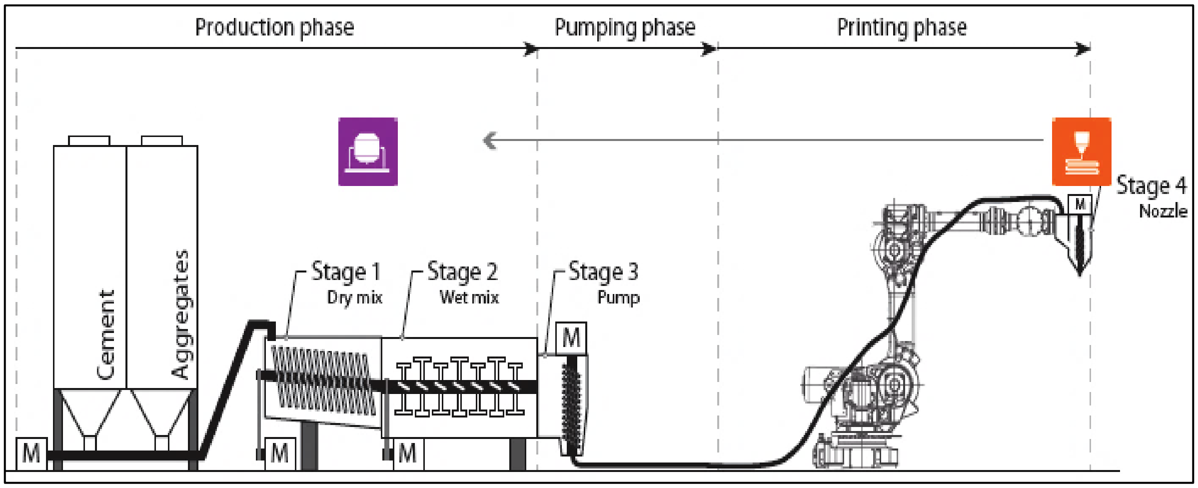


Figure 4.10: 3D Concrete Printing: Machine and Mix Design [67]

Regolith Concrete Mix Design Fused deposition modeling 3D printing construction can range in materials from different concrete mixtures to consolidated soil mixtures. This study will substitute sand and fine grains in concrete mixes with regolith simulant, MMS-2 [67]. Other mixture variables will be tested with the goal of maximizing in-situ construction with resources found on Mars [68]. To ensure 3D printability of the mixes, a maximum aggregate size of 2.0 mm will be used. The use of concrete additives such as superplasticizers, accelerators, and retarders has been added to 3D printing concrete mixes to achieve better results. Since the manufacturing of concrete additives is less likely than other resourced materials on Mars, this study will test mixes with and without additives to provide baseline analysis. The 3D printing mix must balance flowability through the extrusion system and buildability upon pouring. The setting rate must also be slow enough to ensure bonding with subsequent layers while maximizing build time. The table below is a hypothesis of possible feedstock mixes for 3D printed construction on Mars. This will be the first iteration of mixes that will compare water/cement (W/C) ratios and the use of concrete additives. Further mix iterations will be conducted after initial variables have been optimized.

Note that baseline mixes are composed of values that are successful on Earth. The gravitational effects of Mars will likely change these values.

4.7 HARVESTING WITH ELECTROMAGNETIC SOIL SIEVE DISTRIBUTION

Soil sorting of regolith soil is a new develop that holds potential for extracting lime (CaO), silica (SiO2), and alumina (Al2O3) from the soil to produce building lime. This processing method also has the potential to overstep quarrying methods that are cost intensive and disruptive to the environment [60]. The electromagnetic soil sieve distribution is shown in Figure 4.5.

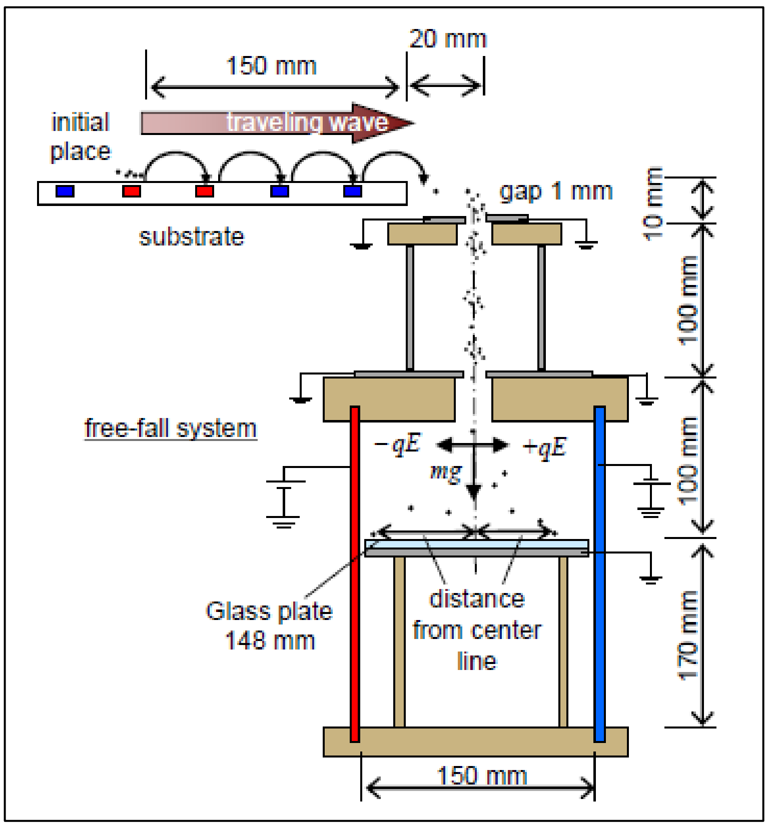


Figure 4.11: The experimental set up for measuring the particle charges utilizing the free-fall method [60]

