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 may potentially only be limited by one's imagination. Consequently, the authors of the paper suspect 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. This concept has previously been demonstrated using a modified commercial printer. However, the demonstration was limited to strictly a conformal, convex print. In pursuance of a printer applied to in-situ printing, we seek an implementation of the solution that is capable of scanning, navigating, and executing toolpaths without manipulating the print environment frame and able to demonstrate a conformal concave print.

Team PRINT Draft Prospectus

by

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Chapter 1: Introduction

The advent of 3D printing has allowed for a wealth of new innovations and creative applications. Additive manufacturing in general 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 may potentially only be limited by one's imagination. Consequently, we suspect 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 stress the importance for this printer to be generalizable to as many print environments as possible. We also recognize the infeasibility for such a statement but ultimately seek some compromise between universality and specificity when considering the environmental constraints. 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 which require acute precision. This may include damages to electronics hardware such as Printed Circuit Boards or a repair that involves limited fill. In-situ printing is one of the primary challenges of the project as this involves enabling the print head to navigate through a priori-unknown surface.

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 DOF. In a later paper, Bausch et al. demonstrated 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 base 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 able to demonstrate a conformal concave print.

The full implementation of such a device could enable repairs made on any suitable structure, minimizing costs by eliminating the expenses of whole yet partially redundant replacement components. Applications may even be found in satellite servicing or self-made rover repairs. [3] describes how this technology 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 [3]. This allows parts to be repaired to near net-shape condition with less wasted material and a stronger finish [3]. 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 [3].

King [4] describes the existing methods of autonomous space servicing. This paper describes several different robotic systems all designed to carry out various tasks on space stations and satellites such as the Shuttle Remote Manipulator System (SRMS) and the Space Station Remote Manipulator System (SSRMS) which are both robotic arms that typically assist with assembly related tasks [4]. The Special Purpose Dextrous Manipulator (SPDM) is another robotic arm currently in development that will be able to install, remove, and transport small payloads [4]. All of the robotic systems described in this paper are designed to transport, maneuver, or assemble various objects and payloads. However, none are capable of conducting basic repairs to damaged surfaces. 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 (EVA) for basic repairs and may increase the lifespan of satellites and space stations.

In general, robotic in-situ printing is desirable in locations which humans cannot immediately access. Repairs for on-orbit satellites and extraterrestrial rovers are applications where the technology could be invaluable. Historically, rovers have experienced physical damage that has compromised abilities to fully complete missions [5]. This includes wheel damage that has led to the mission sites being restricted to relatively flat terrain that is not rocky [5]. This, in addition to NASA's efforts [6] toward the potential of sending multiple small and collaborative rovers on missions, is promising for the potential of a robot specifically designed to repair other rovers in-situ. Furthermore, as many satellites are no longer functional and have been regarded as space debris [4], the need for unmanned on-orbit repair of satellites is evident.

Chapter 2: Literature Review

2.1 Structures

2.1.1 Overview

This section of the literature review consists of prior research involving 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 degrees of freedom, kinematic and inverse kinematic solutions for movement in addition to the research on the required drive trains, gears and materials for an effective design.

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

Robotic arms are used in many different applications. For example, a use of a robotic arm is in the medicine field with the assistance of procedures. Robotic arms during surgery or procedures like pharyngeal and laryngeal microsurgery must be precise and delicate when dealing with human tissues [10].

Existing examples of similar technologies in additive manufacturing as well as 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 [11] 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 six DOF arm allows any number of complex structures to be designed and built, and the layer-by-layer method of printing in addition to the degrees of freedom allows it to print these structures without the need of temporary supports in the manufacturing process [11]. The paper describes a few other concrete printers that all require using temporary supports due to a fewer amount of degrees of freedom [11]. This particular example demonstrates how a 6 DOF robotic arm allowed for an easier and more stable printing process compared to a printer with fewer DOF's. It also shows how additive manufacturing can be used to create strong, resilient structures.

