ABSTRACT

| Title of thesis: | IN SITU CONFORMAL 3D PRINTING FOR TARGETED REPAIRS |
| --- | --- |
|  | Team PRINT: Rohith Chintala, Brendan Cutick, Tyler Han, Elizabeth Myers, Eric Oh, Aidan Sandman-Long, Cynthia Sheng, Nathan Spicer-Davis, Kenji Tsukamoto, Nick Webb, Erik Zavorin |
| Thesis directed by: | Dr. Steven Mitchell  Department of Mechanical Engineering |

Additive manufacturing is a technology that effectively enables the almost limitless creation of any structure. With the help of toolpath algorithms and material properties, modern 3D printers are able to deposit filament with high precision in pre-computed locations to construct structures rapidly and autonomously. We propose that this same technology can be applied within the context of repairs. In this paper, we investigate the implications of such a proposal by conducting a review of current research in robotic manipulators, 3D printer extruders, 3D scanning methods, as well as conformal printing and toolpath generation. The proposal is concluded with a preliminary analysis of the required resources, testing methods for data collection, and potential design considerations for implementing a reparative in situ 3D printer.

Team PRINT Proposal

by

Rohith Chintala, Brendan Cutick, Tyler Han, Elizabeth Myers, Eric Oh, Aidan Sandman-Long, Cynthia Sheng, Nathan Spicer-Davis, Kenji Tsukamoto, Nick Webb, Erik Zavorin

We pledge on our honor that we have not given or received any

unauthorized assistance on this assignment.

# Table of Contents

[**Chapter 1: Introduction**](#_ybzbpdsq7l6o) **5**

[**Chapter 2: Literature Review**](#_87dwtcqry5ji) **7**

[2.1 Introduction](#_k2p3u38o1exr) 7

[2.2 Structures](#_nvtd1pyn44gl) 11

[2.2.1 Overview](#_b81regwubfvl) 11

[2.2.2 Degrees of Freedom](#_wx8yxctd94u6) 11

[2.2.3 Robotic Arms in Other Applications and Modular Attachments to Robotic Arms](#_dduq1pajhlcv) 13

[2.2.4 Kinematic Model and Inverse Kinematic Model](#_asiaagz841dw) 15

[2.2.5 Traditional 3-Axis Printer Exploration and Limitations](#_84ze315c5st2) 17

[2.2.6 Drive Trains/Motors](#_3nrc6qjc0g55) 17

[2.3 Extruder Design](#_o6qwtctw03yq) 20

[2.3.1 Overview](#_4rok81spnmw) 20

[2.3.2 Methods of 3D Printing](#_e84s0jqutj4s) 20

[Aerosol Jet Printing](#_2pn5bj1au7p8) 20

[Electrohydrodynamic Printing](#_av53njds0ljn) 21

[Fused Filament Fabrication](#_iemo11enypt5) 22

[Laminated Object Manufacturing](#_frducua7bf2r) 23

[Selective Laser Sintering](#_kvlqsibw68b2) 23

[2.3.3 Extruder Head Design](#_9swj0utdto2g) 24

[General Design](#_e0hnu8cwe0ny) 24

[Bowden Printer](#_tqdr3an16fio) 26

[Direct Drive Printer](#_kpm8jdlxv509) 26

[2.3.4 Extruder Materials](#_oqreqe8mrv91) 27

[Tensile Strength of PLA](#_yaat2zefoy8z) 27

[Extruder Design and Parameters](#_czc064kh02dv) 28

[2.4 Sensing and Planning](#_p3n5xbkcnei4) 30

[2.4.1 Overview](#_cy6th42drqev) 30

[2.4.2 Light Detection and Ranging](#_h677mb2y39nx) 30

[Noise in LIDAR Data](#_336r1dqxevvg) 31

[2.4.3 Triangulation](#_28urougg9690) 31

[2.4.4 Tactile Scanning](#_kr0x1d87xk9v) 33

[2.4.5 Scanning Using a Robotic Arm](#_bp78tg6omwg) 33

[2.5 Toolpath planning](#_xdl360xuovqs) 35

[2.5.1 Overview](#_oxp1qlb2g9bz) 35

[2.5.2 Geometry](#_jnagd7fshhdn) 35

[2.5.3 Pathing Algorithms](#_zcmhvnvw8l48) 37

[2.6 Conclusion](#_6rn961sfwme7) 38

[**Chapter 3: Methodology**](#_jt8fe3g9c89r) **40**

[3.1 Overview](#_4xyp0dw2byes) 40

[3.2 Structural](#_mcdojsx5bzkg) 41

[3.2.1 Robotic Arm Approach](#_e8frdzufei3r) 41

[3.2.2 Traditional 3-Axis Printer Approach](#_o8arwj39vx91) 42

[3.2.3 Testing Methods](#_4tb4yg46awkl) 43

[3.3 Extruder](#_q2x8bjvhqbui) 45

[3.3.1 Extruder Head Design](#_4vcgdwnlf6h0) 45

[3.3.2 Materials](#_lw953tu12ea5) 45

[3.3.3 Concave Surface Dimensions](#_nz3z18d5o231) 46

[3.4 Sensing and Planning](#_mymi7shgemsm) 47

[3.4.1 Software](#_c8qwrdkgygx7) 47

[3.4.2 Scanning Hardware](#_ctjvdo1qpbid) 48

[3.4.3 Toolpathing](#_au9owu2oraqv) 49

[3.5 Conclusion](#_tioklvxh180g) 50

[**Appendix**](#_cgyhg0t9xaio) **51**

[I. Timeline](#_v24kxucq66nv) 51

[Fall 2019](#_wmrxvcnu4whj) 51

[Spring 2020](#_vv6rqqmcwm83) 51

[Fall 2020](#_8kg7qmtng945) 51

[Spring 2021](#_67ad1v7m3xcz) 52

[Fall 2021](#_9r3tvv3knxa) 52

[Spring 2022](#_r51c5ukgqipq) 52

[II. Budget](#_o45z8tqxvhi4) 54

[Manipulator Options](#_8c7xvectlyu) 54

[Extruder Options](#_n4pmwjy5uyqc) 54

[3D Scanning Options](#_4kkowwdfq4l) 55

[III. Mentor Feedback](#_nj9yjsdimai) 56

[IV. Glossary](#_xp3daepk9nxa) 57

[**References**](#_nxvrp6zd6y1b) **59**

# 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 new 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? These questions combine into the general guiding question: How can a proof of concept for a conformal in situ printer be constructed?