A cost-benefit analysis will be created to illustrate the tradeoffs of initial investments into manufacturing and production versus cost of shipping materials to Mars. Economic value is difficult to determine, because there is no prior market data of materials on Mars. The economic value and benefit of the civil infrastructure that could be constructed by 3D printing will be a speculation based on market trends on Earth. This study will only seek to test a concrete regolith mixture for 3D printed construction. Based on geological availability and feasibility of extraction research conducted in this study, future research could be done with alternative materials that could be resources for construction such as basalt, Sulphur, or ice [69].

Spectroscopy sensors of the soil sensors in combination with electromagnetic sieve stratification can organize the Mars regolith into constituent parts. The harvesting of iron oxide and carbon from the regolith soil can be used to create steel alloys for manufactured parts and structures. The metal can be smelted together via microwaves and infrared lasers. The smelting process can occur in a 3D printed concrete form for large scale structures. Powdered 3D printing material can also be selective laser sintering with focused sun radiation and lasers to manufacture parts [70].

The harvesting of iron on Mars can be done with 3D printed iron bloomeries structures used in chemical engineering. The carbothermic chemical reaction converts iron oxide to iron and carbon dioxide in the presents of carbon. This process can be used to process iron from regolith on Mars.

The Carbothermic Chemical Reaction is described by this relation:

$$2Fe_2O_3 + 3C \rightarrow 4Fe + 3CO_2$$

Material resourcing on Mars will be judged on the effectiveness of using in-situ materials. The effectiveness of the process should feasibly be able to build significant amounts of civil infrastructure from in-situ materials. The use of equipment that is not manufactured on Mars will also be considered for logistical calculations of construction.

4.8 3D PRINTING REGOLITH MATERIAL PROPERTIES

Since the regolith concrete mix will be used for civil infrastructure, research into the materials properties will give insight into the economic value of the different printing mixes. Material properties such as radiation shielding is critical on Mars. Radiation effects are determined by the scattered radiation formula below.

The formula that describes the relationship between the building variables and the radiation dosage. For example, the distance from the radiation source is exponentially related to the radiation dosage. Since radiation is from the sun, the radiation projected onto the building can be modeled as a uniform radiation load [71]. Equation 4.1 describes the barrier transmission factor (B_w) that is required to shield against scattered radiation when the primary beam strikes a wall:

$$B_w = \frac{P d_w^2 d_r^2}{\alpha A T W U} \tag{4.1}$$

where:

P	*is the allowed dose per week (Sv·week^{-1}) outside the barrier*
A	*Is the field area projected on the scattering surface (wall), in m^2*
T	*is the occupancy factor or the fraction of time that the area outside the barrier is likely to be occupied*
W	*is the workload, in Gy·week^{-1} at 1 m*
U	*is the use factor or fraction of time that the beam is likely to be incident on the barrier*
d_w	*is the distance from the radiation source to the scattering surface (wall), in m*
d_r	*is the distance from the scattering surface (wall) to the point of interest, in m*
α	*is the wall reflection coefficient, which depends on the wall material, scattering angle, and beam energy*

Strength test listed in the American Concrete Institute ACI 318 and ASTM International standards should also be conducted to determine to integrity of the 3D printed structure. Thermal insulation tests to compare R-values (or U-values) will be used to understand the materials behavior in the Martian environment. Radiation tests determine the materials effectiveness as a shielding material from solar rays. Outgassing will determine the degradation of the building material, which potentially poses as a threat to building strength.

Material Properties will be successful if the regolith derived feedstock can function as a building material for civil infrastructure given specific design standards to its use on Mars. The material must be able to sufficiently protect the users from radiation and thermal fluctuations within a reasonable wall thickness and economic constraint. Otherwise, composite materials may be developed to compensate for the materials weakness. Out-gassing shall be kept in a reasonable standard to prevent contamination and structural degradation.

3D Printability in Mars Environment will be determined by gravitational and thermal effects of the setting times and adhesion of layers. Suitable considerations and designs for the environment be specific to Mars to ensure a successful 3D printing material that can be used for in-situ Mars construction of civil infrastructure.

4.9 CONCLUSIONS

This research study will be based on determining a suitable material mixture derived from the regolith soil that can be 3D printed into construction applications. The study will be successful if it can identify available 3D printable materials on Mars that can be used for as cementitious binders [72]. In-situ and satellite data on the geological composition of Mars will determine the availability and feasibility of obtaining feedstock material. The material must undergo a set hardening cementation process and possess an optimal viscosity for 3D printing. Optimal 3D printing viscosity is selected by being liquid enough to be able to flow through an extrusion system, yet solid enough to layer on top of itself during fused deposition. Constraints on Mars such as low gravity, radiation, and thermal settings will also dictate the composition of such regolith mixtures.