A patent owned by Weskamp et al. [12] 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 [12]. Such an invention or at least something capable of serving a similar function 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 accidental movement of the extruder relative to the arm would result in a failed print.

3D printing as we know it now is a simple enough premise: an extruder prints filament onto a flat surface. This surface is at a known distance away from said extruder, and is limited to the size of the printer itself. However, in our desired applications, none of these facts can be taken for granted. In the case of printing onto surfaces of unsystematic dimensions and shapes, it is necessary to get an understanding of the surface's characteristics before any printing can be done.

One method of achieving this is itself another application of a robotic arm. A tactile sensor is attached to the end of a robotic arm to accomplish object edge tracing, surface normal and shape recognition. The sensor itself consists of three thin sheets of force-sensitive resistors arranged triangularly with the peripheral circuits [13]. When in use, the arm would extend toward a given object, which could be done autonomously or with human assistance. It would then essentially work its way along the object's surface, using the force sensors to scan and produce a digital model of it.

The implementation of a similar touch-based scanning system could be used in tandem with a printing arm to optimize precision of filament laying. Though pursuing independent development of such a price of technology could be beyond our time and funding frame, it is an interesting concept nonetheless.

2.1.3 Materials

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 a cost, added weight. This weight must be accounted for when determining the design requirements for the motors and gearboxes. If more weight is added that corresponds to increases in loads that must be moved by the drivetrain, 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 ratio is ideal for robotic arm design. This results in common casing materials such as plastics, carbon fiber, graphite, and aluminum. An analysis of the materials and the arm design can be done through a Finite Element Method analysis in order to maximize the strength, stiffness, and payload-to-weight ratio of the robotic arm [13]. One of the advantages of utilizing composites for structures is that in addition to their high strength-to-weight ratio, is the further optimization of the materials for the specific applications by adjusting thickness and angles of the composite layers which can be done through Finite Element Analysis outlined in [20]. However, these optimizations and customizations would add high expenses to a project budget.

2.1.4 Degrees of Freedom

The degrees of freedom of a robotic system are the multiple ways that the system can move. The most common are the three positional movements of the x,y and z axes along with the three rotational movements of pitch, yaw and roll. The amount of degrees is different for every robotic system and varies greatly based on their 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 degrees of freedom needed for the robotic arm will largely depend on the requirements of the printing surfaces. Allowing for a certain redundancy in the degrees of freedom will allow for more fluid motion and easier avoidance of the limits of the joints of the arm [9]. Redundancy in the amount of degrees of freedom will increase the complexity of kinematic analysis of the arm, but will allow for a wider range of surfaces to be printed on. One current design that embraces mobility is the hyper redundant manipulator designed by Chirikjian and Burdrick [18]. Their design involved 30 degrees of freedom 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. A solution with fewer degrees of freedom is found in [7]. Bausch et al. [1] printed on an convex surface and used a 3 axis 3d printer and added 3 rotational degrees of freedom to the base plate of the printer using 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 degrees of freedom need to be used to increase maneuverability.

2.1.5 Drive Trains/Motors

One thing common to many robots is their ability to move. Without any sort of movement in a robot many tasks, such as 3D-printing, are impossible. The drivetrain, the subsystem of a robot that controls the motion of the individual parts or the entire robot, is responsible for creating the kinetic energy required for movements. For the applications discussed in this thesis, the drivetrain will control either the joints in a robotic arm or movement along a set axis if a traditional three-axis 3D printer is chosen. In either application the drivetrain will contain both a motor and a gearbox to move the robot in a controlled manner. The motor translates stored potential energy into kinetic energy 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.

In order to create a cost-effective robot, the drivetrain controlling the joints must not be excessively over-designed. In order to determine the necessary specifications of the drivetrain, multiple factors must be taken into consideration.

$$\mathbf{M}(\theta_i)\ddot{\theta}_i + \mathbf{v}(\theta_i,\dot{\theta}_i) + \boldsymbol{\xi}(\theta_i) = \boldsymbol{\tau} \tag{3}$$

where $\mathbf{M}$ is the mass matrix, $\mathbf{v}$ is the vector of Coriolis and centrifugal terms of the links, $\boldsymbol{\xi}$ is the vector of gravitational forces, and $\boldsymbol{\tau}$ is the vector of joint torques.

