

ABSTRACT

Title of thesis: IN-SITU CONFORMAL 3D PRINTING FOR TARGETED REPAIRS

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Additive manufacturing has enabled the creation of precisely made objects through the ability to place material at calculated locations. It follows directly that any piece created through this process should have few limitations. Consequently, we propose that, given suitable degrees of freedom, a 3D printer can be designed such that it is able to additively print repairs to structures while operating within the environment of the damage. This concept has previously been demonstrated using a modified commercial printer. However, the demonstration was limited to a convex, or externally curving, surface. In pursuance of a printer with in-situ applications, we seek an implementation of the solution that is capable of scanning, navigating, and executing toolpaths within a static environment while being able to demonstrate a conformal concave print.

Team PRINT Draft Prospectus

by

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We pledge on our honor that we have not given or received any unauthorized assistance on this assignment.

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Chapter 1: Introduction

The advent of 3D printing has allowed for a wealth of new innovations and creative applications by allowing for the creation of structures without relying on complex subtractive methods. Current 3D printers are generally restricted to a rigid frame and a limited workspace. This design is sufficient to manufacture objects that can exist or operate independently of its environment. However, we would like to consider the case where this is not necessarily true. Consequently, we propose that given suitable degrees of freedom, a 3D printer can be designed such that it is able to additively print repairs for some ‘greater structure’ in-situ. We loosely define a ‘greater structure’ to be any rigid entity which may be repaired through the addition of its constituent material. Additive procedures are targeted out of consideration for damages that require acute precision. In regards to the engineering challenges, the following questions arise:

(1) What existing manipulators can optimally guide the print head in-situ (in the place of the damage)? (2) How can a traditional 3D printer extruder be modified for conformal printing? (3) How will the printer navigate through the environment?

In general, robotic in-situ printing has several immediate applications. One of these applications arises from the precision of the technique, which lends itself to structures that are geometrically complex and would disallow subtractive processes. Damage to cambered plane wings is an excellent example of this. Imperfections in the structure and the surface of the wing can significantly affect its aerodynamics and therefore any alterations require high precision. Another application originates from the automated or semi-automated component of the technology, enabling repairs to occur in environments that are not easily—or at all—accessible

to humans, yet still permitting a 3D print. While it is unknown how many of these extreme environments would find the technology useful, outer space is one such environment that could benefit in kind from robotic repairs. On-orbit satellite servicing and extraterrestrial rovers are prime examples. There is also potential for the technology to minimize costs of repairs in general by eliminating the expenses of entire, yet partially redundant, replacement components.

This prospectus provides a literature review of the current state of related research and relevant methods for the design and implementation of an in-situ 3D printer. A methodology is supplied in Chapter 3 that discusses the possible engineering designs and methods we choose to investigate further in our research. Finally, an appendix is prepared including the team's timeline and budget for the project, as well as a glossary for defining ambiguous or frequently used terms.

Chapter 2: Literature Review

2.1 Introduction

Bausch et al. [1] have previously proposed a similar concept using the design of a modified Prusa i3 printer. The modifications made to the printer would enable it to perform in multiple degrees of freedom (DOF). In a later paper, Bausch et al. demonstrate the capabilities of such a 3D printer on convex surfaces [2]. The researchers were able to obtain cloud point data for the 3D print and a toolpath for the printer, resulting in a successful test for their prototype. However, the demonstration was limited to a convex print and the printer possessed the ability to manipulate the frame of the print target in one degree of freedom. In addition, the authors note that future work should incorporate all six DOF [2] as originally planned in the design proposal. In pursuance of a printer applied to in-situ printing, we seek an implementation of the aforementioned research that is capable of scanning, navigating, and executing toolpaths without manipulating the print environment frame and is able to demonstrate a conformal concave print.

The full implementation of such a device is needed in order to make repairs to structures that are in unsafe or inaccessible environments for humans. Repairs for on-orbit satellites and extraterrestrial rovers are applications where the technology may be invaluable. Historically, rovers have experienced physical damage that has compromised abilities to fully complete missions [3]. This includes wheel damage that has led to the mission sites being restricted to relatively flat terrain that is not rocky [3]. Extrapolating data from Figure 2.1, Table 2.1 was

created by measuring the distances of the various cracks and holes using an image editing software and scaling the distances based off of the known wheel width of 40 cm [4]. It is also important to note that the wheel thickness is minimal and only .75 mm thick [4]. From Table 2.1, it can be seen that for this future application, voids on the scales of 1cm - 5cm would be ideal for the applications of repairing these holes. However, for the cracks, an extruder capable of printing on the scale of 0.2 - 1 cm gaps would be ideal, assuming that the robotic arm has a wide working envelope that could print along 30cm sections at a time if a continuous print is desired. Furthermore, the implementation of a robotic arm capable of these wheel repairs aligns with NASA's efforts [5] toward the potential of sending multiple small and collaborative rovers on missions. In this situation, it is plausible for there to be a robot specifically designed to repair other rovers in-situ to aid in lengthening future missions and mitigating unforeseen damage.

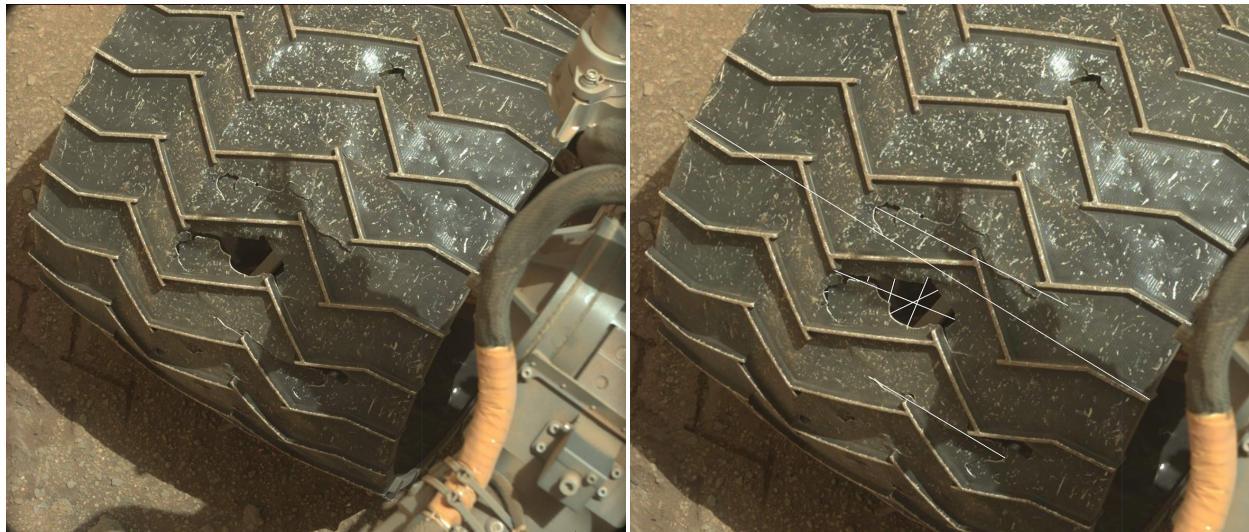


Image from MastCam of Mars Curiosity
Wheel Damage [6]

Image of Curiosity Rover Wheel Damage with
White Lines Indicating Measurements in Table
2.1 [6].