CHAPTER 5

DESIGN AND MODIFICATION OF 3D PRINTING MACHINE FOR PRINTING CONCRETE

5.1 GENERAL

Chapter five discusses the design and modification of a 3D printer for printing concrete. The concrete 3D printer is configured through the steps shown in this chapter. This chapter goes over the hardware and software modifications that must be configured to be able to use a concrete extrusion rather than a typical plastic extrusion. The software and the computer aided design of 3D prints in also shown in this chapter to 3D print with concrete. A daily log of the modification that occurred is shown to convey the configurations of the 3D printer.

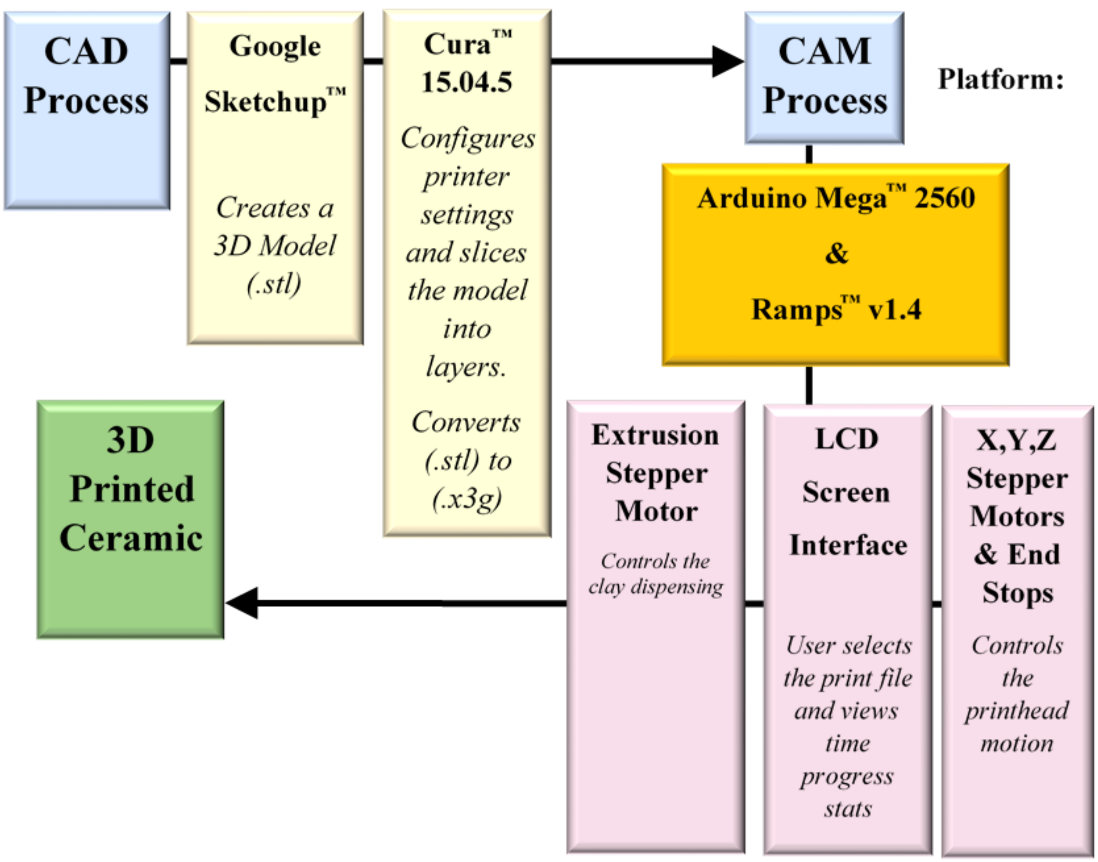


Figure 5.1: 3D Printing Flowchart

5.2 MODIFYING THE 3D PRINTER

A desktop 3D printer that is used for thermoplastics can be modified to print with ceramics to prototype concrete printing with similar software and hardware. When creating a model to 3D print, thermoplastic printers and concrete printer use to same or similar software. The slicing software setting must then be adjusted to account for the differences in material thickness and layer height. Software and hardware modification are then done to add a stepper motor to create a dual stepper motor extrusion system, which dispenses concrete through the nozzle. The Marlin 3D printing firmware was used with the Duet3D circuit board. The viscosity of the 3D printing ceramic is liquid enough to flow through the 3D printer but thick enough to layer the clay into a 3D print. The overall 3D printing process is shown in Figure 5.1.

The mechanisms used to get to the desired coordinate locations are like the typical 3D printers used. The only mechanical difference is modifying the extruder to dispense a paste material such as ceramic or concrete. The extruder is modified by 3D printing a custom nozzle that can hold and dispense concrete or ceramics. In order to move the concrete to the extruded where the programmed coordinate is, the concrete or ceramic can either be compressed in a tank with a motor or an air compressor. The concrete then moves to the extruder head where it is another rotary motor connected to an auger screw dispenses the ceramic or concrete. If an air compressor is used, the extruder head is pressurized, and the paste is dispensed when the auger screw moves. If the extrusion system is a motor driven compressor tank, the compression tank motor and the extruder motor work in unison to extrude the material.