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 [[1]](https://www.zotero.org/google-docs/?xKQN8r). 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. 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 [[2]](https://www.zotero.org/google-docs/?wQG2CP) are prime examples. This technology would not only allow repair in hard to reach places, but also allow missions to carry fewer replacement parts, lowering mass and volume requirements and reducing costs for space travel. 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 proposal provides a literature review in Chapter 2 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. By the end of the paper, we aim to show that there exists methods which make in situ additive manufacturing possible, that it warrants further research and a practical implementation.

# Chapter 2: Literature Review

## 2.1 Introduction

The following literature review presents a survey of recent or related research that may aid the development of an in situ 3D printer in the areas that appear to require the most attention. In pursuance of a printer applied to in situ reparative printing, we seek an implementation that is capable of scanning, navigating, and executing toolpaths without manipulating the print environment frame and is able to demonstrate a conformal concave print. A notable work from Bausch et al. [[3]](https://www.zotero.org/google-docs/?EFvBDj) has previously proposed the concept of an in situ conformal printer using the design of a modified Prusa i3 commercial 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 [[4]](https://www.zotero.org/google-docs/?4Wl7sV). The researchers were able to obtain point cloud 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 [[4]](https://www.zotero.org/google-docs/?y2Cjm4) as originally planned in the design proposal.  
 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 [[5]](https://www.zotero.org/google-docs/?i10rL8). This includes wheel damage that has led to the mission sites being restricted to relatively flat terrain that is not rocky [[5]](https://www.zotero.org/google-docs/?pFnCwt). 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 [[6]](https://www.zotero.org/google-docs/?3Ix4Gk). It is also important to note that the wheel thickness is minimal and only .75 mm thick [[6]](https://www.zotero.org/google-docs/?Y7YM6k). 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 [[7]](https://www.zotero.org/google-docs/?FFEcUh) 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 [[2]](https://www.zotero.org/google-docs/?YZATG4) | Image of Curiosity Rover Wheel Damage with White Lines Indicating Measurements in Table 2.1 [[2]](https://www.zotero.org/google-docs/?GDK65H). |
| **Figure 2.1** | |

| **Table 2.1** Estimated Lengths of Holes and Cracks in Figure 2.1 [[2]](https://www.zotero.org/google-docs/?mMbODw). | |
| --- | --- |
| **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 can also be found in the aviation industry. [[1]](https://www.zotero.org/google-docs/?vu2jIl) describes how an in situ 3D printer can be used to repair components more easily than welding (the current method). 3Dprinting has a lower operating temperature than welding, eradicating the struggle of thermal damage to components normally caused by welding. [[1]](https://www.zotero.org/google-docs/?2zw0Fx). This advantage allows parts to be repaired to near net-shape condition with less wasted material and a stronger finish [[1]](https://www.zotero.org/google-docs/?xPS1bh). The process is also especially useful in the aviation industry because parts must have specific contours that can be more easily matched by conformal printing to decrease drag [[1]](https://www.zotero.org/google-docs/?8Bq4nM).

King [[8]](https://www.zotero.org/google-docs/?5mOpPn) 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]](https://www.zotero.org/google-docs/?U0n9yO). 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.

In addition to spaceflight, another application that this research more actively investigates is the potential for repairs on aircraft and vehicles utilizing a carbon-fiber reinforced PLA. If the original manufacturing involved a specific layup sequence, these patterns can be replicated in the repair. These composites are chosen in these applications because of their high stiffness-to-weight ratio that is required for flight [[9]](https://www.zotero.org/google-docs/?spxgjs). They may also be further optimized by modifying the orientations of layers relative to each other to increase the material strength in additional directions [[9]](https://www.zotero.org/google-docs/?RGzW8s). Aircraft undergo damage throughout their life and averaged 972 damages to composites per one million flight hours on average [[10]](https://www.zotero.org/google-docs/?LHJW6w). In our research, we will test the material properties of specimens with 3D printed repairs of various lay-up sequences with carbon reinforced PLA and controls with no repairs to determine the potential for this technology.

In the following sections, we discuss literature related to the aspects of the project that require immediate attention for implementation. In Section 2.2, the choice and design of the manipulator is discussed and presented. In Section 2.3, the design and possible improvements to the extruder of the printer are assessed. In Section 2.4, viable scanning methods are introduced. In Section 2.5, toolpath generation and related algorithms are discussed. An overview of the sections and concluding remarks are made at the end of the literature review.

## 

## 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. However, DOF are unlimited and may be increased through additional joints or linear motion on new axes. 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 [[11]](https://www.zotero.org/google-docs/?MHsiuc). 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 Burdrick [[12]](https://www.zotero.org/google-docs/?ehsq83). 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, Team PRINT’s research 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 was used by Bausch et al. [[3]](https://www.zotero.org/google-docs/?vWMC7r) who 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 [[3]](https://www.zotero.org/google-docs/?DoZ5mQ). Their targeted printing surface was a curved convex surface with nothing obstructing the path of the printer head [[3]](https://www.zotero.org/google-docs/?wcHlSd). 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. Kubalak et al. [[13]](https://www.zotero.org/google-docs/?yD70Tj) found 6 DOF successful for the implementation of their 3D printing which is similar to our usage of a robotic arm. More DOF can be added to increase applications in the future, but 6 DOF is necessary and most feasible for a functioning design.

|  |
| --- |
| **Figure 2.2** Example 6 DOF robotic arm |

### 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 [[14]](https://www.zotero.org/google-docs/?kBxAa7). The first industrial arm was used in a General Motors plant and soon after robotic arms became common for factories in the 1960s [[14]](https://www.zotero.org/google-docs/?nrdDA8). From this, they began developing robotic arms which mimicked the human anatomy and kinesiology of the shoulder and the human arm [[14]](https://www.zotero.org/google-docs/?LGzX6y). While the degrees of freedom vary significantly, it is common for robotic arms to have around 7 DOF, the same as the human arm [[14]](https://www.zotero.org/google-docs/?WE9FBj). Therefore, additional DOF will not be required if a robotic arm approach is taken.