Figure 2.1

Table 2.1 Estimated Lengths of Holes and Cracks in Figure 2.1 [6].

Overall Span of Cracks (cm.)	Distances Across Holes/Cracks (cm.)
11.9	3.9
16.1	1.8
9.6	0.3
	3.9
	0.4
Avg: 12.5	Avg: 2.1

Applications may even be found in both the space and aviation industry. [7] describes how an in-situ 3D printer can be used in the aviation industry to repair components more easily than welding (the current method). There would also no longer be the struggle of thermal damage to components that is caused by welding because 3D printing has a lower operating temperature [7]. This allows parts to be repaired to near net-shape condition with less wasted material and a stronger finish [7]. This repair process is especially useful in the aviation industry because parts must have specific contours that can be more easily matched by conformal printing to decrease drag [7].

King [8] describes the existing methods of autonomous space servicing and several different robotic systems all designed to carry out various tasks on space stations and satellites. All of the robotic systems described are designed to transport, maneuver, or assemble various objects and payloads [8]. However, none are capable of conducting basic repairs to damaged components. The use of robotics for space servicing is already prevalent, but there is a lack of research and development into a robotic system that could repair, for example, damage caused by

impact with small pieces of space debris. Such a system could decrease the need for astronauts to risk performing extravehicular activity for basic repairs and may increase the lifespan of satellites and space stations.

2.2 Structures

2.2.1 Overview

This section of the literature review consists of prior research involving robotic manipulators. Information on how a manipulator will be designed and how it will move is presented below. This includes prior applications of manipulators, research into the necessary DOF, kinematic and inverse kinematic solutions for movement in addition to the research on the required drive trains and materials for an effective design.

2.2.2 Degrees of Freedom

The DOF of a robotic system are the number of unique ways that the system can move. The most common are the three translational movements of the x, y, and z axes along with the three rotational movements of pitch, yaw, and roll. The amount of degrees in a robotic system varies greatly based on the intended use. As movement becomes more complex and constraints are tightened, the number of degrees will need to increase to allow for such movements.

The DOF needed for the robotic arm will largely depend on the requirements of the printing surfaces. Allowing for a certain redundancy in the DOF will allow for more fluid motion and less constraint in potential overall movement [9]. However, this will increase the complexity of kinematic analysis of the arm. One current design that embraces mobility is the hyper redundant manipulator designed by Chirikjian and Burdick [10]. Their design involved 30 DOF which allows the manipulator to inch along the ground through tightly constrained areas. While their research consisted of the robot not being connected to a base plate, the concept will prove useful as the targets of printing become more complicated and specialized. However, as research

on printing conformally onto convex surfaces is a new subject, this prospectus will focus on a simple target shape that will require little or no redundant degrees of freedom which may be required for more complex shapes with obstructions.

A solution with fewer DOF is found in [11]. Bausch et al. [1] printed on a convex surface and used a 3-axis 3D printer and added 3 rotational DOF to the extruder head of the printer using stepper motors. This allowed them to print while keeping the printer head perpendicular to the printed surface [1]. Their targeted printing surface was a curved convex surface with nothing obstructing the path of the printer head [1]. With concave surfaces where the printer head can encounter obstructions, higher DOF need to be used to increase maneuverability.

For the scope of this project, 6 DOF will be used to allow for the extruder head to remain perpendicular to the printing surface. The extruder head remaining perpendicular to the surface is necessary for the quality of the print. This orientation reduces error caused by the dripping of the 3D printed material and ensures that the structure of the print will not be compromised. More DOF can be added to increase applications in the future, but 6 DOF is necessary and most feasible for a functioning design.

2.2.3 Robotic Arms in Other Applications and Modular Attachments to Robotic Arms

As technology has improved, there have been new implements of machinery to reduce physical labor requirements of humans, such as robotic arms. At first, robotic arms were only used for doing small tasks, but were able to complete more complex tasks after years of being rapidly developed and enhanced [12]. The first industrial arm was used in a General Motors plant and soon after robotic arms became common for factories in the 1960s [12]. From this, they

began developing robotic arms which mimicked the human anatomy and kinesiology of the shoulder and the human arm [12]. While the degrees of freedom vary significantly, it is common for robotic arms to have around 7 DOF, the same as the human arm [12]. Therefore, additional DOF will not be required if a robotic arm approach is taken.

A modern robotic arm application can be seen in the medical field in surgeries. Three different surgical arms commonly used for procedures are the AESOP, Zues robot, and da Vinci surgical system [13]. AESOP has 7 DOF and is voice controlled with a laparoscopic camera holder. Zues has 4 DOF and has the ability to perform long-range telepresence surgery [13]. Da Vinci Surgical System has 7 DOF and the first to have an immersive 3D interface [13]. Da Vinci is most commonly used for general laparoscopic surgery, however, can be used for other surgeries [14]. Robotic arms during surgery or procedures like pharyngeal and laryngeal microsurgery must be precise and delicate when dealing with human tissues [15].

Existing examples of technologies in additive manufacturing with robotic arms can help illustrate some potential applications of this research as well as provide guidance for the purposes of this project. Gosselin et al [16] present research for a way of 3D printing large concrete structures via a 6-axis robotic arm to be used primarily in architectural and construction projects. Typically, concrete structures are created by using a cast or mold, but through the use of a robotic arm and additive manufacturing, a much wider range of complex structures and shapes can be created for a much lower cost than custom-making a mold. The 6 DOF in addition to the layer-by-layer method of printing allows for prints without the need for temporary supports in the manufacturing process [16]. Gosselin et al describe other concrete printers that all require using temporary supports due to a fewer amount of DOF [16]. This particular example

demonstrates how a 6 DOF robotic arm allows for an easier and more stable printing process compared to a printer with fewer DOF's.

Another important consideration unique to a robotic arm approach is the need for methods of attaching an end effector, in this case an extruder, to the robotic arm. A patent by Weskamp et al. [17] describes a coupling system for a robotic arm which allows any of a number of different end effectors for the arm to be attached and switched out quickly and easily. The system uses air and spring pressure to lock the attached tool in place and keep it from unintentionally slipping or twisting relative to the arm while it is in use [17]. Such an invention could be a very effective way to attach a material extruder to the end of a robotic arm. The attachment needs to be secure since 3D printing requires a high level of precision and accuracy. Any unintentional movement of the extruder relative to the arm could result in an inaccurate print.

2.2.4 Arm Frame Material

A practical arm design requires more than motors, gearboxes, and control mechanisms. Many of these components are small and susceptible to damage if the parts lack a protective casing. However, this additional protective layer comes at the cost of added weight. This weight must be accounted for when determining the design requirements for the motors and gearboxes. If more weight is added the drivetrain will have to support and move increased loads, resulting in the requirement of more robust, stronger, and more expensive drivetrains or a smaller payload. These sacrifices are why a material with a high strength-to-weight and high stiffness-to-weight ratio is ideal for robotic arm design. Stiffness of a material indicates the materials ability to resist deformation while in the elastic region, where a material will return to its original position after

deformation. This will be vital to the robotic arm as even small deformations will contribute to errors in the extruder location. However, yield strength, the type of strength most important to elastic and ductile materials, is a measure of the maximum stress that a material can absorb before any permanent deformation occurs. The constraints requiring a material with a relatively high yield strength, high stiffness, and low weight, result in common casing materials such as plastics, carbon fiber, graphite, aluminum, and titanium.