5.3 MATERIALS AND EQUIPMENT

5.3.1 Air Compressor, Hose, and Valves

A larger air compressor tank works better, because pressure fluctuations can negatively affect the prints. For this system, the operating pressure is between 20 and 50 psi (137-344 kPa). Make sure all connections are sealed with Teflon tape to prevent air leakage. When disconnecting the air compressor and its parts, make sure the compressor is shut off.

5.3.2 Clay Mixing Tools

Dispensing Gun and Cartridges

The dispensing gun and cartridges are from Techcon dispensing systems (http://www.techconsystems.com)

5.3.3 Nozzle Tips

Nozzle tips are also from Techcon. When changing nozzles tips, check if the tips are the same length. If the lengths are different, you will need to configure the z_height in the Arduino firmware. Steps for configuration are in the section called 'Configuring in Arduino'.

5.3.4 Clay Plate

A base plate helps when removing prints after they are completed. As with changing nozzle tips, base plates change the z-height, so the printer will need Arduino configuration.

5.4 CONFIGURING IN ARDUINO

To properly calibrate the printer, you will need to edit the firmware in arduino software. The Arduino software can be downloaded here: https://www.arduino.cc/en/Main/Software

5.4.1 Opening the 3D Printing Firmware in Arduino

1. Download the folder in the Google Drive: "Anycubicplus_ceramic (Download Entire Folder)"

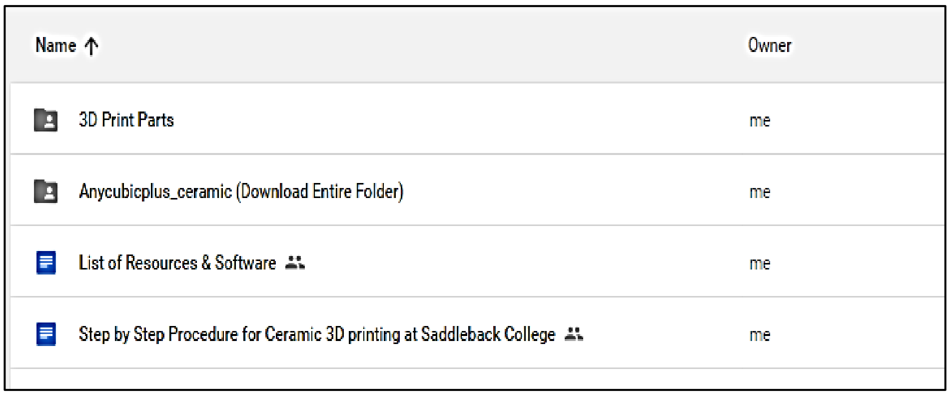


Figure 5.2: Google Drive Anycubic Download

2. Open "Anycubicplus_ceramic.ino" with Arduino

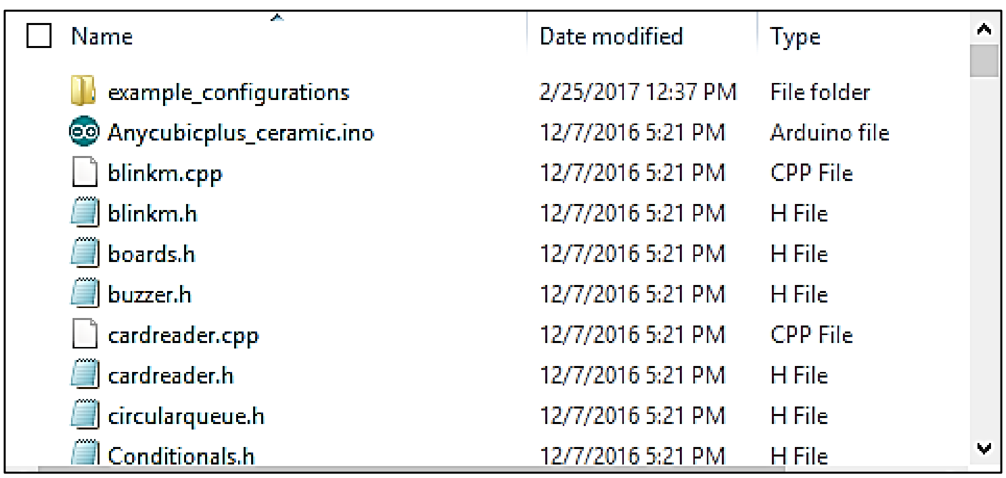


Figure 5.3: Open Arduino from Anycubic folder.

Make sure the code includes the .h tabs. Here is what your code should look like.