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 [[15]](https://www.zotero.org/google-docs/?KQSPSB) 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 support in the manufacturing process [[15]](https://www.zotero.org/google-docs/?1aXJAg). Gosselin et al describe other concrete printers that all require using temporary supports due to a fewer amount of DOF [[15]](https://www.zotero.org/google-docs/?jl0nva). 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. [[16]](https://www.zotero.org/google-docs/?6BC0ZY) 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 [[16]](https://www.zotero.org/google-docs/?ZLx5SE). 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 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. [[17]](https://www.zotero.org/google-docs/?kUZmQV) 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 ±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. Cubero [[18]](https://www.zotero.org/google-docs/?8d18ye) 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. [[11]](https://www.zotero.org/google-docs/?cRADTK) describes the kinematics of a robotic arm where each joint has 1 DOF as shown in Figure 2.3. They show that going from the orientations of each internal joint q to the position of each part is straightforward. where is the position of the arm, is the orientation of each joint, and 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 an inverse function is needed. [[11]](https://www.zotero.org/google-docs/?k5H0BD) shows how this has only one solution when the number of degrees of freedom equals the required degrees of freedom of . 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 [[11]](https://www.zotero.org/google-docs/?0aetcE). This allows us to generate orientations of the joints that would put the arm in the required position. Then, a final can be chosen that is quickest to get to. This process is described in Section 2.5 Toolpath Planning.

|  |
| --- |
| **Figure 2.3** Simple 2-DOF arm with kinematic model |

### 2.2.5 Traditional 3-Axis Printer Exploration and Limitations

Using a traditional 3-axis 3D printer is one potential approach to 3D printing onto uneven, concave surfaces. Unfortunately, there are multiple limitations unique to this method. The main limiting factor of using a traditional 3-axis 3D printer is the fact that there are only 3 DOF. However, in Section 2.2.2, solutions to this problem in [[3]](https://www.zotero.org/google-docs/?WNHmOy) 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.

### 2.2.6 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. 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 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 and the motor torque can be calculated using the gear ratio, gear inertia, motor inertia and gear efficiency [[19]](https://www.zotero.org/google-docs/?cYvXkP). The main considerations for motor selection are the nominal torque, stall torque, and the angular velocity of the output shaft [[19]](https://www.zotero.org/google-docs/?V5aqZi). 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. More important is the repeatability and step angle of motors. Step angles are typically relatively large, commonly 1.8°, which is too large for the precision required for 3D printing. Therefore, microstepping may be implemented to artificially reduce the step angle and increase the smoothness of movements. Unlike gearboxes, microstepping does not change the output torques or change the maximum speed. However, because the maximum speed of movement will be relatively small for 3D printing, this advantage of microstepping is irrelevant. 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 [[19]](https://www.zotero.org/google-docs/?2NJ3Lx). 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, however, the use of the numerous metal control cables is expensive and complicates the maintenance of the robotic arms [[20]](https://www.zotero.org/google-docs/?lJOIZh). 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 [10].

## 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, the size of the extruder body, and the materials used in the extrusion process. A typical 3D printer uses very specific dimensions when describing extruder parts; however, for our purposes it is important 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

Manufacturers utilize 3D printing in a variety of different ways depending on the application. Not every application is the same, so naturally, engineers have developed different methods of 3D printing. While the most common method is Fused Fabric Fabrication, this section discusses and compares alternative techniques. These techniques are used in various industries and were all considered for use in this research.

#### **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 [[21]](https://www.zotero.org/google-docs/?6ZDUb6).

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 [[21]](https://www.zotero.org/google-docs/?zfnInc).

#### **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 [25]. 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 [[22]](https://www.zotero.org/google-docs/?VlF9eZ).

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 [25]. 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 [[22]](https://www.zotero.org/google-docs/?KhsL8m).

#### Fused Filament Fabrication

Fused Filament Fabrication (FFF), or more commonly known as 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 [[23]](https://www.zotero.org/google-docs/?Juy95x).

#### **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 FFF 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 [[23]](https://www.zotero.org/google-docs/?OjnQ0b).

#### **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 FFF. 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 [[23]](https://www.zotero.org/google-docs/?hdioV5).

For the purpose of our project, we will use the FFF method. We do not need our project to be durable or of the best standards. Our project is a proof of concept, and the benefits of FFF match our design needs. The inexpensive material, easy on-campus access, and relatively low melting points make this technique the best choice to experiment with. In addition, the FFF method will be easiest to work with due to the simplicity of the extruder head and heating method in comparison to other methods. Our innovation of the extruder head requires heat dispersion through a longer nozzle, and the process of building and testing would be significantly more difficult with a more complicated method of 3D printing.

### 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 until pliable. The material is then 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 such 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].

Extruder head shape is one of the main parameters to consider in additive manufacturing. Researchers at the University of Miskolc, Hungary [24], 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.

|  |
| --- |
| **Figure 2.4** Comparision between Bowden and Direct Drive extruders |

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 [[24]](https://www.zotero.org/google-docs/?NNcX51). This tube creates separation between the hot and cold ends. In comparison, the Direct Drive printer places the cold and hot parts directly against each other [[24]](https://www.zotero.org/google-docs/?RGJu0F).

#### 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 [[25]](https://www.zotero.org/google-docs/?CInyVx). A consequence is this can lead to irregularities in 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 [[24]](https://www.zotero.org/google-docs/?DuDFWs).

#### Direct Drive Printer

A Direct Drive printer excels 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. In addition, less torque is required from the motors due to the decreased distance the filament travels [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 depend on many factors such as cost, feasibility, and the application of the product.

### 2.3.4 Extruder Materials

For the purpose of our project, we seek to acquire a material that can carry the biggest stress while keeping the melting temperature at the operating temperature of our extruder head, which is 200 degrees Celsius. Our main focus in the extruder material lies in the durability and strength of the polymer. The two plastic filaments we have in mind are PLA and Carbon-fiber reinforced PLA (CFPLA). Effective in-situ repairs will require a filament that closely resembles the material properties of the surrounding body; if it does not, the repair is worthless. An example of this is seen in a small aircraft wing. The wing endures high stresses, and if the material we use cannot hold up to those standards, our repair will fail.

It may be easy to assume that CFPLA can carry a higher stress than PLA before yielding. However, for our project, we also have to consider other factors such as melting point and adhesive properties. If CFPLA proves to be lacking in these categories, we may opt with PLA. For these reasons, it is necessary to investigate the differences between the two.

#### PLA

#### CFPLA

The print settings used for effective printing of PLA are very similar to that of CFPLA. The melting point is still anywhere from 200-230 degrees Celsius, and the bed adhesion will behave similarly to PLA. However, the added fibers in the filament can cause clogging and increasing oozing while printing. Experts recommend using a hardened steel nozzle to prevent damage to the extruder. To prevent clogs from starting to form in the tube, experts also suggest initially reducing the print speed by 25-50%. These tradeoffs must be considered when deciding on a filament to test for our extruder.