Figure 1.2 [16]

$$\tau_{m,i} = \left\{(J_m + J_g)\ddot{\theta}(t)\rho + \frac{\tau(t)}{\rho\eta_g}\right\}_i; \quad i = \mathbf{1},\ldots,5 \tag{4}$$

where ρ_i is the gear ratio, $J_{g,i}$ is the gear inertia with respect to the input motor axis, $J_{m,i}$ is the motor inertia, and $\eta_{g,i}$ is the gear efficiency.

Figure 1.3 [16]

To calculate the required torque at the joints of the arm two equations are needed. Figure 1.2 calculates the required torque at each joint while figure 1.3 calculates the required torque of the motor at each joint when taking the gears into account. The main considerations for motor selection are the nominal torque, stall torque, and the angular velocity of the output shaft [16]. 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, 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 3 main considerations are rated torque output limit, the maximum torque output and maximum input speed [16]. 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 inputs of the motor. 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 jolts that the printer head will experience as it conducts complex movements.

Using robotic arms to accomplish delicate tasks is not a new concept. The medical field already has implementations in the form of surgical robots, which could give us some new insights on how to approach our project as a whole. In particular, advancements in drivetrain technology for said arms could potentially be implemented in an arm of our own making.

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 plurality of metal control cables is expensive and complicates the maintenance of the robotic arms [17]. With this, there has been research into a cheaper and more reliable method in the form of a strap drivetrain.

The basic idea behind this 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 [18]. 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.

2.1.6 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 degrees of freedom. This requires an analysis of the kinematics of the designed arm. A forward kinematic model allows one to represent the position and orientation of the robot's end-effector relative to its base. An inverse kinematic (IK) model takes a desired target position as an input and determines the joint angles in the arm that are necessary for the end-effector to reach said position. Iqbal et al. [7] have developed an IK model for the ED7220C robotic arm which can correctly determine the joint angles for any location within the arm's work envelope with a precision of ±0.5cm. 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. In a paper on inverse kinematics, Cubero [8] 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 order for a 3D printer to operate well, it must be able to move accurately and consistently to coordinates given by the controller. To do this, 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 1.1. They show that going from the orientations of each internal joint q to the position of each part is straightforward. $\mathbf{x} = \mathbf{f}(\mathbf{q})$ where $\mathbf{x}$ is the position of the arm, $\mathbf{q}$ is the orientation of each joint, and $\mathbf{f}$ 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 $\mathbf{q} = \mathbf{g}(\mathbf{x})$ we need an inverse function. [9] shows how this has only one solution when the number of degrees of freedom equals the required degrees of freedom of $\mathbf{x}$. 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.