Figure 5.4: Arduino Ceramic Firmware

5.5 CONFIGURING FIRMWARE

1. Open the Configuration.h tab

2. Ctrl + F “Delta Settings” and change values to fit the printer

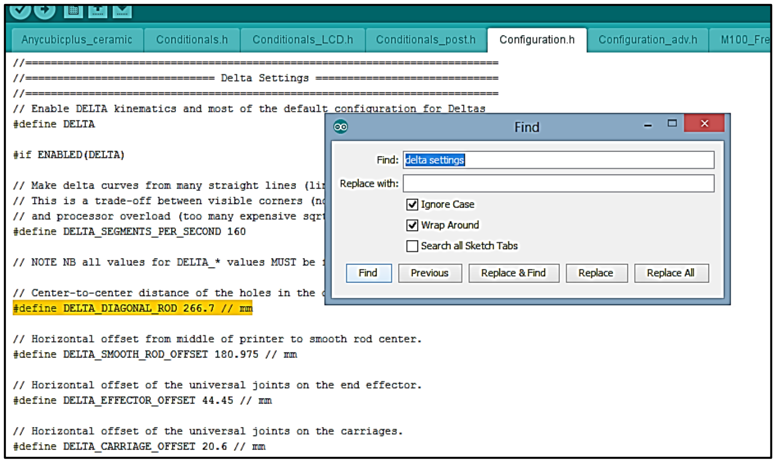


Figure 5.5: Calibrate Delta Printer

3. Values represent the printer measurements below. The below image is an example of measurements for another printer. [73]

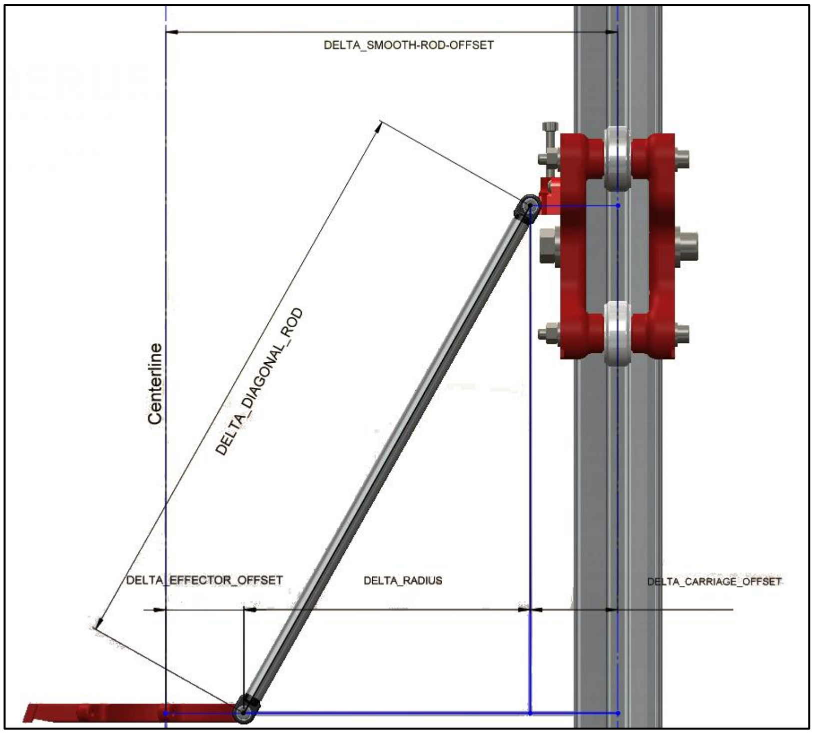


Figure 5.6: Delta Inverse Kinematics [73]

4. Ctrl + F “MANUAL_Z_HOME_POS” to configure the z-height when changing nozzles and base plates. The value is the distance between the nozzle and the print bed when the nozzle is at its maximum height at the top of the printer.

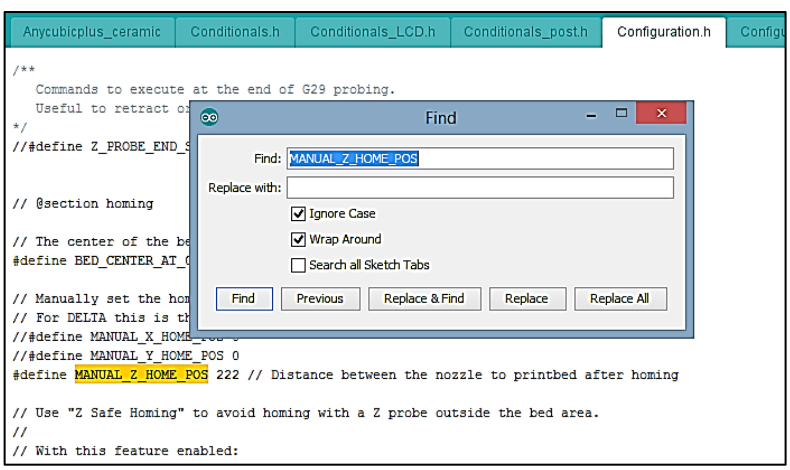


Figure 5.7: Homing the Z axis.

5.6 UPLOADING FIRMWARE TO 3D PRINTER

1. Connect the printer to the computer with the USB cable

2. Open the “Tools” tab and under “Boards” make sure “Arduino/ Genuino Mega or Mega 2560” is selected

3. In the “Tools” tab and under “Ports” select the USB port you are using. When switching between connecting the printer to slicing software and the ARDUINO® software, make sure to select the “Port”. An error message will open when uploading if this is not done.

