# Chapter 2: Literature Review

## 2.1 Introduction and Applications

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

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/?broken=VcqyD1). 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/?broken=Ts5ZvV). 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/?broken=eGjBM3). It is also important to note that the wheel thickness is minimal and only .75 mm thick [[6]](https://www.zotero.org/google-docs/?broken=bz5n4J). 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. It would be possible for a 3D printer to attach to a robotic arm and navigate to a desired location for printing. Implementation of a robotic arm capable of these wheel repairs aligns with NASA’s efforts [[7]](https://www.zotero.org/google-docs/?broken=NgKgZY) 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/?broken=g7pc6I) | Image of Curiosity Rover Wheel Damage with White Lines Indicating Measurements in Table 2.1 [[2]](https://www.zotero.org/google-docs/?broken=m0k0Yb). |
| **Figure 2.1** | |

| **Table 2.1** Estimated Lengths of Holes and Cracks in Figure 2.1 [[2]](https://www.zotero.org/google-docs/?broken=7sEMTF). | |
| --- | --- |
| **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/?broken=TV0LqL) describes how an in situ 3D printer can be used to repair components more easily than welding, which is the current method. 3D printing 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/?broken=cpVdr3). This 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/?broken=dhv35V). 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/?broken=IDvEgj).

King [[8]](https://www.zotero.org/google-docs/?broken=0knZWA) 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/?broken=3vyBDz). 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 [[1]](https://www.zotero.org/google-docs/?broken=bFkO1V). They may also be further optimized by modifying the orientations of layers relative to each other to increase the material strength in additional directions [[1]](https://www.zotero.org/google-docs/?broken=GmNaWR). Aircraft undergo damage throughout their life and averaged 972 damages to composites per one million flight hours on average [[1]](https://www.zotero.org/google-docs/?broken=WkAjhL). In our research, we will test the material properties of specimens with 3D printed repairs of various lay-up sequences with PLA 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 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 [[19]](https://www.zotero.org/google-docs/?broken=KVjr9W).

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 antennas onto uneven surfaces such as aircraft fuselages. Using 3D printing for these instances decreases the overall weight of the structure [[19]](https://www.zotero.org/google-docs/?broken=9jCrjn).

#### **Electrohydrodynamic Printing**

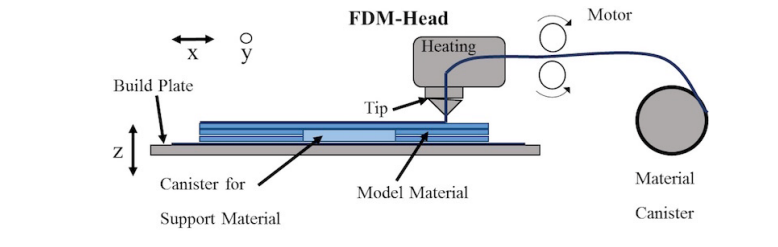
Similar to aerosol jet printing, electrohydrodynamic printing generates small droplets of liquid material that are only a few microns in diameter. This system was developed for the primary purpose of manufacturing organic printed electronics [25]. These electronics are made of polymeric composites because they can withstand a substantial level of mechanical deformation. During the process of electrohydrodynamic printing, the 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 [[20]](https://www.zotero.org/google-docs/?broken=yZUz9L).

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 [[20]](https://www.zotero.org/google-docs/?broken=b38s9D).

#### **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 [[21]](https://www.zotero.org/google-docs/?broken=foxb8E).



Source, Bagsik and Schoppner (2011) -- source #3 from lit review bullets 2021

#### **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 [[21]](https://www.zotero.org/google-docs/?broken=T8fu5R).

#### **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 [[21]](https://www.zotero.org/google-docs/?broken=2kjSr6).

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 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.

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| **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 [[22]](https://www.zotero.org/google-docs/?broken=dUOp4A). 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 [[22]](https://www.zotero.org/google-docs/?broken=3OJPon).

#### **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 [[23]](https://www.zotero.org/google-docs/?broken=8udtEY). 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 [[22]](https://www.zotero.org/google-docs/?broken=H1kXNF).

#### **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.

## 2.4 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 for PLA. For these reasons, it is necessary to investigate the differences between the two.