An analysis of the materials and the arm design can be done through a finite element analysis (FEA) in order to maximize the strength, stiffness, and payload-to-weight ratio of the robotic arm [18]. If a composite were chosen, in addition to their high strength-to-weight ratio, there is potential for further optimization of the materials for the specific applications by adjusting thickness and angles of the composite layers by utilizing FEA outlined in [18]. However, these optimizations and customizations would add high expenses to a project budget.

2.2.5 Kinematic Model and Inverse Kinematic Model

In order to ensure accurate and reliable printing that is perpendicular to the printing surface, the robotic arm must be able to move precisely with at least six DOF. Section 2.2.2 has a more in depth discussion of the required DOF. The precise movements require an analysis of the kinematics of the designed arm. A forward kinematic model creates a mathematical representation for the position and orientation of the robot's end-effector relative to its base. An inverse kinematic (IK) model takes a desired target position and orientation as inputs and determines the joint angles in the arm that are necessary for the end-effector to reach said position. Iqbal et al. [11] have developed an IK model for a commercial robotic arm which can correctly determine the joint angles for any location within the arm's work envelope with a

precision of $\pm 0.5\text{cm}$. The joint angles of the waist, shoulder, elbow, and tool pitch are solved for using a transformation matrix in which the position and orientation of the end effector with respect to the base are known inputs. Many different IK models have been developed and tested, many of which are specific to certain types of robotic arms. Cubero [19] proposed a “general purpose IK method” which can be applied to any robot with one degree of freedom per link. Essentially, the described algorithm first determines the forward kinematic solution for a given end effector position, and from that can determine the optimum inverse kinematic solution for a position that is suitably near the current position.

In addition to an IK model, the arm and extruder must each have a kinematic model. This model allows the arm to know the location of all of its linkages, and most importantly, the location of the extruder. [9] describes the kinematics of a robotic arm where each joint has 1 DOF as shown in Figure 2.2. They show that going from the orientations of each internal joint q to the position of each part is straightforward. $\vec{x} = \vec{f}(\vec{q})$ where \vec{x} is the position of the arm, \vec{q} is the orientation of each joint, and \vec{f} is the function that relates them. This is not useful when trying to plan a path for the printer as we will have a location for the print head but require the orientation of the joints. So to get $\vec{q} = \vec{g}(\vec{x})$ an inverse function is needed. [9] shows how this has only one solution when the number of degrees of freedom equals the required degrees of freedom of \vec{x} . However, there are infinitely many solutions to this when there are more degrees of freedom than required. To find the solutions that work, the solution to n linear equations must be solved [9]. This allows us to generate orientations of the joints that would put the arm in the required position. Then, a final \vec{q} can be chosen that is quickest to get to. This process is described in section 2.5 Toolpath Planning.

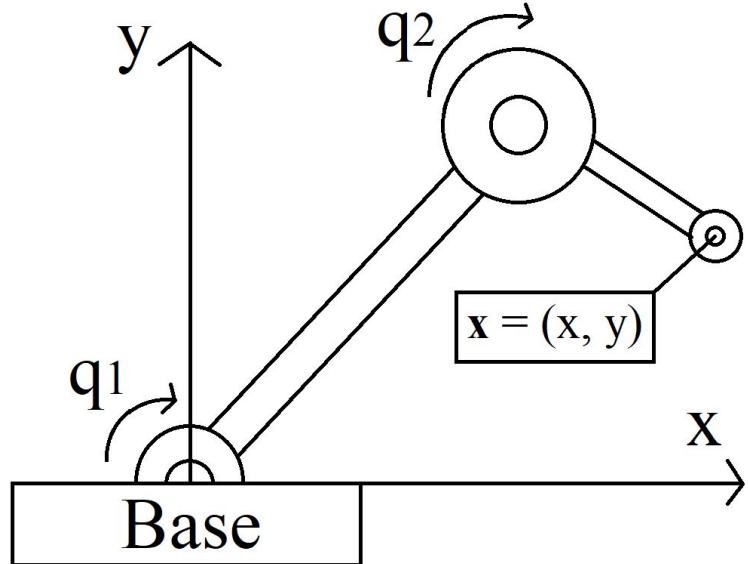


Figure 2.2 Simple 2-DOF arm with kinematic model

2.2.6 Traditional 3-Axis Printer Exploration and Limitations

In 3D printing's short history, its utilization has spread to numerous STEM fields.. Though each field has its own unique utilization of 3D printing, one concept that sees indiscriminate use is scaled production of models. Smaller sized examples of a given model are more cost effective and take significantly less time to create. Small scale development also allows for a higher degree of customization [20] of the model, making it more feasible to explore concepts without the commitment to a to-scale example. The easy production of custom printed shapes at different scales will be useful for creating prototypes of the shape we will eventually aim to print onto.

Building exact but small scale examples alone economize vital resources, which is a key consideration of any large scale research project that has funding concerns. Besides creating small scale models, other representations of objects that require significantly less materials and time can be created by wire printing. Wire printing is the practice of printing models of solid objects in a simplified representation that is hollow and only contains important edges and vertices. To accomplish this, material is extruded directly in 3D space, as opposed to printing a solid object layer-by-layer. Models made with this method are still accurate representations of the object, but also save material costs and expedite the printing process by up to a factor of 10 [21]. The time savings is significant because with traditional methods, even small scale models take several hours, or even days, to complete printing.

The main limiting factor of using a traditional 3-axis 3D printer is the fact that there are only 3 DOF. As discussed in Section 2.2.2, three additional DOF are required and solutions in [1] for a traditional 3-axis printer are discussed. Another consideration for traditional 3-axis 3D printers is the baseplate. For in-situ printing applications, the baseplate would need to be removed to allow for printing directly onto the surface. This may result in a less stable 3D printer due to less support in the base, potentially causing negative implications in the accuracy of the print. This will need to be considered in determining the robotic manipulator chosen.

2.2.7 Drive Trains/Motors

As discussed in Section 2.2.2, 6 DOF will be pursued in this project. In order to implement additional degrees of freedom into traditional 3-axis 3D-printers, drivetrains that can manipulate the angle of the extruder with respect to the printing surface will be required. The drivetrain is the subsystem of a robot that controls the motion of the individual parts or the entire

robot. If a robotic arm is chosen to maneuver the extruder instead of a modified 3-axis printer, the drivetrain will control the movement in the joints of the robotic arm. In either application, the drivetrain will contain both a motor and potentially a gearbox for controlled movement. The motor translates electrical energy into rotational movement in its output shaft. While the purpose of the gearbox is to both increase the torque that the drivetrain outputs and to decrease the speed that the motor shaft outputs to the connected systems. It is important to note that a gearbox is not necessary and a motor alone can directly output kinetic energy; this is a direct drive system.