4. Press the upload button in the top left corner

5.7 CREATING A 3D MODEL

1. Any 3D modeling software can be used as long as you are able to create a .STL or .OBJ file. Objects without overhangs print out the best. SketchUp is a 3D modeling tool used to create and draft 3D objects. The program creates objects by creating flat polygon surfaces. This is used to make meshes of free form objects. In other words, the program generates a mesh out of the 3D object by discretizing the surface into numerous flat polygons to create the desired geometry. SketchUp saves the object as a vector file that has the coordinates of line and curves. When 3D printing that require no gaps such as objects that hold water, solid drafting with close solid geometries. Solid shapes are created with the push/pull tool in SketchUp™ [7].

2. Export the .STL/.OBJ file.

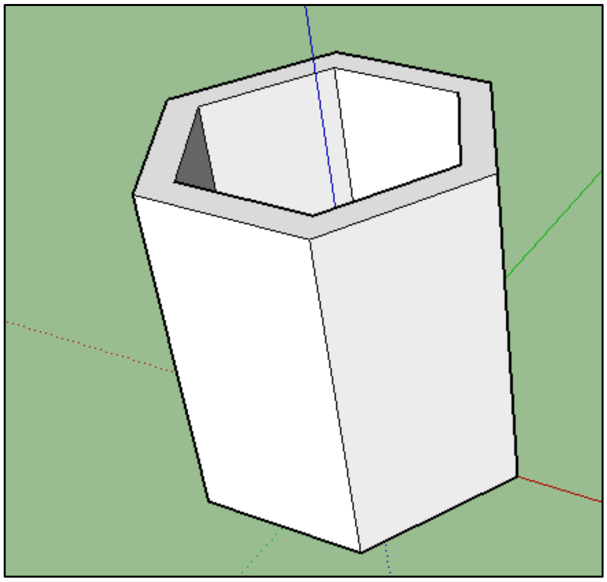


Figure 5.8: Google SketchUp CAD Drawing

5.8 SLICING THE 3D MODEL (Cura®, Slic3r®, Makerware®, etc.)

1. Open the .STL/ .OBJ file in the slicing program

2. Configure Slic3r® to the printer under "Printer Settings". In Cura®, select "add new machine" and follow the prompts to configure the printer settings. You will need to specify the bed shape and size and the maximum printing height.

   The slicing software has parameters that affect the quality of the 3D printed object. The properties that can be adjusted are infill, print speed, shells, supports, raft, and bridge. When printing in concrete, the infill can be set to a low density because the 3D print is form work. The print speeds are slower when printing in concrete to get an even extrusion flow. The number of shells is typically one when printing in concrete. Supports, rafts, and bridges are used in plastic 3D printing and not concrete 3D printing [7].

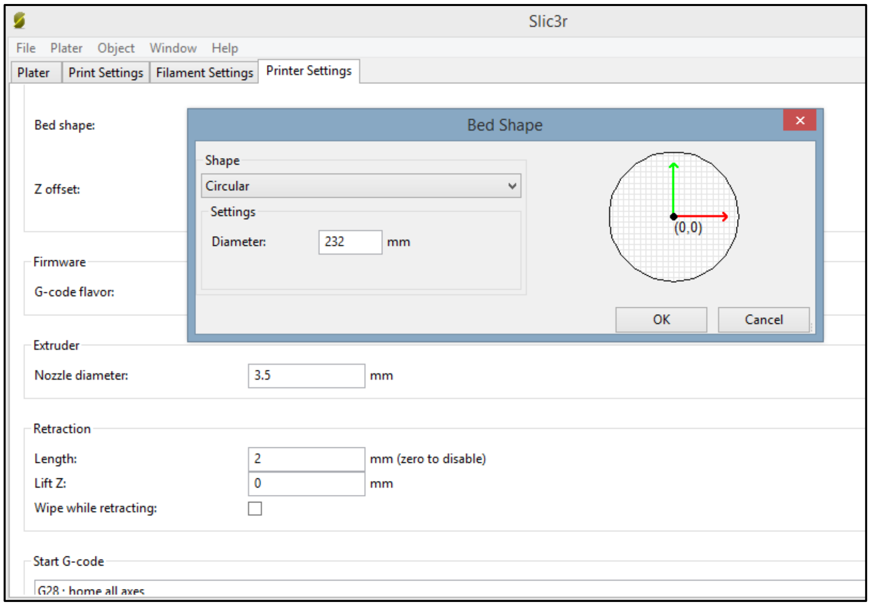


Figure 5.9: Slic3r® Printer Configuration.

3. Scale the object to the size you want. The "Print Settings" and "Filament Settings" tabs will control how the Slic3r slices the 3D model. Properly calibrate the settings for layer height and filament diameter.