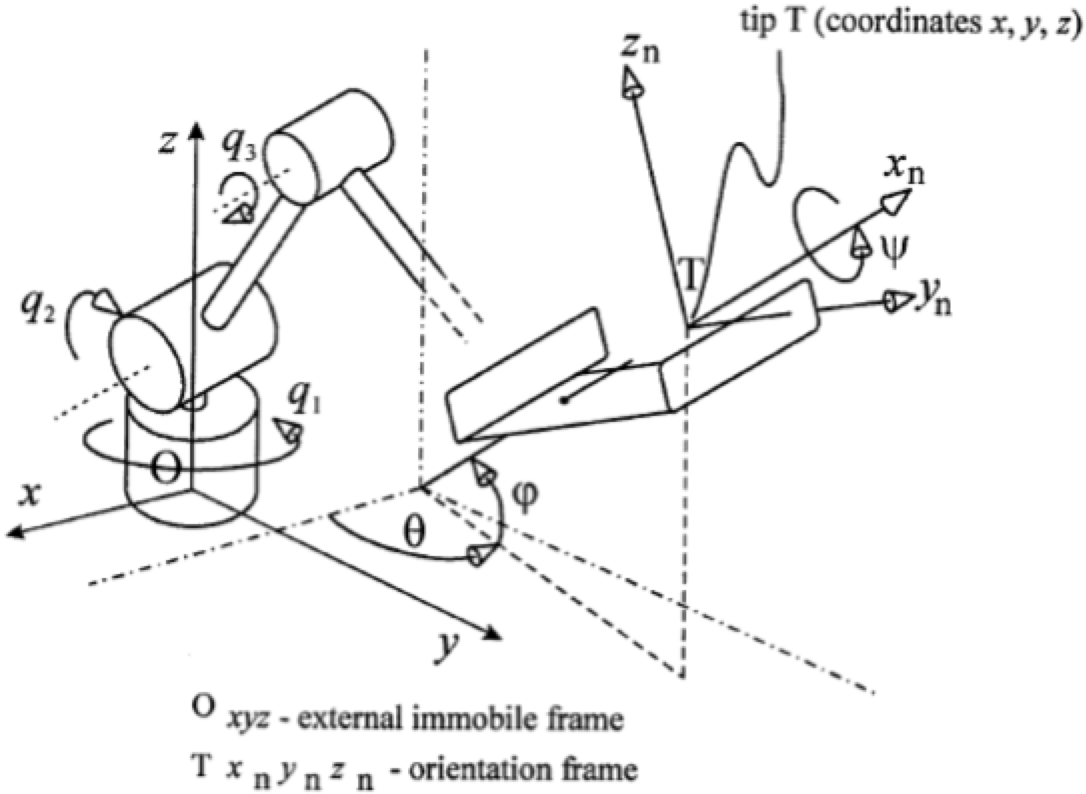


Figure 1.1 [9]

2.1.7 Traditional Three-Axis Printer Exploration and Limitations (Solutions in methodology)

3D printing, though a fairly new concept as a whole, has progressed a great deal in its short existence. With this, the applications have expanded to almost every aspect of STEM imaginable. Though each field has its own unique utilization of 3D printing, one concept that sees indiscriminate use is scale production.

Generally, when it comes to prototyping and modeling, smaller sized examples of a given model are more cost effective and take significantly less time to create. While being beneficial in these aspects, it also allows for a higher degree of customization [14] of the model, making it more feasible to explore radical but potentially fruitful concepts without the commitment to a to-scale example.

Building exact but small scale examples alone economizes vital resources, a key consideration of any large scale research project that has funding concerns. To further advance this, there has been development in printing known as wire printing. Even small scale models take several hours, or even days, to complete printing. To combat this, wireframe previews can be printer alternatively. Rather than printing a solid object layer-by-layer, material is extruded directly into 3D space. 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 [15].

2.2 Extruder Design

2.2.1 Overview

When considering a printer design that would allow for printing on uneven surfaces, important factors include: multiple degrees of freedom and a low profile extruder. The multiple DOF would enable the print to conform to a surface as needed and maneuver into correct orientations which would not otherwise allow for a conformal print. A low profile extruder, or one that is able to fit in confined spaces, provides the printing algorithm freedom in choosing toolpaths. Contributing to the challenge of concave 3D printing is the requirement for the extruder to be able to navigate freely within a given space and apply material wherever it is needed.

2.2.2 Methods of 3D Printing

Aerosol Jet Printing

Due to the interests of the aerospace and electronics industries, researchers have developed a relatively new method of printing that uses aerosolized droplets to deposit materials onto the designated surface. The chosen material must be aerosolized into a liquid with small droplets and then sent through a collimated beam. For best accuracy, these droplets typically have diameters that are between two and five microns. Once this process is complete, the beam leaves the aerosol head at about 80 m/s and the droplets land 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 [22].