Carbon Reinforced PLA is a material steadily increasing in popularity due to its strength and ability to be 3D printed. There are two types of this material with the first being short fiber reinforced thermoplastics (SFRT) and the second being continuous fiber reinforced thermoplastics (CFRT) [[26]](https://www.zotero.org/google-docs/?rMiJHb). Short fiber reinforced thermoplastics consist of small pieces of carbon fiber embedded in the PLA filament. Continuous fiber reinforced thermoplastics consist of a long strand of carbon fiber embedded into the filament usually during the process of printing.

For continuous fiber reinforced thermoplastics, flexural strength was found to increase with higher printing temperatures up to 240 degrees celsius where inaccuracy of the print started to rise [[27]](https://www.zotero.org/google-docs/?WphIuy). Strength also increased as layer thickness decreased and hatch spacing decreased and it reached a high with a feed rate of 80 mm per minute before decreasing slowly. The flexural strength of the tested continuous carbon fiber composite was able to reach a maximum of 335 MPa with a carbon content of 27%[[27]](https://www.zotero.org/google-docs/?AvWWzJ).

## 2.4 Sensing and Planning

### 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. This allows the software to determine where and how to print. 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. The primary methods of 3D Scanning involve ranging with LIDAR and triangulation methods. 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 Light Detection and Ranging

Light Detection and Ranging (LIDAR) technology is often used to construct high-resolution maps of general geography [[28]](https://www.zotero.org/google-docs/?39r7UK). 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. This reduces the amount of error that would otherwise occur in time-of-flight based technology. 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 errors in the range of some millimeters [[29]](https://www.zotero.org/google-docs/?wzCT2r). Considering that commercial 3D printers offer nozzle sizes in the range of tenths of millimeters, error of this magnitude is undesirable as this would cause misalignment or overall failure over multiple layers. An implementation of in situ printing utilizing ranging techniques would require additional consideration of the suitable print profile and improved filtering methods (discussed below).

#### 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 printing in a space environment 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 [[30]](https://www.zotero.org/google-docs/?FxnIGN). 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.

### 2.4.3 Triangulation

Typically, the lowest cost 3D scanners are triangulation laser scanners, which generally operate with only a laser source and a camera [[3]](https://www.zotero.org/google-docs/?E9uxOi). This method offers the best combination of accuracy, working volume, robustness, and portability [[31]](https://www.zotero.org/google-docs/?UVN7db). 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 laser beam itself that is 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 2.5. Using these values, the coordinates of the scanned point can be calculated [[32]](https://www.zotero.org/google-docs/?AkxoQf). The 3D position of the reflecting surface element can then be derived from the resulting triangle.

|  |
| --- |
| **Figure 2.5** Simplified Laser Triangulation |

An important factor that must be considered while doing in situ 3D printing is the resolution. The Michaelangelo project [[31]](https://www.zotero.org/google-docs/?toptCc) was able to scan statues with enough detail to capture the chisel marks. The resolution acquired was 250 microns along the laser stripe and depth resolution of 50 microns which gave a field of view 14 cm wide (along the laser stripe) by 14 cm deep. This resolution should be more than what would be necessary to perform conformal printing. An implementation of an FFF conformal printer [[33]](https://www.zotero.org/google-docs/?aGpb16) used a resolution that was the same size as the filament width (400 microns). Their [[33]](https://www.zotero.org/google-docs/?O75SHu) implementation used a mathematical function for the surface, so it is most likely possible to perform this with even lower resolutions.

### 2.4.4 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. A tactile sensor can be attached to the end of a robotic arm to accomplish object edge tracing, surface normal, and shape recognition [[34]](https://www.zotero.org/google-docs/?IZ02yY). 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 [[34]](https://www.zotero.org/google-docs/?48L2Ol). 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. An effective implementation of this method of sensing is complex and may take additional development time. Its implications on planning is further discussed in section 2.5.

### 2.4.5 Scanning Using a 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 have the data match 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.

## 

## 2.5 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, both the geometry of the surface as well as the geometry of the print arm will 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 [[35]](https://www.zotero.org/google-docs/?WTRc26) 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. [[35]](https://www.zotero.org/google-docs/?jFsovV) 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 [[36]](https://www.zotero.org/google-docs/?RusgV5) 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:

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 [[36]](https://www.zotero.org/google-docs/?OklxRC) (fig. 2.6).

|  | |
| --- | --- |
| Two Convex Polygons | Minkowski Difference |
| **Figure 2.6** Minkowski difference between two colliding convex polygons | |

An OBB of the print surface would not be accurate enough to generate tool paths, so another method must be used. [[37]](https://www.zotero.org/google-docs/?7VKnVS) outlines an algorithm that creates progressively smaller OBBs around complex geometry so every vertice does not 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 [[36]](https://www.zotero.org/google-docs/?FJIlSA) 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. [[4]](https://www.zotero.org/google-docs/?puevk2) 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. Other researchers [[33], [38]–[40]](https://www.zotero.org/google-docs/?vsAxTY) have also used similar methods. The technique of using iso-curves has been proven to be useful in non-planar printing. In theory, the strategy should be applicable to conformal in situ printing as well.

## 

## 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 perform research and development on their respective goals. A group dedicated to the extruder will evaluate potential designs and materials for permitting this component to successfully perform an in situ print. A second group will be reconsidering the possible design for a manipulator and its kinematics. Finally, a third group will be developing and testing algorithms for in situ conformal printing. The groups are divided so that research can occur independently, but the final product ultimately relies on an integration of these systems (see Timeline in Appendix). In theory, well-tested subsystems should integrate with little resistance into the final product.

## 3.2 Structural

### 3.2.1 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) [[13]](https://www.zotero.org/google-docs/?50BK8J). 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 [[16]](https://www.zotero.org/google-docs/?C14pWQ), 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. The best way to keep costs at a minimum will be to utilize available university resources. The Robotics Realization Lab at the University of Maryland houses a UR3E, UR5E, and a KUKA LBR IIWA 7 800. Because of ease of use, the UR3E and UR5E arms will be the main arms considered. All of these robotic arms have the required degrees of freedom for the project and a low error position repeatability. While traditional 3D printers have z-axis position repeatability of less ±0.01mm [[41]](https://www.zotero.org/google-docs/?JqF4E9), the pose repeatability of the ABB IRB 1200-7/0.7 used in [[13]](https://www.zotero.org/google-docs/?M9rVr1) is ±0.02mm. The pose repeatability of both the UR3E and UR5E are both ±.03mm [[42]](https://www.zotero.org/google-docs/?nFAFvo). Therefore, a pose repeatability of ±0.03mm should also be suitable without significant issues. The UR3E and UR5E arms have respective maximum payloads of 3 and 5 kg both of which are large enough to support a 3D printer [[42]](https://www.zotero.org/google-docs/?U1wJn5). They also both have a ISO 9409-1-50-4-M6 tool output flange which will be used to mount the extruder assembly [[42]](https://www.zotero.org/google-docs/?cHqaxp). Therefore, both of these robotic arms will be applicable for our project and will likely be our chosen method of structure manipulation and positioning.