In order to determine the necessary specifications of the drivetrain, multiple factors must be taken into consideration. The required torque at each joint of a robotic arm can be calculated using the mass and gravitational forces acting on the joints while the motor torque can be calculated using the gear ratio, gear inertia, motor inertia and gear efficiency [22]. The main considerations for motor selection are the nominal torque, stall torque, and the angular velocity of the output shaft [22]. The nominal torque is the maximum torque the motor can output without causing excess damage to the motor. This value is the maximum amount of torque that can be used while maximizing the life of the motor. The stall torque is the maximum torque of the motor which occurs when the angular speed produced is zero. When selecting motors, the stall torque of the motor must be greater than the required maximum torque of the system, otherwise motion will be impossible. The final motor consideration is the maximum angular speed of the motor. However, in the applications of 3D-printing where slow and precise movements are required, the angular speed of the motor is not likely to be a constraining factor. While considering motors, it is also essential to investigate gearboxes simultaneously because the

gearbox will be able to increase the output torque of the system and reduce the rotation speed of the output shaft.

For gearbox selection, the three main considerations are rated torque output limit, the maximum torque output and maximum input speed [22]. The rated torque output limit is the torque outputted by the gearbox at the rated speed of the engine. The maximum torque output is the absolute largest amount of torque the gearbox can provide and the maximum input speed is the maximum speed that a motor can input into the gearbox. When choosing a gearbox, the choice largely depends on the motor chosen because the gearbox needs to be carefully selected to permit the torque and angular speed outputs of the motor it is attached to. For this project, both the motor and the gearbox should be chosen with slower speed in mind to maximize the accuracy of the arm. The higher the output speed of the motor and the gearbox, the more inaccurate the print will be because of the constant need to slow the various parts of the arm. A slower gearbox and motor combination will lessen the instability caused by the momentum of the arm that the printer head will experience.

Other drivetrain systems that do not utilize rigid connections between joints exist as well. In particular, advancements in drivetrain technology with medical applications may be of interest for creating precise movements. Past examples of surgical arms have featured an extensive network of metal cables, moved mechanically from the base to control the motion of the entire arm. However, the use of the numerous metal control cables is expensive and complicates the maintenance of the robotic arms [23].

In contrast, there has been research into a cheaper and more reliable method in the form of a strap drivetrain. This method involves several sets of straps throughout the arm. Each set is

paired with a specific group of joints or links, controlling their movement. For example, in an arm with four links there are two straps. As the linkage assembly is moved about a pitch axis, the first set of straps ensures the third link maintains the same angle relative to the first link, and the first and second set of straps ensures the fourth link maintains the same angle relative to the second link [10]. The implementation of this exact system is limited because of existing patents, but it gives us useful insight on potential drivetrain solutions of our own.

2.3 Extruder Design

2.3.1 Overview

Designing an extruder head to print on concave surfaces requires careful consideration in multiple areas such as the length of the extruder head and the size of entire extruder. A typical 3D printer uses very specific dimensions in both of these, however, for our purposes, it is important for us to adapt these in order to print on a concave surface as needed. A low profile extruder is advantageous for printing in concave surfaces as it has the ability to fit in confined spaces, which provides the printing algorithm freedom in choosing toolpaths.

2.3.2 Methods of 3D Printing

Aerosol Jet Printing

Due to high interest in aerospace and electronics industries, researchers have developed a relatively new method of printing that utilizes aerosolized droplets to deposit materials onto a surface. The chosen material must be aerosolized into a liquid with small droplets and sent through a collimated beam. For optimal accuracy, these droplets have diameters between two and five microns. Once this process is complete, the beam leaves the aerosol head at about 80 m/s and the droplets reside on the designated surface, which is a predetermined substrate. Aerosol jet printing differs from other methods of direct-write printing because there is no contact with the substrate until the droplets are placed; the jet propels the droplets down to the surface using aerodynamics. This methodology allows the device to print on different surfaces

while using multiple layers and multiple materials. For example, aerosol jet printing can be used to generate multi-layered circuits [24].

Researchers have also found that aerosol jet printing can be used to print on non-planar surfaces such as those that have slight curvature or topography. This is of interest because additive manufacturing can be used in embedding sensors and antenna onto uneven surfaces such as aircraft fuselages. Using 3D printing for these instances decreases the overall weight of the structure [24].

Electrohydrodynamic Printing

Similar to aerosol jet printing, electrohydrodynamic printing generates small droplets of liquid material that are only a few microns in diameter. This system was developed for the primary purpose of manufacturing organic printed electronics. These electronics are made of polymeric composites because they can withstand a substantial level of mechanical deformation. During the process of electrohydrodynamic printing, liquid material is forced through capillary tubing that ends in a small nozzle. The liquid is applied to the designated substrate using the electric force on the ions in the material, which results from the applied electric field in the printer. By modifying the strength of the electric field, researchers were able to alter the size and drip frequency of the droplets [25].

When compared to other more complicated methods of 3D printing, electrohydrodynamic printing is easier to use in testing processes. This is due to the fact that the process does not require high temperatures, high pressure, a vacuum, or high-functioning generators. Experiments can be conducted at room temperature and are not affected by changes in humidity.

Although this method has proven to be useful, it does have some drawbacks. This method may not be useful to print onto uneven surfaces because the distance between the nozzle and the substrate must be within 2-3mm, which would be much more difficult to maintain over a substrate that is not level. In addition, the width of the line that is printed is dependent on the diameter of the droplet of material. These sizes can be altered by changing the inner diameter of the nozzle. However, the nozzle can get clogged if the inner diameter is too small or if the chosen material is too dense [25].

Fused Deposition Modeling

Fused deposition modeling (FDM) is a more common method of 3D printing that is used to construct models and prototypes. During this additive manufacturing process, the 3D printer constructs a part by building it up with individual layers. The chosen material, typically a type of plastic, is heated and directed onto the surface through the printer's extruder. The material solidifies to the previous layer after it leaves the extruder head. This method of printing is cheaper than many other methods because it requires less expensive materials, and the technology tends to be less complex. However, there is a decrease in the accuracy of the models and prototypes formed using this technique. In addition, the process is more time consuming than other methods of printing [26].

Laminated Object Manufacturing

Laminated object manufacturing (LOM) is a process that involves fusing sheets of plastic materials together by using high temperatures and pressures. A laser or blade is used to manipulate the materials into the required form after they have been fused together. This method

is similar to FDM because the printed objects are formed using layers of material, but the LOM method trims away excess material in the layers instead of initially printing the exact shape. Due to these differences, LOM products require additional processes such as sanding or varnish after the printing process is completed. Overall, this often leads to a final product with a lower level of accuracy and it would not be ideal for this research project [26].

Selective Laser Sintering

Selective laser sintering (SLS) is the process of fusing small particles of material together using the heat from a high-powered laser beam. Common materials used in this process are glass, ceramics, and plastic. The material is initially formed into a compressed powder bed inside a sealed chamber, and then the laser moves across the bed to trace the design of the object. The powder solidifies into the object and then requires a cool-down period before it can be removed from the sealed chamber. This process is advantageous due to the fact that structure support is not necessary, even for complex objects. In addition, the objects produced by this printing method tend to be more durable than more traditional methods of 3D printing, such as FDM. However, the technology required for this process is more expensive than other methods of 3D printing, which makes it a less than ideal choice for this research project [26].