Researchers have also found that aerosol jet printing can be used to print on non-planar surfaces, such as surfaces 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 instances such as these decreases the weight of the structure [22].

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 [23].

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 its downsides. 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. Theses 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 [23].

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. 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, the trade-off is that this comes with 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 [24].

Laminated Object Manufacturing

Laminated object manufacturing (LOM) is a process that involves fusing together sheets of plastic materials 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 cuts away excess material in the layers instead of printing the exact shape initially. Due to these differences, objects produced using LOM 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 [24].

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 [24].

2.2.3 Extruder Head Design

General Design

In basics, the 3D printer's extruder works by taking a material, in practice usually the thread of plastic material of some sort, which is then, in turn, heats out and pushes through the nozzle of the extruder [27]. It all starts out in what is called the cold end where the solid cold filament is pushed along a tube in the next direction of the process using a system of gears and a motor [27]. In a very simplistic design such as the Bowden, 3D printer extruder gets clamped on both ends which allows it enough push to move the filament along the tube great distances. Often time a motor is used that is attached to a pointed gear. The whole point of this is in the cold end, the points on the end of the gear can gain traction into the filament that can then be moved along a Bowden's tube, or if its a direct extruder directly to the hot end [28].

The hot end where the solid filament is pushed towards a heated chamber which in turn changes the solid filament into a more liquid one which can be thus be sent out of the nozzle and onto a surface [27]. When using a 3D printer in the manner we want to will involve the nozzle to be much longer and more accurate in order to print in the manner we want it to do. This might make it so that the nozzle might also be slightly heated in order for the filament to not solidify before it is pushed out of the nozzle. There are a lot of different methods for this type of 3D printing and they will heavily depend on the material we are going to be trying to use as the filament [28]. The hot end is usually made up of a heat sink inside a brass nozzle along with a cooling fan to send out the filament [28]. There are many different types of printers though and the cold and hot end can be different in these designs.

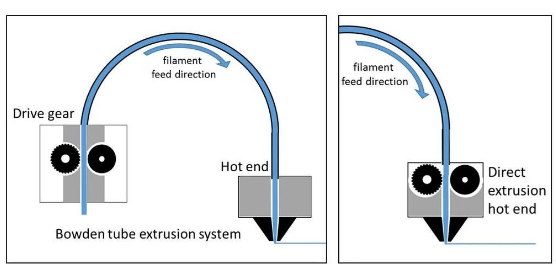


Figure 2.1 [25]

There are two main types of cheaper 3D printer head designs. They are the Bowden printer and the direct drive printer. The main difference between these two is what separates the cold and hot ends of the machine. In a Bowden printer, they are connected to each other by a tube called the Bowden tube [28]. In comparison, the Direct Drive printer does not have this part and instead, the cold and hot parts are directly connected to each other [28]. This means that when the extruder head moves both the cold end and hot end have to move together whereas with a Bowden extruder only the hot end would need to move.

Bowden Printer

Some of the benefits of using a Bowden printer design are that since only the hot end has to move it can print faster due to less weight. It is also more precise and more accurate since it can get to the exact spot it needs to print a lot more easily [29]. Consequently, the problem with this design is due to the tube there is a lot of lag in printing due to the increased distance from the gears in the cold end and hot end [29]. This can lead to large problems with the final product that gets created. Also with the tube, there can be a large number of problems with blocking in the tube. Often times to get around that Bowden printers print with a diameter filament of 3 mm instead of 1.75 mm [28].