### 3.2.2 Traditional 3-Axis Printer Approach

In order to print on an uneven surface as is the goal of this project, a traditional 3-axis printer would need to be modified to have additional degrees of freedom. Bausch et al [[3]](https://www.zotero.org/google-docs/?iCNh5y) accomplished this in their prototype printer by adding three stepper motors to allow rotation about all three axes. The two most likely options we would use to accomplish this are either adding rotational capabilities to the baseplate of a printer or by modifying the extruder itself to allow rotation. A rotating base plate 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. Due to the limitations of a traditional 3-axis printer as well as our easy access to multiple robotic arms via UMD’s Robotics Realization Lab, we will be pursuing the robotic arm approach and will no longer consider the 3-axis printer approach.

### 3.2.3 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 will be tested for accuracy and maneuverability. This will both be conducted with and without our mount and 3D printer attached in order to test the error our mount design adds. Furthermore, the original testing will provide an idea of what constraints need to be placed on printing sites 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.

In addition to the movement of the mount, we will also need to test how the mount reacts to the temperatures it will be exposed to by the hot end of the 3D printer extruder. This testing will first be done separately from the extruder subteam and we will use thermometers and a method of controlled heating to test if the mount and motors will be compromised structurally or electronically by temperatures that the hot end will reach. Furthermore, this test will be conducted with the extruder subteam when the extruder is built before everything is integrated and tested on the robotic arm.

Other integration tests with the extruder subteam will include test prints. First a print will be completed on a flat surface with minimal layers. Secondly, a print will be tested on a surface that requires rotation along one axis but is printed on the same plane. Finally, a print will be tested of similar geometry to our final print.

## 

## 3.3 Extruder

### 3.3.1 Extruder Head Design

The path forward for our team revolves around the physical construction of the extruder head. Thanks to the help of the Robotic Realization Lab, we have access to a fully-functioning 6 degrees of freedom robotic arm. The team will design an attachment that can slide on and off of the arm, allowing us to use the arm for the duration of the project. We plan to utilize on campus 3D printers to create the part. An added benefit of the attachment is the flexibility this brings our team in terms of scheduling times to use the arm. This will be a multi-year project, and we must be able to share the arm with other organizations on campus. We will construct our own extruder using premade parts; however, we will remove the tip and replace it with an extended length copper tip. The new tip will be 3 cm longer than the original tip to allow for rotation along the z-axis of the printer arm. Copper is an extremely good conductor of heat, and because our extension is only 3 cm, we anticipate that the material will still be able to flow through the copper tip. If this is not the case, we plan to wrap a thin wire around the extended tip and use this to provide additional heating. We will also have multiple sensors on the extruder at all times that help to monitor movement and temperature. Once we ensure the extruder head is functioning as it should, we will begin integrated testing with the Structures team and begin work on combining the two teams.

### 3.3.2 Materials

Our team has opted to use CFPLA filament for the repairs since regular PLA will not be sufficient enough for our purposes. CFPLA is cheap, is readily available, and adds additional structural integrity. Although, the melting point of CFPLA has a wide range of anywhere between 200-230 degrees Celsius. Given that our first tests are a proof of concept, using an expendable, yet sturdy material such as CFPLA makes the most sense. Other researchers who experiment with small-scale 3D printing recommend the use of plastic filaments [24].

### 3.3.3 Concave Surface Dimensions

We will test our extruder by using a simple concave hemispherical surface. As discussed in Section 2.1, the first test void to be filled will be 3 cm in radius. The software team will develop a toolpath that the extruder can follow to fill with our carbon fiber reinforced PLA. The size of the first test site is within the range found for one of the possible applications, which is repairing rover tires [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 more closely resembles the tire repair application.

### 3.3.4 Feed Rate and Gear Spin Rate

Two important variables that we will need to be able to control are the feed rate and the gear spin rate. The feed rate is defined as the volume of material that can be extruded per second (, and can be calculated theoretically with the hot end temperature, nozzle size, and filament diameter. The gear spin rate is how fast our gears will spin to feed the filament to the hot end, and is measured in radians per second (). For example, 1.75mm ABS on a printer with 0.40mm nozzle has a feed rate of 13.5 . Depending on the path of the extruder head, the feed rate may have to be adjusted once we begin printing on concave surfaces. The only way to control this is by changing the gear spin rate. One of our goals is to be able to model this system as a differential equation to ensure we have complete control over the feed rate.

## 3.4 Sensing and Planning

### 3.4.1 Software

The choice of software and manipulator control methods will depend primarily on their convenience and deployment time. Depending on the robotic arm that is available to us for research, the Robot Operating System (ROS) architecture can aid in quick prototyping and development for low-level control. Research-related software such file formatting, file transfer, and the in situ slicing tool will be written in the Python programming language. There are many open source slicing tools that can be referenced for development. This choice of programming language is due to the fact that we do not put significant restraints on performance or efficiency, so instead we opt for convenience and faster development time. For mesh processing, the Point Cloud Library (PCL) an OpenCV package is able to process point cloud data from a 3D scan into a usable mesh file. The choice of file format will depend on the algorithm developed to slice the reparative print. A logical block diagram to represent data flow is shown in figure 3.1.

|  |
| --- |
| **Figure 3.1** Logical Flow of System Data |

### 

### 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 [[29]](https://www.zotero.org/google-docs/?EomGBc). 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. One option in the OpenCV library is the Point Cloud Library package. The library is a large scale, open project that is capable of 3D point cloud processing, including filtering outliers and object recognition.

### 3.4.3 Toolpathing

There has been research conducted in developing algorithms to execute conformal and in situ printing toolpaths. One method, described in Chapter 2 [[3], [4], [33], [38]–[40]](https://www.zotero.org/google-docs/?O8Fs6p) 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 [[4]](https://www.zotero.org/google-docs/?eKzn8U).  
 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.

## 3.5 Conclusion

The final product will be an integrated version of all the subsystems. Each subsystem has its own goal ultimately contributing to the task of an in situ print. The division supports independent development for each subteam. Thus, every subsystem is, in theory, capable of integrating without significant changes.