2.3.3 Extruder Head Design

General Design

A 3D printer's extruder takes a material, usually a plastic filament of some sort, and heats it up. Once the material is liquified, the material is pushed out through the nozzle head and onto the desired surface [25]. The filament starts at the "cold end" and is fed through a tube using a

gear and motor system until it reaches the “hot end”. The hot end is the section of the extruder head in which the material changes phase to a liquid [25]. Once in a liquid state, the material can very easily be deposited onto a surface. In a typical 3D printer, the nozzle of the extruder head is short compared to the entire extruder and is very close to the surface. In concave surfaces, the extruder may be blocked by the curved nature of the surface. A possible solution to this problem is extending the length of the nozzle so that the extruder body does not interfere with the actual surface. A challenge that comes with this option is the extra heating that would be required since the material needs to be in a liquid form for the entire length of the nozzle. The hot end is typically composed of a heat sink inside a brass nozzle, along with a cooling fan that keeps the extruder head from melting [26].

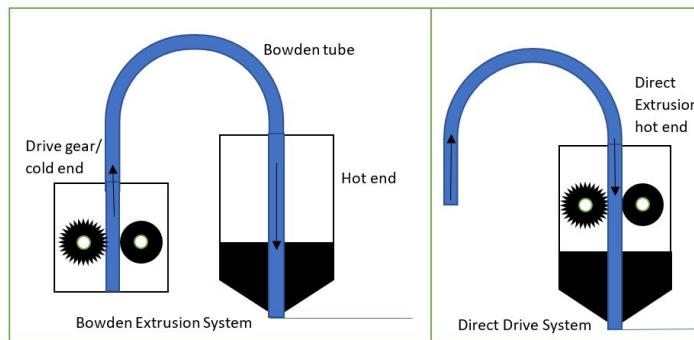


Figure 2.3

Two relatively cheap 3D printer head designs are the Bowden printer and the Direct Drive printer. The difference between these two printers lies in the spacing of the cold and hot ends (fig. 2.3). In a Bowden printer, the hot and cold ends are connected to each other by a tube [27]. This tube creates separation between the hot and cold ends. In comparison, the Direct Drive printer places the cold and hot parts are directly against each other [27].

Bowden Printer

A benefit of the Bowden printer is that since only the hot end needs to be moved, there is less weight that needs to be moved which can lead to a faster printing time if desired. Consequently, the problem with this design is the 3D printer is less responsive. This is due to the increased distance from the cold and hot end in addition to more friction in the tube [28]. A consequence is this can lead to large problems with the final product that gets created. Also, there can be a large number of problems with blocking in the tube. A solution to this is printing with a diameter filament of 3 mm instead of 1.75 mm to limit blocking [27].

Direct Drive Printer

A Direct drive printer exceeds where Bowden printers struggle. Due to the short distance between the hot and cold end of the printer, the entire system has a better response time. It may also be easier to move the entire system as one unit so that the filament resists bending. Less torque is required from the motors since the filament doesn't need to cross through a tube [27]. Despite all the benefits, the Direct Drive printer has many issues revolving around the size and weight of the extruder. The frame may be unstable and can oscillate due to the large mass moving around [26]. Overall both designs are very different and we will need to look into both to see which will be better for our overall design. Both designs have fundamental differences, and the design we choose will decide on many factors such as cost, feasibility, and the application of the product.

2.3.4 Extruder Materials

When selecting a filament to use for FDM printing, the user needs to consider the thermal properties and adhesive strength of the material. Adhesion is extremely important, otherwise,

layers may slip off of each other. Thermal properties are necessary to consider because a relatively low melting point is ideal for a student-made 3D printer. Other factors include the strength of the material, as that is important in most real world applications..

The challenge of printing onto uneven surfaces necessitates a method of preventing structural flaws in the materials laid due to gravity or the nature of the surface. One possible approach to solving this, especially if metals are being printed, is through the utilization of magnets. The extruder would apply a low magnetic field to the material printed, and the material would be mixed with magnetized platelets. Using a two-component material would also optimize control.

Tensile Strength of PLA

Researchers at Northwestern Polytechnic University conducted a study testing the ultimate tensile strength (UTS) of PLA with different printing orientations and thicknesses. They printed a thin, plate-like structure at 0, 15, 30, 45, 60, 75, and 90 degrees with respect to the flat surface, and did this for thicknesses of 0.1, 0.2, and 0.3 mm [28]. The researchers used a tensile machine to determine the UTS of each plate. In this case, the direction of the filament grain determines which angle will be strongest, and the filament was strongest at 90 degrees. Both their theoretical and experimental results showed that the UTS decreased as the angle went from 90 to 0 degrees; specifically, for angles between 85 and 45 degrees, there was a sharp linear decrease from 55 MPa to 30 MPa, then the UTS levels off at around 27 MPa for angles less than 45 degrees [28]. Findings also showed that as layer thickness increased from 0.1mm to 0.3mm, the UTS decreased.

Extruder Design and Parameters

Extruder head shape is one of the main parameters to consider in additive manufacturing. Researchers at the University of Miskolc, Hungary [29], conducted a study on how changing the extruder head geometry affects the physical properties of the material, while keeping the product size and production method constant. They found that a spherical head shape generates the highest extrusion pressure compared to a cone and torus.

Students at the University of Denmark [30] created their own 3D printer and discussed their results in a published paper. In order to effectively print PLA filaments, they determined that the extruder head temperature should be set to 190 degrees Celsius. Furthermore, the students realized lubrication was an issue in such a low budget 3D printer. To solve this, they ran the filament through oil prior to passing through the extruder head. Finally, they saw that maintaining proper insulation was an issue. To overcome this issue, they used PEEK materials and insulation tape. PEEK materials have an upper continuous use temperature of 250 degrees Celsius. Overall, they concluded that the extruder is the most problematic aspect of constructing a 3D printer. Knowing this, we chose to designate a large section of research and design for the extruder.

2.4 3D Scanning

2.4.1 Overview

Being able to print onto an unknown and uneven surface requires an accurate 3D model of the surface to be rendered, allowing the software to determine where and how to print. Lowering the cost of hardware is always useful, but it is especially crucial for the eventual goal of using this technology for in-situ repairs.

The primary methods of 3D Scanning involve ranging and triangulation methods. For the purposes of this project, these scanning methods will produce an elevation map for discrete points in the workspace, effectively representing the target surface for analysis by a toolpath algorithm. Aside from the common scanning techniques, we additionally investigate a method of tactile sensing which may be applicable to non-tactile-sensitive print environments.

2.4.2 Robotic Arm

Most 3D scanners consist of a mounted scanner with a turntable for rotating the object being scanned. This would not work for in-situ because the object that requires being scanned cannot be placed on a turntable as it is assumed to be fixed. An alternative way of scanning the print surface would be using an arm to position a scanner and work its way around the surface. [31] and [32] have created systems to do this, but they are impractical as the triangulation scanner they use are exceedingly large. They [31], [32] also required large arms with high precision because the location of the scanning sensor must be accurately known in order to scan from different positions and coordinate the data. This would be infeasible with our resources and

so it is outside the scope of our project. Instead we will assume that a scanning system can be implemented into a cohesive design with the in-situ printer as future work.

2.4.3 LIDAR

Light Detection and Ranging (LIDAR) technology is often used to construct high-resolution maps of general geography [33]. In these cases, the laser emitter is typically mounted onto the bottom of a plane or helicopter. The use of LIDAR for these purposes is optimal as the distances between the vehicle and the target surface is large. In relation to this project, LIDAR may prove to be a useful asset to produce high-res images but will depend greatly on the quality of the sensor. Boehler et al. notes that close-range time-of-flight scanning instruments may have error in the range of some millimeters [34]. This of course will depend on internal clock speeds and hence the quality of the LIDAR sensor will determine the resolution of the scan.