Direct Drive Printer

A Direct drive printer exceeds in a lot of the issues that Bowden printers deal with. Due to the short distance between the hot and cold end of the printer has a better response time. This could play massively if we decide to use sensors or things of that nature in our project [28]. This would result in cleaner prints. Also since the motor doesn't need to push the filament through a long tube meaning the torque required from the motor doesn't need to be as large [29]. Lastly, a huge problem with Bowden printers is with the tube there is a lot of oozing and leaking issues that can make prints inaccurate, an issue that Direct Drive printers do not have to deal with [29] That all being said the Direct Drive printer has a lot of issues revolving around how much bigger and heavier the part of the extruder needs to be moved during the print [29]. They can deal a large amount with accuracy causing things like overshooting which can be very problematic. Also, Direct Drive printers deal with frame wobble where due to the size of the extruder that moves, it can result in the whole component wobbling when the extruder moves too quickly [28]. Overall both designs are very different and we will need to look into both to see which will be better for our overall design.

2.2.4 Materials

The material that must be used for printing directly onto a surface must be carefully selected so that it will bond with the surface. Another consideration is the strength of the material as that is important when doing repairs.

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. To optimize control, the material could be 2-component based.

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, and did this for thicknesses of 0.1, 0.2, and 0.3 mm [29] 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 [29]. 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 also an important parameter to consider in additive manufacturing. Researchers at the University of Miskolc, Hungary [30], conducted a study on how changing the extruder head geometry would affect the physical properties of the material, all while keeping the product size and production method constant. They [30] found that a spherical head shape generates the highest extrusion pressure compared to a cone and torus.

Students at the University of Denmark [31] took to the web to create their own 3D printer. They [31] discussed their results in a published paper and wish to help others construct their own. They [31] determined that the extruder head temperature should be set to 190 degrees Celsius for the effective printing of PLA filaments. Aside from that, the students realized lubrication was an issue in such a low budget 3D printer. To solve this, they ran the filament through oil before passing through the extruder head. Finally, they saw that maintaining proper insulation was an issue. To overcome this issue, they [32] used PEEK materials and insulation tape. Overall, they [32] concluded that the extruder is the most problematic aspect of constructing a 3D printer. They [32] replaced the original PTFE material with PEEK. Also, sometimes the PLA material would stick to the internal surface of the extruder head. As stated above, they [32] overcame this by using oil.

2.3 3D Scanning

2.3.1 Overview

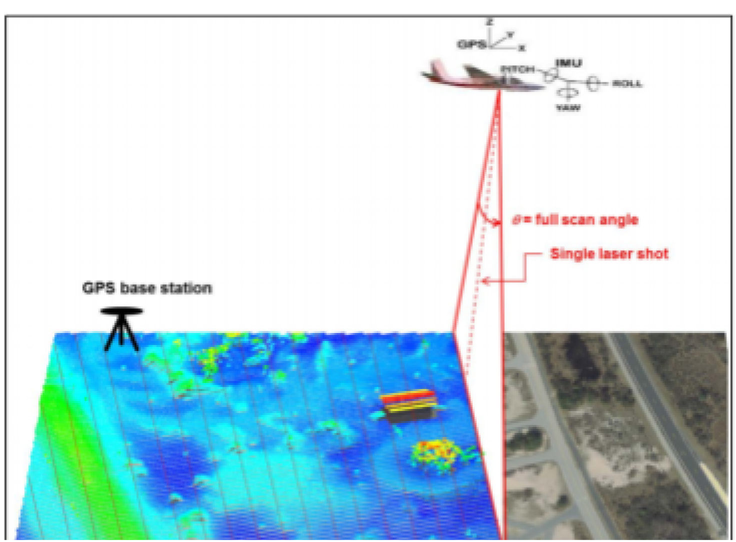
Being able to print onto an unknown and uneven surface first requires an accurate 3D model of the surface to be rendered so that the software knows where and how to print. Lowering the cost of hardware is always useful, but it is especially crucial for the eventual goal of using this technology for in-situ repairs. Typically, the lowest cost 3D scanners are triangulation laser scanners, which operate essentially with only a laser source and a camera [1]. The distance between the laser source and the camera as well as the laser 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, and using these values, the coordinates of the scanned point can be calculated [33]. These types of scanners can be very low-cost, however they require a background surface with known control points to be behind the scanned object in order to calibrate the laser [34]. This means that triangulation laser scanners cannot be used for the types of in-situ repairs that are in the scope of this project.