#### **PLA**

Polylactic acid (PLA) is a common filament used for 3D printing due to its high strength and low cost. The average price per kilogram of generic PLA ranges from 20-40 dollars. In addition, the melting point of PLA is between 200-240 degrees Celsius, which is obtainable with FDM printing.

[Conformal additive manufacturing using a direct-print process | Elsevier Enhanced Reader](https://reader.elsevier.com/reader/sd/pii/S2214860419308048?token=744A4564E4E8EF6B7B8E2F00A1B6909D0B0FF879EA5F6E7A1D860E65BF169011D05D9A180AF3171EAE4E8FDE387D2BA1&originRegion=us-east-1&originCreation=20211027181607)

Researchers at Northwestern Polytechnic University conducted a study testing the ultimate tensile strength (UTS) of PLA with different printing orientations and thicknesses. They printed a thin, plate-like structure at 0, 15, 30, 45, 60, 75, and 90 degrees with respect to the flat surface, and did this for thicknesses of 0.1, 0.2, and 0.3 mm [[23]](https://www.zotero.org/google-docs/?broken=aAg66B).

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 [[23]](https://www.zotero.org/google-docs/?broken=Um9W4O). Findings from [[23]](https://www.zotero.org/google-docs/?broken=FZ7Thi) also showed that as layer thickness increased from 0.1mm to 0.3mm, the UTS decreased.

#### **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/?broken=0DkZBR). 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.

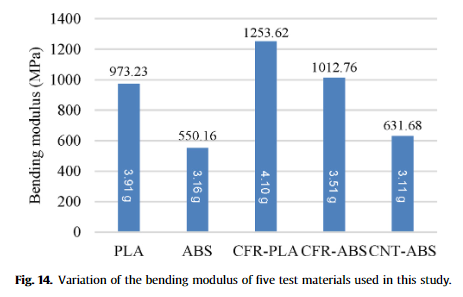
For continuous fiber reinforced thermoplastics, flexural strength was found to increase with higher printing temperatures up to 240 degrees celsius where inaccuracy of the print started to rise [[27]](https://www.zotero.org/google-docs/?broken=w3bF7q). Strength also increased as layer thickness decreased 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%[[1]](https://www.zotero.org/google-docs/?broken=uY9bI2).

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**Materials**

* Talk about PLA, Carbon fiber pla, abs, etc

It is well established that reinforcing PLA or ABS with carbon fiber significantly increases the tensile properties of the printed parts. Researchers analyzed five 3D printed beams of different printing filaments. They found that PLA is stronger than ABS, and adding carbon fiber increases the strength even more.



The bar graph above shows the Bending modulus for the different PLA and ABS variations.

## 2.5 New material that doesn’t have a section yet

**Printing Parameters and Mechanical Properties of 3D printed structures**

In order to maximize the durability of our repaired parts, it is beneficial to have the optimal print settings for our tests.

Researchers at the University of Manchester conducted a study to find the optimal modeling parameters for FDM printing using pure PLA filament. They varied infill pattern, infill density, infill speed, and nozzle temperature. The researchers analyzed the data using a combination of tensile and compression testing, as well as scanning electron microscopy (SEM) to reach a conclusive set of optimal printing parameters [2]. Their findings showed that a linear infill pattern, 100% infill density, 90mm/s infill speed, and 215 degrees Celsius nozzle temperature were most effective for maximizing the Young’s Modulus of PLA 3D printed parts under tension and compression loadings. The maximum Young’s Modulus the researchers recorded for PLA was 1538 MPa [2].

Similar to the researchers at the University of Manchester, Tanner Harpool, a thesis candidate at Wichita State University, investigated the effects of infill patterns on tensile strength properties of 3D printed parts. He analyzed four different infill patterns: rectilinear, diamond, hexagonal, and solid (the control). He found that the hexagonal pattern had the highest strength. Harpool also noticed that prints with 100% infill behaved like brittle materials, which actually decreased their strength. Parts with a lower infill percentage experienced behavior more closely resembling a ductile material [4].