Noise in LIDAR Data

Noise reduction and removal will also have to be considered if using a LIDAR instrument. While applications of an in-situ print in outer space (and/or extraterrestrially) requires extensive research due to radiation bombardment, we consider the limitations of the technology to prototyping purposes. Depending on the environment in which the print will be made, classifications must be given to the surface in order to differentiate between noise and surface roughness. Zuowei et al. find that finite-element analysis (FEA) is able to eliminate noise effectively in airborne point-clouds [35]. In their paper, the researchers implement a ‘neighborhood’ classification scheme where sections of the cloud with high density are labelled

and the algorithm is called recursively on adjacent elements. Sections that lie above a certain threshold are tagged as noise and removed.

2.4.4 Triangulation

Typically, the lowest cost 3D scanners are triangulation laser scanners, which generally operate with only a laser source and a camera [1]. This method offers the best combination of accuracy, working volume, robustness, and portability [32]. The single camera solution of triangular scanning systems consists of a transmitting device that sends a laser beam at a defined, incrementally changed angle from one end of a mechanical base onto the object and a CCD camera at the other end of this base which detects the laser spot (or line) on the object. The distance between the laser source and the camera as well as the as the laser beam itself, reflected off the scanned surface, form a triangle. The distance between the laser source and the camera as well as two of the angles of the triangle are known, as shown in figure 2.4. Using these values, the coordinates of the scanned point can be calculated [36]. The 3D position of the reflecting surface element can then be derived from the resulting triangle.

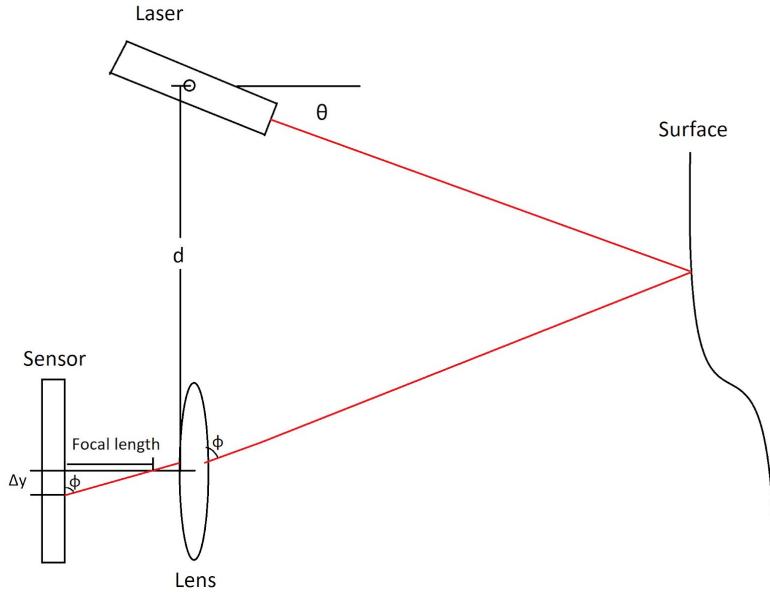


Figure 2.4 Simplified Laser Triangulation

An important factor that must be considered while doing in-situ 3D printing is the resolution. The best solution to this problem is the one proposed for the Michaelangelo project [32] that 3D scanned all the statues (except one under restoration) including the chisel marks left intentionally by Michaelangelo himself. The resolution chosen was a Y sample spacing (along the laser stripe) of 1/4 mm and a Z (depth) resolution at least twice this fine which gave a field of view 14 cm wide (along the laser stripe) by 14 cm deep.

2.4.5 Tactile Scanning

A downside to laser scanning is that edges and boundaries must be determined by some algorithm or classification scheme that acts on the produced elevation map. An effective implementation of this is complex and may take additional development time. It is further discussed in section 2.5. A tactile sensor can be attached to the end of a robotic arm to accomplish object edge tracing, surface normal, and shape recognition [37]. Edge tracing is of

particular importance as this would enable the toolpath algorithm to distinguish the print boundaries for arbitrary layers. The sensor itself consists of three thin sheets of force-sensitive resistors arranged triangularly with the peripheral circuits [37]. When in use, the robotic arm the sensor is attached to would extend toward a given object, and then essentially work its way along the object's surface, using the force sensors to scan and produce a digital model of it.

2.5 Toolpath planning

2.5.1 Overview

For the printer to print conformally it will need to create toolpaths that align with the geometry of the print surface. This will involve knowing the print surfaces' geometry and its correct location in space relative to the extruder. The toolpath will have to take into account the volume of the extruder and printer arm so that there are no collisions with the print surface. Toolpath planning is simple with a flat print surface because the head is confined to the plane and thus it is only necessary to move up one layer at a time. With conformal printing the printer will have to create non-flat layers taking into account the geometry of the surface and location, orientation, and geometry of the print head.

2.5.2 Geometry

When printing onto an unknown surface, the geometry of the surface and the print arm will both need to be known in order to create pathing algorithms that avoid collisions. The geometry of the print surface can be known through either 3D scanning or modelling. The arm will need to be 3D modeled as well to know its geometry. Once these geometries are known, to create a path or do any movements at all, the system must be able to avoid collisions. To determine collision detection, a method called “Oriented Bounding Boxes” (OBB) from [38] can be used. This method involves wrapping complex surfaces in bounding boxes (or any convex shape) and checking if those boxes collide with one another. This method creates false positives, as it is conservative and will detect collisions where none will occur, but it is computationally efficient. [38] shows that for any two boxes, only 6 operations need to be made to check if there

is a collision. OBBs can be created that tightly enclose the entire print arm and can easily have their location and orientations calculated from knowing the angle at each joint. With the OBBs known, a collision can be detected using a Minkowski Difference, as [39] demonstrates. If $A =$ vertex of every point on one OBB and $B =$ vertex of every point on another OBB, the Minkowski Difference is defined as the following:

$$A - B = \{a - b | a \in A, b \in B\}$$

If the boundary formed by surrounding this set contains the origin, the two boxes are in collision. This can be seen in this example in 2D from [39] (fig. 2.5).