2.3.1 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 it's way around the surface. [35] and [36] have created systems to do this, but they are exceeding large as the triangulation scanner they use are large. They [35], [36] also required large arms with very high precision because the location of the scanning sensor must be accurately known in order to scan from different positions and have the data line up. 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.

2.3.2 LIDAR

Light Detection and Ranging (LIDAR) technology is often used to construct high-resolution maps of general geography [37]. The laser emitter is typically mounted onto the



bottom of a plane or helicopter (Fig. 3.1). 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 [39]. 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 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 [40]. 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 as seen in figure 3.2.

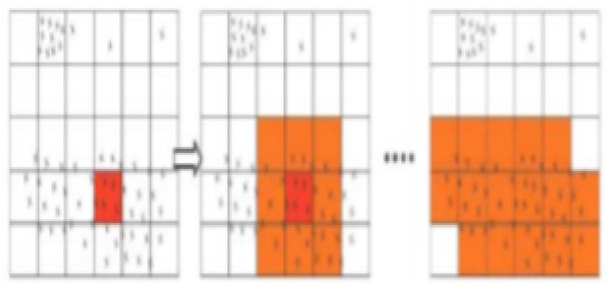


Figure 3.2: An illustration of the neighborhood scheme for noise-detection [40]

2.3.3 Triangulation

Laser-stripe triangulation offers the best combination of accuracy, working volume, robustness,and portability [36]. 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 3D position of the reflecting surface element can then be derived from the resulting triangle. 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 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 1 which gave a field of view 14 cm wide (along the laser stripe) by 14 cm deep.

2.4 Toolpath planning

For the printer to print conformally it will have to be able to create toolpaths that align with the geometry of the print surface. This will involve knowing the print surfaces' geometry and it's 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.

2.4.1 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 it's geometry. Once these geometries are known, to create a path or do any movements at all, the system must know if any collisions will occur so these can be avoided. To determine collision detection, a method called "Oriented Bounding Boxes" (OBB) from [42] 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. [42] 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 [43] 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 this set contains the origin, the two boxes are in collision. This can be seen in this example in 2D from [43] (fig. 4.1).

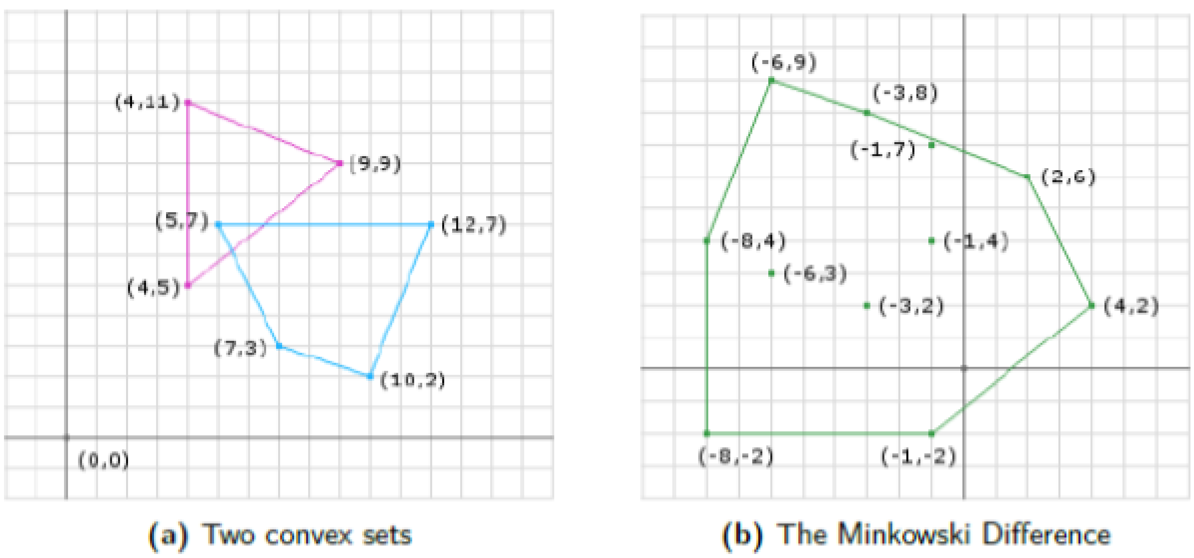


Figure 4.1 []