4. Under the "Plater", view the "Preview" tab on the bottom bar to see how the printer will print the 3D object.

5. Export G-code to the SD card. Insert SD into printer

The 3D print detail and quality are affected by nozzle diameter and layer resolution. A higher resolution and smaller nozzle diameter will increase the quality and details of a 3D print but increase the time it takes to print the object. The layer height is measured in microns and has a typical value of 100 microns for plastic 3D printing. The nozzle diameter for plastic 3D printer is around 0.4 mm diameter. [7]

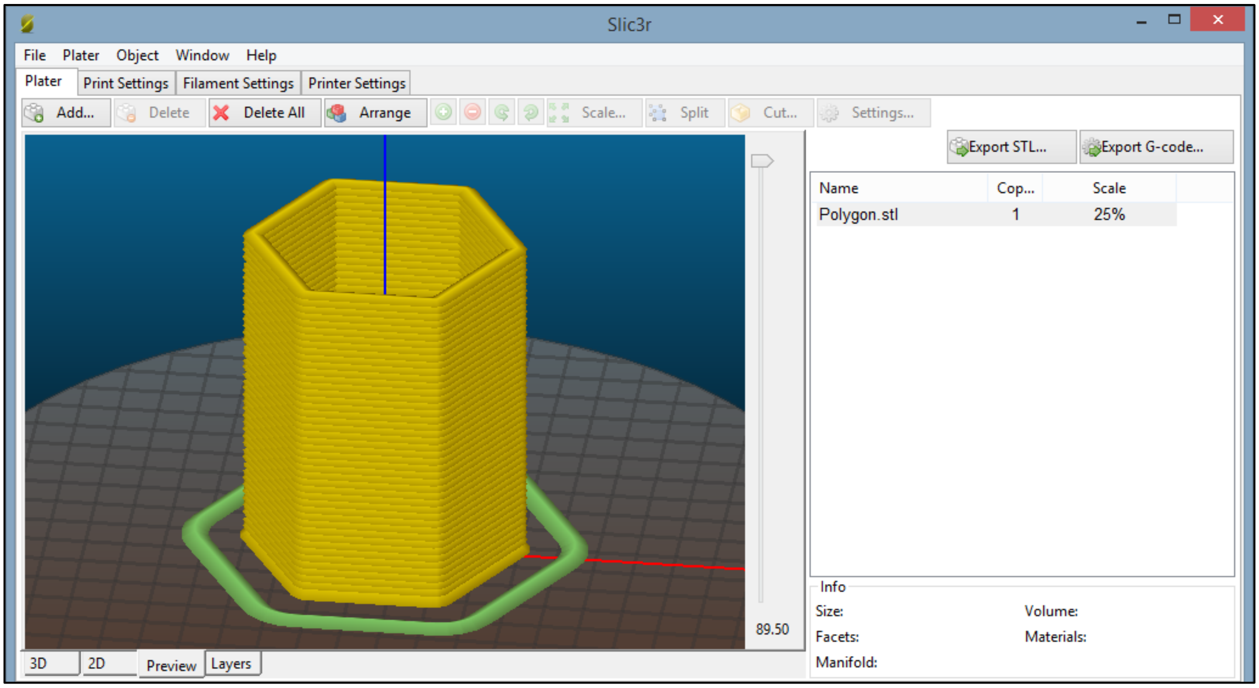


Figure 5.10: Slic3r 3D Layering

5.9 PRINTING 3D OBJECT

Guide to 3D Printing

1. Load the cartridge with clay,

2. Load the dispensing gun with the cartridge,

3. Connect the air compressor to the dispensing gun,

4. Raise the printer extruder to the top of the printer,

5. Slowly turn on the air pressure until clay starts to extrude. There is a delay, so avoid turning up the pressure too quickly,

6. On the printer LCD screen, select "Print with SD" and select your object,

7. Watch the print to make sure the printer is moving as fast the clay extrusion, and

8. Adjust the pressure to dispense large or small quantities of clay,

9. Check the layer height to see if the clay is being dispensed directly above each layer.

10.

5.10 TROUBLESHOOTING

5.10.1 Incorrect Nozzle Height

-When changing nozzles or base plates, you must go into Arduino and change the "MANUAL_Z_HOME_POS" value. If the value is too low, the printer will start the print in the air. If the value is too high, the printer will crash into the base plate.

5.10.2 Inaccurate Printing

-Inaccurate Arduino Settings. Go to 'Configuring Arduino' and correct the values with the correct measurements.

-Printing Homing Error. If the three printer arms did not hit the endstops correctly, you will have an error in printing. Raise the three arms to the endstops before printing so that there is less risk of the arms not hitting the endstops correctly.

5.10.3 Clay is not able to be pushed through

-Mixing Softer Clay

-Sealing Air Valves with Teflon tape. If there is a pressure leak, there will not be enough pressure to push the clay through the nozzle.

5.11 CONFIGURATION LOG

	Task: Calibrate Printer for Heavier Extruder Methods: Software and Carriage Adjustments. Change carriage type from profiled linear guide rail to bearing wheels. https://3dprinting.stackexchange.com/questions/475/what-could-be-causing-my-y-axis-to-slip http://boim.com/DeltaUtil/CalDoc/Calibration.html Log: Assembled Large Silver Printer Electronics. Moving WASP extruder to Silver Printer to better handle the extruder weight. 1 stepper motor not working. The motor is jammed and won't turn when the electricity is off.
	Task: Assemble Large Silver Printer with WASP extruder Methods: Switch Stepper Motor. Install larger diagonal rods. Log: Installed Larger diagonal rods and carriage. Switched broken motor with new motor. Motor/Belt not working properly. Calibrate motors and change belt.