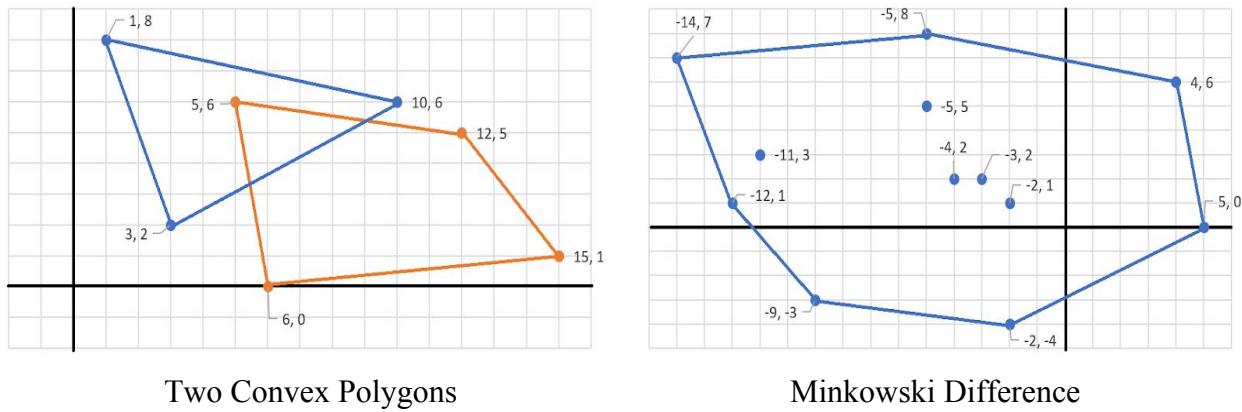


Figure 2.5

An OBB of the print surface wouldn't be accurate enough to generate tool paths, so another method must be used. [40] outlines an algorithm that creates progressively smaller OBBs around complex geometry so every vertex doesn't need to be checked. Using this "OBBtree" method along with OBBs already known for the print arm, a fast collision detection method can be developed. This is the method used by [39] when designing their print arm and it was fully implemented by them. With these collision detection techniques, print surfaces can be tested to

make sure it is possible to be printed on without colliding with them and can be used when generating toolpaths.

2.5.3 Pathing Algorithms

When printing on a flat surface, the toolpath can be generated by knowing only the outer boundary and the infill. Evidently, the algorithm to generate the toolpath travels layer by layer, following the outermost boundary then making end-to-end prints at each layer. A simple pathing algorithm for a concave surface may directly follow from this standard flat-bed printing. Bausch et al. [2] explores a similar toolpath generation algorithm while considering iso-curves. When considering a convex surface, the researchers layered iso-curves, which were layers analogous to flat-bed print layers but were instead normalized to the scanned surface. After determining these iso-curves, the final print could be produced by layering them on top of one another. Additional consideration was put into the print head's trajectory such that it could follow the topology of the surface in order to avoid making contact with the print.

2.6 Conclusion

In order to implement a 3D printer for applications to in-situ repairs, there are three basic requirements and thus potential research interests. One of these requirements is the manipulator of the print head. In our literature review, we explored the current uses, applications, and constraints of both the linear axis and robotic arm manipulators. The driving factor for the consequent design will ultimately be the DOF, payload, stiffness, and weight of the manipulator. As discussed in Section 2.2, both a robotic arm and a modified linear axis 3D printer can sufficiently meet the requirements of the project. Regardless of the approach, the basic requirements for the manipulator are: 6 DOF, a large enough payload to support the extruder, relatively high stiffness, and low weight. Adhering to these constraints will allow us to print with precision perpendicular to the surface.

Another basic requirement is the design of the extruder. An in-situ print requires that the print head and extruded materials be compatible with its environment. For the print head, a low profile body and lengthy nozzle are important factors in the design. In contrast to a typical 3D printer that can maneuver horizontally without interference, an in-situ printer's workspace is restricted by the size of its extruder. In the same vein, the extruded material must be able to bond to the surface on which it is printed, as well as to itself. PLA is a common plastic filament for 3D printing. However, if printed at an angle, the bond between layers may tend to slip. All of these factors must be considered when designing our extruder.

The final basic requirement of the technology is 3D scanning and sensing. An accurate description of the print environment is critical for conformal printing. In section 2.4, a discussion

of scanning methods using LIDAR as well as a method to compensate for noise is given. We find that relevant scanning methods for the project are triangulation, ranging, and tactile sensing. Section 2.5 gives a brief analysis into potential methods of guiding the print head once the scan is acquired, using tool path algorithms. Here, we encounter the OBB approach and iso-curve pseudo-algorithm in toolpath planning.

From our literature review, we ultimately find that the full implementation of an in-situ 3D printer requires further research. A multitude of individual methods and practices are investigated but we observe there to be a lack of literature discussing a design that is immediately applicable to in-situ repairs. Given the potential applications for the technology, we conclude that a proof-of-concept is feasible but necessitates further work for any apparent applications.

Chapter 3: Methodology

3.1 Overview

The following section is an outline of the methods we choose to explore in our research. Evaluation and execution of these methods are divided into corresponding focus groups which include: extruder, structural, and 3D scanning subteams. A full implementation of the proposed in-situ 3D printer will follow the products and results made from each focus group.

3.2 Extruder

3.2.1 Extruder Head Design

The other option would be buying a 3D printer head design online. To determine which option we will look into, we have to examine the options based on time to complete, simplicity, and price. Individual components for a 3D printer are largely cheap and wouldn't be very expensive to buy and make from scratch. A large amount of uncertainty would revolve around how much time it would take to build an extruder and get it to work properly. If this ends up taking longer than we expect it would be beneficial to buy a printer. A cheaper 3D printer extruder such as the E3D V6 ranges around 30 - 100 dollars whereas a much better extruder head E3D Titan Aero ranges from 100 - 220 dollars [25]. It is important to look at all the differences between the quality of each possible printhead and then decide which quality would be best matched for our 3D printer design.

3.2.2 Materials

The material our team decides to use will depend on a few factors: cost, thermal properties, and practicality. Using a material such as concrete would require a larger overall system and a greater force to extrude the material. Given that this is mainly a proof of concept project, using a dense material like concrete wouldn't make sense. An alternative material is plastic filament. Plastic filaments such as PLA are commonly used in recreational 3D printing, but can also be used in real-world applications. Considering the small scale of our project and the

pre-existing technologies surrounding PLA extrusion, we believe using this plastic filament will yield the best results.

3.2.3 Concave Surface Dimensions

The extruder will be tested using a simple concave surface. As discussed in section 2.1, a general void to be filled will be in the radius of a couple centimeters. PLA will then be used to fill in this area using a pre-determined toolpath developed by the software team. The size of the site that will be used for the preliminary testing is within the range found for one of the possible applications, which is repairing the tires of rovers [6]. Subsequent testing will be based on our preliminary results; for example, if the initial tests are successful, we can plan further testing with a more complex surface that is more similar in shape to the tire repair application.

3.3 Structural

3.3.1 Robotic Arm Approach

The functionality of robotic arms is derived from the end effector that interacts with the environment. In the robotic arm approach for this project, the end effector would consist of the 3D-printing extruder and its constituent parts. A compact filament feed system and hot end of an extruder head has been implemented and attached to a 6 DOF robotic arm, (ABB IRB 1200-7/0.7) [41]. In order to attach a unique end effector, such as an extruder, the chosen robotic arm for the project must have the flexibility to accommodate different and unique end effectors. This requirement should not be constraining as most robotic arms have this functionality. For this project, the end effector mount will likely be constructed using CNC machines on campus and constructed from aluminum and an overall more temporary solution. Although, a similar system to [17], discussed further in Section 2.2.3, may be required for accuracy, precision, and durability. One further consideration to be made is that there is not complete standardization of the end of robotic arms and how to mount the end effectors. Therefore, we must first determine the robotic arm most likely for success before designing the mount of the end effector. In order to determine the robotic arm, a consideration of factors will be taken into account, cost will be a priority, followed by the working envelope, payload, degrees of freedom, and the accuracy and precision of the positioning of the robotic arm. Because this project aims at being a proof of concept, the cost will be kept at a minimum while sacrifices to other factors will be considered.