The group focused on the research of the extruder will be testing for successful designs which permit in situ printing, specifically for the challenges unique to the print head. This includes parameters such as minimizing its profile and material slippage.

Research relating to the spatial manipulation of the print head will be investigated by the structures subteam. Successful research in this subteam will result in a design with maximized DOF for the print head.

Scanning and toolpathing are explored by the final subteam. Expected results are a suitably efficient scanning method and toolpath algorithm when both in situ and conformal challenges are considered.

Results from each task will be evaluated to determine the timeline of preparing the final product. A successful overall project will prove that there exists a design capable of performing an in situ conformal print and thus targeted repairs using additive manufacturing has potential in application.

# Appendix

## I. Timeline

| Fall 2019 | |
| --- | --- |
| Overall | * Completed draft prospectus * Draft Presentation in November (informal) * Subteams target one or two methodologies for detailed analysis |
| Extruder | * Compare different brands and the potential of building our own * Either decide on an extruder to buy or come up with a design to build one. |
| Structures | * Conduct further research into potential 6 DOF robotic arms and 3D printers   + Determine robotic arm/3D printer for project |
| Sensing | * Narrow down software choices * Obtain available scanning instruments |
| Spring 2020 | |
| Overall | * Determine detailed budget and expenses * Complete and defend proposal * Apply and prepare for funding |
| Extruder | * Begin modifying or building extruder |
| Structures | * Design end effector mount or means of increasing DOF of 3D printer |
| Sensing | * Test different 3D scanners for resolution and convenience * Determine optimal scanning method * Begin and finish software for data streaming |
| Fall 2020 | |
| Overall | * Do Good Showcase * Systems and integration for minimum viable product |
| Extruder | * Continue to modify/build extruder * Begin checking integration of extruder with structures |
| Structures | * Begin construction and testing of extruder mount * Testing of accuracy of robotic manipulator |
| Sensing | * Determine toolpathing algorithms   + Implement and simulate algorithms * Obtain and account for physical constraints |
| Spring 2021 | |
| Overall | * A minimum viable product from each subteam is demonstrated * Results and findings are written into thesis |
| Extruder | * Fully finished extruder * Finish fully integrating with structures |
| Structures | * Finalized extruder mount |
| Sensing | * Complete comparison of scanning methods and analysis for thesis * Complete comparison of toolpathing algorithm and analysis for thesis * Package software and complete documentation |
| Fall 2021 | |
| Overall | * Further research into additional features * Continue integration testing and optimization |
| Extruder | * Have a completely built 3D printer * Integrate with scanning team |
| Structures | * Integrate with scanning team and extruder to create prototype |
| Sensing | * Robustness testing for further development |
| Spring 2022 | |
| Overall | * Results and findings completed and ready for presentation * Demonstrate necessity for future work and research |
| Extruder | * Complete and test extruder head |
| Structures | * Document work in written thesis |
| Sensing | * Robustness testing for refinement * Prepare documentation for further work |

## 

## 

## II. Budget

| **Manipulator Options** |  |
| --- | --- |
| URE3, URE5, or KUKA LBR IIWA 7 800 in Robotics Realizations Lab | $0.00 |
| Materials and Production of End-Effector Mount | $150.00 |
| **Extruder** |  |
| [Extruder Bowden Hot End](https://gulfcoast-robotics.com/collections/hotends/products/all-metal-v6-hotend-1-75mm-bowden-extruder-for-prusa-i3-reprap-3d-printer-deluxe-kit) | $25.00 |
| [Extruder Bowden Cold End](https://www.amazon.com/Redrex-Upgraded-Aluminum-Extruder-Creality/dp/B07DDGGN92/ref=sr_1_3?keywords=bowden+extruder&qid=1582002415&s=industrial&sr=1-3) | $14.00 |
| [Bowden Tube](https://www.amazon.com/Capricorn-Bowden-Filament-Genuine-Premium/dp/B079P92HN9/ref=pd_bxgy_img_2/130-9753526-6494605?_encoding=UTF8&pd_rd_i=B079P92HN9&pd_rd_r=158d1690-bf52-46ca-8514-5b768b31f968&pd_rd_w=KaQSz&pd_rd_wg=R0AYx&pf_rd_p=fd08095f-55ff-4a15-9b49-4a1a719225a9&pf_rd_r=S1GXB7PVDT930GDRKWB6&psc=1&refRID=S1GXB7PVDT930GDRKWB6) | $14.00 |
| [PLA: PLA Filament 1.75mm with 3D Build Surface](https://www.amazon.com/HATCHBOX-3D-Filament-Dimensional-Accuracy/dp/B00J0ECR5I/ref=sr_1_3?crid=3LKYR2MDKV4WM&keywords=pla+filament+1.75mm&qid=1581308287&s=industrial&sprefix=PLA+filam%2Cindustrial%2C172&sr=1-3) | $23.00 |
| Micro Controller for Hot End | $63.50 |
| Power Supply for Hot End | $20.00 |
| **3D Scanning** |  |
| Various LIDAR Instruments From Mentor-Taught Course | $0.00 |
| **Total** | $373 |

## 

## III. Mentor Feedback

Our mentor was primarily concerned with the applications and practicality of the project and encouraged us to conduct some research into where the technology could be currently useful. In response to this, we incorporated some immediate applications (rover and airplane wing repair) as opposed to just satellite servicing which is not a convincing application of the technology.

Another concern that directly followed from finding applications was clarifying the research problem. Our mentor suggested that we find research that would better define the dimensions and nature of the void we would be attempting to repair. In order to accommodate this, we extrapolated data from research that posed the rover wheel damage problem.

## IV. Glossary

**Cold End** The component of the extruder that pushes filament through to the hot end

**Conformal** Fitting to the contour of; preserving angles and orientation

**DOF** Degrees of freedom

**FEA** Finite Element Analysis

**FFF** Fused Filament Fabrication

**Hot End** The component of the extruder that heats up the material for extrusion

**IK** Inverse Kinematics

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

**LIDAR** Light Detection and Ranging

**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

# References

[[1] Alex Derber, “Next Steps For Using Additive Manufacturing For Repairs,” *MRO-Network*, Jul. 11, 2019. https://www.mro-network.com/emerging-technology/next-steps-using-additive-manufacturing-repairs (accessed Oct. 16, 2019).](https://www.zotero.org/google-docs/?3pczXG)

[[2] NASA/JPL-Caltech/MSSS, *Sol 962: Mast Camera (Mastcam)*. 2015. Accessed: Oct. 23, 2019. [Mastcam]. Available: https://mars.jpl.nasa.gov/msl-raw-images/msss/00962/mcam/0962ML0042560020403852E01\_DXXX.jpg](https://www.zotero.org/google-docs/?3pczXG)