Another important aspect to consider in this project is the adhesion between the base part and the infill repair. In the study mentioned above, the researchers used SEM technology to reveal that the strength of the samples is dependent on the arrangement of their layers [2]. This tells us it is worthwhile to pursue the optimal infill pattern for 3D printed repairs because the orientation and layout of the filament along the 3D printed base will most likely have an effect on the overall strength of the repaired part.

There is some correlation between these parameters. For example, researchers found that increasing the nozzle temperature leads to an increase in strength; however, at a certain point, the increase in temperature becomes detrimental [2]. This is because if the temperature is too high, it can lead to poor layer bonding, which does more harm than good. It is important to note that the change in one parameter may have an adverse effect on another parameter. In our case, we are varying the infill pattern and infill density of our repaired print. By varying the infill pattern, we may also alter the adhesion between the filament layers, and it is something that needs to be noted during data analysis.

**Cost Analysis**

Source 3 did some cost analysis. Read this source and summarize findings.

<https://www.researchgate.net/publication/295396135_Study_of_infill_print_design_on_production_cost-time_of_3D_printed_ABS_parts?_esc=publicationCoverPdf&el=1_x_3&enrichId=rgreq-da4bea36505e0ce206b7a3597275906e-XXX&enrichSource=Y292ZXJQYWdlOzI5NTM5NjEzNTtBUzozNzg0NzA5ODgzMDQzODZAMTQ2NzI0NTkyMzM1NQ%3D%3D>

Researchers at the department of mechanical and industrial engineering at Youngstown State University investigated the relationship between infill print design and production cost-time of 3D printed ABS parts. This relationship is extremely important to consider in our research, because while users would want to select the infill print pattern that provides them with the best strength retention, they also need to review production costs associated with each infill pattern. Selection of an infill pattern can significantly affect mechanical properties, total cost, and production time.

The researchers printed multiple specimens of four different infill patterns: low density, high density, double dense, and solid infill. The prints were subject to ASTM standards, which are the same standards we are using in this project. Once printed, the researchers tested the tensile, compressive, and bending strength of each infill pattern. To calculate the total cost of each print, they estimated the cost per minute of printing ABS on their print setup, then multiplied this by the time it took to print the sample. Certain infill patterns will contain more material, which leads to higher costs; furthermore, the toolpath the extruder head takes for complex infill patterns can also increase the print time. These are all factors that need to be accounted for in a cost-benefit analysis. In a practical cost-benefit analysis, situation is everything. For a Mars Rover, the extra cost associated with a stronger repaired piece may be well worth it. On the other hand, in a mass production application, cost would likely be the driving factor.

The Youngstown State University researchers \_\_

**Slicing Tool Path Generation**

When 3D 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. However with nonplanar layers, the extrusion precisely follows the actual surface contour of an object instead. Since only surfaces with a 1D-curvature are printable with linear extrusions without distortions and usually a 5-axis machinery is required to do the print, a different path generation must be used. The toolpath must also take into account of self-collisions and transitions between different nonplanar surfaces.

In a paper by Ahlers et al [45] an extension to the open-source Slic3r was created to support the ability of nonplanar printing while taking account to the limitations as stated previously states. Slic3r is a free slicer that turns 3D models into printable G-Code: a set of sequential instructions containing toolpath coordinates and amount of material to extrude that the printer then receives and prints the part. To make the Slic3r support non-planar layers, the object model is first sliced into horizontal slices, generating layers. The layers are then processed so that outer surfaces oof the part were filtered by its suitability for nonplanar printing. This filtration included comparing each facet normal in the parsed STL mesh to a threshold angle and was modified afterwards to allow the printing of nonplanar layers on top. The nonplanar toolpahts were the generated and appended to the G-code instructions. The nonplanar G-code generation is similar to that of planar toolpaths where individual extrusion paths are chained togethe to a layer extrusion path. The payers are then chained together bottom up to an extrusion path of the whole object.

Utilizing nonplanar toolpaths still run the risk of collisions, which Aulers et al. [45] solves through checking the whole nonplanar tool path for collisions, removing the surface, and print planarly instead when a collision does occur. Collisions can also occur when traveling from or to a points that lies below the highest printed layer, in which can also be solved through lifting up the printhead to the current maximum printing height, travel to the desired positions, and lower the printhead again.