An OBB of the print surface wouldn't be accurate enough to generate tool paths, so another method must be used. [44] outlines an algorithm that creates progressively smaller OBBs around complex geometry so every vertice 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 [43] 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.

2.4.2 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.

Chapter 3: Methodology

Extruder

Extruder Head Design

Overall our team hopes to build a fully functioning extruder head. This could be either a Bowden or direct drive printer head design. The other option would be buying a 3D printer head design online. To judge 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 [23]. 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.

Materials

The material our team decides to use will depend on two factors: feasibility 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.

Concave Surface Dimensions

The extruder will be tested using a simple concave surface. We will use a hemispherical shape with a diameter of 5-8 cm, and then use PLA to fill in this area using a pre-determined toolpath developed by the software team. 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.

Structural

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) [32]. 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. As this projects aim is to create a proof of concept and not a commercially viable product, the end effector mount would be conducted of a less durable and cheaper material, likely 3D-printed PLA as opposed to something more robust such as metal. Although, a similar system to [12], discussed further in Section 2.1.2, 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.

Traditional Three-Axis Printer Approach (adding degrees of freedom and other considerations)

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. 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.

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.

3D Scanning

We anticipate that improvements to software choice and control methods will reveal themselves over time. However, we anticipate beginning with the software used by Bausch et al. [1]. This would include Rhino for 3D modeling and visualization and Python to pipe data between the extruder interface to the operator and visa versa.

The choice of 3D scanner will have to be investigated thoroughly as this equipment is vital to obtaining information about the surface. Our mentor, Dr. Mitchell, 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 close-range and ranging scans are not suitable for this [39]. 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 possibly be handled by OpenCV packages. Again, more experience is needed with possible methods before definitive choices can be made.

Appendix

Timeline

Fall 2019

1. Completed draft prospectus
2. The goal for the rest of the semester is to finalize a design and order any parts over winter break
3. Draft Presentation in November (informal)

Spring 2020

1. Complete and defend proposal
2. Apply/prepare for grants
3. Begin design implementation and testing of methods

Fall 2020

1. Do Good Showcase
2. Systems testing
3. Construction and integration
4. Integration testing

Spring 2021

1. Results and findings are written into thesis
2. Integration testing and optimization

Fall 2021

1. Continue integration testing and optimization

Spring 2022

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

Budget

Printer Head: E3D Titan Aero 1.75mm Standard 12V Full Aero Kit	https://www.amazon.com/Genuine-E3D-Standard-Bracket-TITAN-AERO-ST-175-12V/dp/B07B6788Y7/	$132.00
PLA: PLA Filament 1.75mm with 3D Build Surface	https://www.amazon.com/HATCHBOX-3D-Filament-Dimensional-Accuracy/dp/B00J0ECR5I/	$20.00
Robotic Arm/Traditional 3-axis printer	https://www.google.com/search?safe=active&tbm=shop&q=lightweight+robotic+arm+6+dof&tbs=vw:g,mr:1,price:1,ppr_min:500	$1000 - $4000
	https://www.google.com/search?safe=active&tbm=shop&q=3d+printer&tbs=vw:l,mr:1,cat:6865,root_cat:529682,price:1,ppr_min:500,ppr_max:1000	$500 - $3000
6 Stepper Motors	https://www.amazon.com/STEPPERONLINE-Stepper-Bipolar-Connector-compatible/dp/B00PNEQKC0/	$84
Total		$736 - $4236

Glossary

DOF: degrees of freedom

EVA: Extravehicular Activity

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