[[3] N. Bausch, D. P. Dawkins, R. Frei, and S. Klein, “3D Printing onto Unknown Uneven Surfaces\*\*This work is supported by the University of Portsmouth – Research Development Framework (RDF) 2015.,” *IFAC-Pap.*, vol. 49, no. 21, pp. 583–590, Jan. 2016, doi: 10.1016/j.ifacol.2016.10.664.](https://www.zotero.org/google-docs/?3pczXG)

[[4] N. Bausch, D. P. Dawkins, and R. Frei, “InSPIREd - advances in Conformal Printing: 3D printing onto unknown uneven surfaces,” in *2017 IEEE International Conference on Advanced Intelligent Mechatronics (AIM)*, Munich, Germany, Jul. 2017, pp. 430–435. doi: 10.1109/AIM.2017.8014055.](https://www.zotero.org/google-docs/?3pczXG)

[[5] M. Doran, R. Sterritt, and G. Wilkie, “Autonomic Self-Adaptive Robot Wheel Alignment,” in *Adaptive 2016: The Eighth International Conference on Adaptive and Self-Adaptive Systems and Applications*, 2016, pp. 27–33.](https://www.zotero.org/google-docs/?3pczXG)

[[6] L. D. July 06, 2015 Science, and Astronomy, “Wheel Worries: Mars Rover Curiosity Dealing With Damage,” *Space.com*. https://www.space.com/29844-mars-rover-curiosity-wheel-damage.html (accessed Oct. 23, 2019).](https://www.zotero.org/google-docs/?3pczXG)

[[7] S. Siceloff, “Meet The ‘Swarmies’- Robotics Answer to Bugs,” *NASA*, Mar. 02, 2015. http://www.nasa.gov/content/meet-the-swarmies-robotics-answer-to-bugs (accessed Oct. 16, 2019).](https://www.zotero.org/google-docs/?3pczXG)

[[8] D. King, “SPACE SERVICING: PAST, PRESENT AND FUTURE,” 2001.](https://www.zotero.org/google-docs/?3pczXG)

[[9] R. Kirubakaran, D. Lokesharun, S. Rajkumar, and R. Anand, “Aircraft Wing Weight Optimization by Composite Material Structure Design Configuration,” p. 10.](https://www.zotero.org/google-docs/?3pczXG)

[[10] P. M. Gary and M. G. Riskalla, “Development of Probabilistic Design Methodology for Composite Structures,” VOUGHT AIRCRAFT CO DALLAS TX, Aug. 1997. Accessed: May 05, 2020. [Online]. Available: https://apps.dtic.mil/docs/citations/ADA331612](https://www.zotero.org/google-docs/?3pczXG)

[[11] V. Potkonjak, S. Tzafestas, D. Kostic, and G. Djordjevic, “Human-like behavior of robot arms: general considerations and the handwriting task—Part I: mathematical description of human-like motion: distributed positioning and virtual fatigue,” *Robot. Comput.-Integr. Manuf.*, vol. 17, no. 4, pp. 305–315, Aug. 2001, doi: 10.1016/S0736-5845(01)00005-9.](https://www.zotero.org/google-docs/?3pczXG)

[[12] G. S. Chirikjian and J. W. Burdick, “A hyper-redundant manipulator,” *IEEE Robot. Autom. Mag.*, vol. 1, no. 4, pp. 22–29, 1994.](https://www.zotero.org/google-docs/?3pczXG)

[[13] J. R. Kubalak *et al.*, “Design and realization of a 6 degree of freedom robotic extrusion platform,” in *Solid Freeform Fabrication Symposium*, 2016, pp. 1314–1332.](https://www.zotero.org/google-docs/?3pczXG)

[[14] M. E. Moran, “Evolution of robotic arms,” *J. Robot. Surg.*, vol. 1, no. 2, pp. 103–111, Jul. 2007, doi: 10.1007/s11701-006-0002-x.](https://www.zotero.org/google-docs/?3pczXG)

[[15] C. Gosselin, R. Duballet, Ph. Roux, N. Gaudillière, J. Dirrenberger, and Ph. Morel, “Large-scale 3D printing of ultra-high performance concrete – a new processing route for architects and builders,” *Mater. Des.*, vol. 100, pp. 102–109, Jun. 2016, doi: 10.1016/j.matdes.2016.03.097.](https://www.zotero.org/google-docs/?3pczXG)

[[16] R. Weskamp and M. R. Tennerstedt, “Quick change coupling system for robotic attachments,” US4906123A, Mar. 06, 1990 Accessed: Oct. 01, 2019. [Online]. Available: https://patents.google.com/patent/US4906123A/en](https://www.zotero.org/google-docs/?3pczXG)

[[17] J. Iqbal, R. U. Islam, and H. Khan, “Modeling and analysis of a 6 DOF robotic arm manipulator,” *Can. J. Electr. Electron. Eng.*, vol. 3, no. 6, pp. 300–306, 2012.](https://www.zotero.org/google-docs/?3pczXG)

[[18] S. N. Cubero, “Blind search inverse kinematics for controlling all types of serial-link robot arms,” in *Mechatronics and Machine Vision in Practice*, 2008, pp. 229–244.](https://www.zotero.org/google-docs/?3pczXG)

[[19] L. Zhou, S. Bai, and M. R. Hansen, “Design optimization on the drive train of a light-weight robotic arm,” *Mechatronics*, vol. 21, no. 3, pp. 560–569, Apr. 2011, doi: 10.1016/j.mechatronics.2011.02.004.](https://www.zotero.org/google-docs/?3pczXG)

[[20] T. R. Solomon and T. G. Cooper, “Multi-ply strap drive trains for surgical robotic arms,” Feb. 2016](https://www.zotero.org/google-docs/?3pczXG)

[[21] J. A. Paulsen, M. Renn, K. Christenson, and R. Plourde, “Printing conformal electronics on 3D structures with Aerosol Jet technology,” in *2012 Future of Instrumentation International Workshop (FIIW) Proceedings*, Oct. 2012, pp. 1–4. doi: 10.1109/FIIW.2012.6378343.](https://www.zotero.org/google-docs/?3pczXG)

[[22] S. Maktabi and P. R. Chiarot, “Electrohydrodynamic printing of organic polymeric resistors on flat and uneven surfaces,” *J. Appl. Phys.*, vol. 120, no. 8, p. 084903, Aug. 2016, doi: 10.1063/1.4961421.](https://www.zotero.org/google-docs/?3pczXG)