[redacted]

Task: Fix motor and belt slippage

Methods: Tighten belt and calibrate stepper motor driver potentiometer

Log: Slippage was reduced, but the printer experience some slipping during prints. Motors are difficult to turn by hand when disabled. Switch out motors from smaller printer.

Task: Fix motor and belt. Dry test print.

Methods: Motors were stuck and not turning. After turning the motors by hand, the motors started to turn smoothly. Most likely ceramic dust in the printer.

Log: Increased motor current to eliminate slippage. The motors voltage probed as follow: x - 0.45v, y - 0.97v, z - 1v

Task: Test Print with clay

Methods: Load Printer with clay. Adjust clay moisture.

Log: z motor calibrated to 1.1v. Calibrate delta settings. Parabolic layer movements need to be adjusted to a smooth line. Possibly adjust reported diagonal rod length. Clay mixture is too gummy or too dry. First test print mildly successful. Print was accomplished with major defects. Wooden base plate is a better base plate than cement board. Cement board dry out the bottom layer and causes shrinkage.

[redacted]	***Task: Level printer, improve clay mixture*** Methods: Delta Calibration. Adjust Delta Radius to flatten printing path from hyperbolic trajectory. Log: Printer is printing level after Delta Radius was adjusted. Mixture is too sticky and does not extrude properly. The clay is flowing continuously. Adding too much water allows the clay to flow backwards into the motor. Too little water, and the clay doesn't adhere to the build plate.
[redacted]	***Task: Determine clay mixture*** Methods: Use cone 6 porcelain deflocculant slip and nara powder Log: 250g of nara powder 750g slip: too dry. Couldn't push through feed tube. 250g nara 965g slip: good mix that was printable. No complications with clay. Printed two items: honeycomb and double vase. Honeycomb experiences some curling when printing layers. Adjustments to the z_home_positin corrected some issues by extruding closer to the base plate. Adjusting layer height also corrected extrusion issues by printing directly on top of each layer.

Double vase is a successful print.

Task: Print Honeycomb

Method: Same procedure and mixture as Double Vase print

Log: print was successful. adjusted layer height to 1.5 and filament diameter to 2.

Task: Install Z Probe Auto Level

Method: Configure marlin software and install z probe

Log: Firmware was successfully configured. Z probe appears to be broken. The LED light no longer lights up when tested on aluminum.

Task: Print Twisted Vase

Method: Level the base plates and calibrate motors

Log: Motors Y and Z adjusted to 1.6v.

Motors skip steps and print fails

Task: Print Twisted Vase

Method: Motors calibrated down to 0.9v and motor skipping was eliminated.

Log: Used thicker clay. Increased pressure to 6 bars and increased extrusion flow rate by decreasing “filament diameter” value in Cura. Print was working until the Y motor skipped a step. The print was then shifted, and the printer was turned off.

CHAPTER 6
CONCLUSIONS & RECOMMENDATIONS FOR FUTURE RESEARCH

6.1 GENERAL

This chapter is the conclusion and future research that can be done to improve the technological advancements in 3D printing and construction. The conclusion sums the thesis and the main points of 3D printing in the industry of construction. The overall process of 3D printing and the applications of the technology are presented. The types of 3D printing that are currently being used in construction are displayed. The potential use of 3D printing on Mars and 3D printing in general is conveyed. Future research and technology that can improve the state of 3D printing and construction is used to end the thesis.

6.2 CONCLUSIONS

The field of 3D printing technology is rapidly innovating an improving the housing market. The recent developments of 3D printing a house that is structurally more efficient and economically advantageous has shown its potential for future developments. Research and development into the range of applications of 3D printing in construction is the beginning of a new building industry standard. The development of multistory construction will further increase market viability. While automated reinforcement, mechanical, electrical, and plumbing will increase construction speed and architectural design. The development of 3D printing thermoplastics with timber composites will make 3D printed houses competitive with suburban houses because homeowners will be able to hang picture frames and cabinets without anchoring into concrete. Prices for timber 3D printing filament is like 3D printing thermoplastics, because of the lack of an industrialized method of manufacturing the timber filament. Since the filaments are made of sawdust, the filament should be able to be manufactured at a lower price. Several develops in the 3D printing construction industry will lead to the ubiquity of 3D printing construction and infrastructural changes in construction will provide an efficient method of building.

6.3 RECOMMENDATIONS FOR FUTURE RESEARCH

Houses consist of various components such as mechanical, electrical, and plumbing work. 3D printed houses have automated to construction of the structural part of the house. In order to have a complete end-product, the 3D printed house should also have mechanical, electrical, and plumbing systems that have been automatically constructed. The components of the house could possibly be constructed in a traditional method with robotics. A new system of mechanical, electrical, and plumbing could also be constructed to be compatible with 3D printing the structure of the house [74]. Three-dimensional printing with steel is another area of research that can be developed. Steel is a ubiquitous building material that has several uses. Recent developments have been in 3D printing steel from welding machines. The welding machine creates 3D printed steel that is stronger than typical cast steel. 3D printing could create topologically optimized trusses that are lightweight and structurally efficient. The complete use of 3D printed steel and concrete will allow for a wide variety of structures to be built [75].

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