3.3.2 Traditional 3-Axis Printer Approach

Traditional 3D printers have three degrees of freedom, namely translation in the x, y, and z directions. This is suitable for printing objects on a flat surface, but in order to print on an uneven surface as is the goal of this project, additional degrees of freedom are required. Bausch et al [1] accomplished this in their prototype printer by adding three stepper motors to allow rotation about all three axes. Determining how we would most likely add these rotational DOF's will depend on feasibility, cost, and qualitative analysis of effectiveness. The two most likely options to accomplish this are either adding rotational capabilities to the baseplate of a printer or modifying the extruder itself to allow rotation. A rotating baseplate would be less applicable to in-situ repairs of damaged surfaces since it would require the print surface to be placed on the baseplate, but could still demonstrate a proof of concept for conformally printing on convex surfaces. Constructing a rotating extruder would likely be more useful to future research, but that may not be in the scope of this particular project, so feasibility and cost will still be large determining factors.

3.3.3 Testing Methods

Initial testing will be conducted by each subteam before the entire printing assembly is constructed. The chosen solution for the movement of the printer head whether it be a robotic arm or not will be tested for accuracy and maneuverability. This will provide an idea of what constraints need to be placed on printing site for the chosen solution to work. Testing for error caused by the movement of the arm will also need to occur to allow for easier development of

the design once the printer head is implemented. The solution will be programmed to make multiple movements that will be common when printing and the effect of velocity on the stability of head will be analyzed. This will allow for initial constraints to be placed on the movements of the printer so that accurate printing can occur.

3.4 3D Scanning

3.4.1 Software

The choice of software and manipulator control methods will depend primarily on their convenience and deployment time. We anticipate beginning with the software used by Bausch et al [1], because a working prototype has already been demonstrated in their research. This would include Rhino for 3D modeling and data visualization and Python to stream data between the extruder interface to the operator and visa versa.

3.4.2 Scanning Hardware

The choice of 3D scanner will have to be investigated thoroughly as this equipment is vital to obtaining information about the surface. Our mentor is well-versed and well-equipped with scanner hardware that is available for our use. Alternatively, we may purchase a commercial LIDAR scanner. The primary method of scanning will most likely be triangulation because the scan will be short-distance and ranging scans are not suitable for this due to their measurement error in this domain [34]. However, we will run scans on objects and compare relative resolutions to ultimately decide on a scanning technique. The equipment has been made available to us by our mentor. As a preliminary method to eliminate and identify potential scanners, we will use a decision matrix containing the following factors (in no particular order): ease of programming, cost, availability, resolution, and deployment time. The weights on these factors will be evident after considering the number of available options.

Filtering methods and visual classification schema may be handled by OpenCV packages. More experience is needed with possible methods before definitive choices can be made.

3.4.3 Toolpathing

We observe there to be a deficit of literature exploring conformal printing toolpaths and plan to explore various methods. One method, described in the literature review and by Bausch et al. [1] conceptualizes iso-curves and builds these layer-upon-layer, while each layer preserves the geometry of the last. However, we suspect that there would be difficulty in creating a print that deviates from the geometry of the environment. This speculation is supported by Figure 11 and 12 in [2].

An alternative approach may be to limit printed layers to a cartesian height throughout the print. A popular computer science problem similar to this is called ‘rain trapping’. Given an elevation map for the xy-plane (note that this is directly related to the data given back by a 3D scan), we find how much fluid can be held and where within this environment. For the purposes of this project, an additional constraint is the width of the extruded material, which would define the units of the elevation map and matrix.

Appendix

Timeline

Fall 2019

Overall:

1. Completed draft prospectus
2. Draft Presentation in November (informal)
3. Subteams target one or two methodologies for detailed analysis

Extruder:

1. Compare different brands and the potential of building our own
2. Either decide on an extruder to buy or come up with a design to build one.

Structures:

Sensing:

1. Narrow down software choices
2. Obtain available scanning instruments

Spring 2020

Overall:

1. Determine detailed budget and expenses
2. Complete and defend proposal
3. Apply and prepare for funding

Extruder:

1. Begin modifying or building extruder

Structures:

1. Conduct further research into potential 6 DOF robotic arms and 3D printers
 - a. Determine robotic arm/3D printer for project
2. Design end effector mount or means of increasing DOF of 3D printer

Sensing:

1. Test different 3D scanners for resolution and convenience
 - a. Determine optimal scanning method
2. Begin and finish software for data streaming

Fall 2020

Overall:

1. Do Good Showcase
2. Systems and integration for minimum viable product

Extruder:

1. Continue to modify/build extruder
2. Begin checking integration of extruder with structures

Structures:

1. Begin construction and testing of extruder mount
2. Testing of accuracy of robotic manipulator

Sensing:

1. Determine toolpathing algorithms
 - a. Implement and simulate algorithms
2. Obtain and account for physical constraints

Spring 2021

Overall:

1. A minimum viable product from each subteam is demonstrated
2. Results and findings are written into thesis

Extruder:

1. Fully finished extruder
2. Finish fully integrating with structures.

Structures:

1. Finalized extruder mount

Sensing:

1. Complete comparison of scanning methods and analysis for thesis
2. Complete comparison of toolpathing algorithm and analysis for thesis
3. Package software and complete documentation

Fall 2021

Overall:

1. Further research into additional features
2. Continue integration testing and optimization

Extruder:

1. Have a completely built 3D printer
2. Integrate with scanning team

Structures:

1. Integrate with scanning team and extruder to create prototype

Sensing:

1. Robustness testing for further development

Spring 2022

Overall:

1. Results and findings completed and ready for presentation
2. Demonstrate necessity for future work and research

Extruder:

1. Complete and test extruder head

Structures:

1. Document work in written thesis

Sensing:

1. Robustness testing for refinement
2. Prepare documentation for further work

Budget

Manipulator Options

Plan A: Purchasing Robotic Arm

6 DOF Robotic Arm	\$305 - \$1,285
Materials and Production of End-Effector Mount	\$35

Plan B: Modifying a Linear Axis 3D Printer

3D Printer	\$395 - \$999
6 STEPPERONLINE Nema 17 Stepper Motor	\$84
Wires	\$10

Plan C: University Resources

Kuka Arm OR Space Systems Lab NBV Arm	\$0.00
Materials and Production of End-Effector Mount	\$35

Extruder Options

Plan A: Purchasing Extruder

Printer Head: E3D Titan Aero 1.75mm Standard 12V Full Aero Kit	\$132.00
PLA: PLA Filament 1.75mm with 3D Build Surface	\$20.00

Plan B: Making Extruder

Printer Head Parts (If greater than purchasing we will purchase instead)	< \$132.00
PLA: PLA Filament 1.75mm with 3D Build Surface	\$20.00

3D Scanning Options

Plan A: University Resources

Various LIDAR Instruments From Mentor-Taught Course	\$0.00
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Plan B: Purchasing a Commercial Scanner

GoMeasure3D Metron E 3D Scanner	\$5,990.00
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Glossary

Conformal Fitting to the contour of; preserving angles and orientation

DOF Degrees of freedom

FEA Finite Element Analysis

IK Inverse Kinematics

In-Situ In-place; in the natural environment.

Payload The maximum weight that a robotic manipulator can lift

Toolpath The path which a tool follows, commonly in reference to an additive or subtractive manufacturing process.

UTS Ultimate Tensile Strength

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