[[23] S. Jasveer and X. Jianbin, “Comparison of different types of 3D printing technologies,” *Int. J. Sci. Res. Publ. IJSRP*, vol. 8, no. 4, pp. 1–9, 2018.](https://www.zotero.org/google-docs/?3pczXG)

[[24] 3D Printer Power, “Bowden Vs Direct: Quest for the Best 3D Printer Extruder,” *3D Printer Power*, Jan. 17, 2018. https://3dprinterpower.com/bowden-extruder-vs-direct-extruder-showdown/ (accessed Oct. 07, 2019).](https://www.zotero.org/google-docs/?3pczXG)

[[25] T. Yao, Z. Deng, K. Zhang, and S. Li, “A method to predict the ultimate tensile strength of 3D printing polylactic acid (PLA) materials with different printing orientations,” *Compos. Part B Eng.*, vol. 163, pp. 393–402, Apr. 2019, doi: 10.1016/j.compositesb.2019.01.025.](https://www.zotero.org/google-docs/?3pczXG)

[[26] M. Heidari-Rarani, M. Rafiee-Afarani, and A. M. Zahedi, “Mechanical characterization of FDM 3D printing of continuous carbon fiber reinforced PLA composites,” *Compos. Part B Eng.*, vol. 175, p. 107147, Oct. 2019, doi: 10.1016/j.compositesb.2019.107147.](https://www.zotero.org/google-docs/?3pczXG)

[[27] X. Tian, T. Liu, C. Yang, Q. Wang, and D. Li, “Interface and performance of 3D printed continuous carbon fiber reinforced PLA composites,” *Compos. Part Appl. Sci. Manuf.*, vol. 88, pp. 198–205, Sep. 2016, doi: 10.1016/j.compositesa.2016.05.032.](https://www.zotero.org/google-docs/?3pczXG)

[[28] J. B. Campbell, *Introduction to remote sensing*, 2nd ed. New York: Guilford Press, 1996.](https://www.zotero.org/google-docs/?3pczXG)

[[29] W. Boehler and A. Marbs, “3D Scanning Instruments,” *Proc. CIPA WG*, pp. 9–18, 2002.](https://www.zotero.org/google-docs/?3pczXG)

[[30] H. Zuowei, H. Yuanjiang, and H. Jie, “A Method for Noise Removal of LIDAR Point Clouds,” in *2013 Third International Conference on Intelligent System Design and Engineering Applications*, Jan. 2013, pp. 104–107. doi: 10.1109/ISDEA.2012.32.](https://www.zotero.org/google-docs/?3pczXG)

[[31] M. Levoy *et al.*, “The Digital Michelangelo Project: 3D Scanning of Large Statues,” in *Proceedings of the 27th Annual Conference on Computer Graphics and Interactive Techniques*, New York, NY, USA, 2000, pp. 131–144. doi: 10.1145/344779.344849.](https://www.zotero.org/google-docs/?3pczXG)

[[32] O. Akyol and Z. Duran, “Low-Cost Laser Scanning System Design,” *J. Russ. Laser Res.*, vol. 35, no. 3, pp. 244–251, May 2014, doi: 10.1007/s10946-014-9419-2.](https://www.zotero.org/google-docs/?3pczXG)

[[33] R. J. A. Allen and R. S. Trask, “An experimental demonstration of effective Curved Layer Fused Filament Fabrication utilising a parallel deposition robot,” *Addit. Manuf.*, vol. 8, pp. 78–87, Oct. 2015, doi: 10.1016/j.addma.2015.09.001.](https://www.zotero.org/google-docs/?3pczXG)

[[34] K. Suwanratchatamanee, M. Matsumoto, and S. Hashimoto, “Robotic tactile sensor system and applications,” *IEEE Trans. Ind. Electron.*, vol. 57, no. 3, pp. 1074–1087, 2009.](https://www.zotero.org/google-docs/?3pczXG)

[[35] D. Eberly, “Dynamic Collision Detection using Oriented Bounding Boxes,” *Magic Softw. Inc*, Mar. 1999, [Online]. Available: http://www.gingaminga.com/Data/Note/oriented\_bounding\_boxes/DynamicCollisionDetection.pdf](https://www.zotero.org/google-docs/?3pczXG)

[[36] M. De Geir, “Control of a robotic arm: Application to on-surface 3D-printing.” 2015. [Online]. Available: https://pdfs.semanticscholar.org/4312/0aa4897952bbe2c636d839de4d99c2a5b29c.pdf](https://www.zotero.org/google-docs/?3pczXG)

[[37] Gottschalk, Stefan, Ming C. Lin, and Dinesh Manocha, “OBBTree: A hierarchical structure for rapid interference detection,” in *Proceedings of the 23rd annual conference on Computer graphics and interactive techniques*, 1996, pp. 171–180.](https://www.zotero.org/google-docs/?3pczXG)

[[38] F. Alkadi, K.-C. Lee, and J.-W. Choi, “Conformal Additive Manufacturing using a Direct-Print Process,” *Addit. Manuf.*, p. 100975, Nov. 2019, doi: 10.1016/j.addma.2019.100975.](https://www.zotero.org/google-docs/?3pczXG)

[[39] G. Zhao, G. Ma, J. Feng, and W. Xiao, “Nonplanar slicing and path generation methods for robotic additive manufacturing,” *Int. J. Adv. Manuf. Technol.*, vol. 96, no. 9, pp. 3149–3159, Jun. 2018, doi: 10.1007/s00170-018-1772-9.](https://www.zotero.org/google-docs/?3pczXG)

[[40] A. V. Shembekar, Y. J. Yoon, A. Kanyuck, and S. K. Gupta, “Generating Robot Trajectories for Conformal Three-Dimensional Printing Using Nonplanar Layers,” *J. Comput. Inf. Sci. Eng.*, vol. 19, no. 3, p. 031011, Apr. 2019, doi: 10.1115/1.4043013.](https://www.zotero.org/google-docs/?3pczXG)

[[41] “Replicator+ Desktop 3D Printer,” *MakerBot*. https://www.makerbot.com/3d-printers/replicator/ (accessed Feb. 17, 2020).](https://www.zotero.org/google-docs/?3pczXG)

[[42] Universal Robots A/S, “Universal Robots e-Series User Manual.” Universal Robots A/S, 2018. Accessed: Feb. 11, 2020. [Online]. Available: https://s3-eu-west-1.amazonaws.com/ur-support-site/41166/UR3e\_User\_Manual\_en\_Global.pdf](https://www.zotero.org/google-docs/?3pczXG)