

Bachelor’s Thesis

Optimization and Control of

5D (Bio-)printing

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Abstract

The goal of this thesis is to enable the printing process in the project ‘SonoBone’. It aims to print in-vivo and in-situ bone structure using an acoustically assisted 5D-printing process. The work done as part of this thesis is the creating of a program with a graphical user interface that can interpret .gcode files, connect the program to the robotic arm as well as an arduino, print 3D str

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Abbreviations

01 Introduction

1.1 Additive manufacturing overview

Additive Manufacturing, commonly referred as 3D printing, is a transformative approach to traditional industrial manufacturing techniques as well as prototyping which has been gaining massive interest in the past 10 years. While operating on different principles, all AM technologies utilize a bottom-up approach by adding material selectively and fusing it to existing geometry while more traditional manufacturing employ a subtractive process. Both the consumer and industrial sectors have benefited from the development of different technologies in AM. The ability to quickly produce very intricate models into the physical space from just a digital model is a powerful ability for all prototyping. While not optimal for large batch sizes, there exist also mass production facilities that employ AM for smaller volume parts as well certain complicated parts. There exist many techniques for AM such as SLA, FDM, Binder Jetting, SLS and more with their respective applications and advantages. Commercially available machines for consumer focus mostly on SLA and FDM principles. [1]

SLA is a photopolymerization technique, which generally refers to the curing of a liquid or viscous photoreactive polymer resin using a laser. By having a laser cure an entire planar layer at once, this technique can print quickly for high volume parts. The main downsides to this is the requirement for post-processing such as cleaning and post-curing. It is possible to achieve very high details using SLA.

The other commonly used technique is FDM. With FDM, the printer deposits material at the desired places using a gantry that is able to move in 3D-space. Commercial systems use solid filament that is melted in a hot end so that is viscous and able to fuse to the previous layers. The main downside is the slow printing speed and low details. Newer developments have been improving the speed and details. The advantage of this method is the rather simple utilization and the lack of post-processing needed. This has been the main factor in the commercial success of FDM machines.

1.2 Bioprinting

Bioprinting is an emerging technology that is used to patch dead cells or even print entire new biostructures such as organs and bones. It is an advanced form of Am that that can create complex biological structures by depositing different bioinks to mimic living structures. Bioinks are a combination of cells and bio-compatible cell-supporting materials. Although bioprinting is still in its infancy, its versatility has accelerated the applications in tissue engineering. Further use can be gained in the development and testing of drugs, especially for personalized medicine.

With the emergence of 3D-Bioprinting the scientific community has gained a higher degree of control using multiple bioinks to compile increasingly complex structures. The main bioprinting methods can be classified into laser-assisted bioprinting, inkjet bioprinting/droplet bioprinting and extrusion bioprinting.[2] explain different conecpts

In many bioprinting processes, scaffolds are required. They can be temporarily used until the main body becomes self-sustaining or permanent depending on the requirements. One main challenge is the utilization of the correct bioink. There exists a vast amount of bioinks, optimized for the type of cells, type of printing process and target tissue. The main metrics are the structural and functional integrity as well as cell survivability. While it is easier using 3D-Bioprinting, vascularization, the development of a network of blood vessels in the cell structure as well as the complexity and scale of the printed structure remain a challenge.

1.3 5D (bio-) printing

The classical cartesian based systems face various downsides such as the effect of staircasing, which leads to a lack of feature size in the vertical direction. The main way to combat this is the reduction of the layer height to the desired size of the features which reduces the printing time drastically. Another downside is that the strength of parts is highly dependent on the orientation of layers. While the part strength in the direction of the layers is strongest and dependent on the material strength. The part strength across layers is significantly less than inside a layer and depends on the quality of layer adhesion.

Another downside of classical FDM approaches is that layers of filament or ink are deposited and supported by previous layers. This makes printing overhangs difficult as there is no supporting material beneath. A certain overhang (classical FDM machines can handle 45 ° well) is possible as the previous layer does offer some structural support, even if not completely. This can lead to sagging in the affected parts depending on the print settings. When working with liquid or viscous materials overhangs are even more critical.

Methods like the S^3 slicer have tackled these problems by employing a multi-axis approach to AM. The proposed method introduces additional degrees of freedom to classical 3D printers to achieve various optimizations. This leads to a variety of advantages compared with the planar layer-based 3D printing including the reduction of supporting structures (SF), enhanced mechanical strength (SR) by printing in curved lines perpendicular to projected stresses and improved surface quality (SQ) by avoiding classical stepping effects. [3]

Current bioprinters mostly utilize modified versions of cartesian 3D printers with a layer-based approach to stack cells on simple-shaped flat planes with the assistance of polymerized biomaterials. [4] This method has multiple downsides such as the inability to provide nutrients during the printing process and the glue-like biomaterial inhibiting cell-to-cell contact.

5D Bioprinting has the potential to tackle these challenges in a similar way that new multi-axis methods have enabled the recent advances in AM. By employing the extra degrees of freedom, it will be possible to print more complex and detailed geometries. Combined with multi-material printing intricate details such as vascularized tissues and curved anisotropic shapes can be created. By adding the precision of highly accurate machinery and increasing structural integrity and stability, cell viability can be improved by precisely positioning cell material.

02 Goal

The goal for this thesis is the enablement of 5D bioprinting in the project ‘SonoBone’. This encompasses the handling of the robot arm including print-assisting components. Also, part of this thesis is the collaborations of the other team members in their advancements and coordination to achieve the aforementioned goal.

‘SonoBone’ is a cutting-edge research project set to develop an acoustically assisted 5D (bio)printer for bone (bio)applications [X-prajwal]. It aims to print in-situ and in-vivo bone structures using a multi-axis multi-material extrusion based system that aligns cells acoustically. The goal is to develop a workings prototype of the SonoBone-Bioprinter.

02 Methods

2.1 Robotic Arm

This project is based on the Mecademics 6-axis industrial robot arm Meca500 [5 mecademics]. This robotic arm claims to have a precision of 1 µm and a repeatability of 5 µm. It weights less than 5 kg and is rated for a payload up to 500 g. It comes with an integrated controller in the base of the robot that connects to a PC via an ethernet cable. The Meca500 supports Ethernet/IP, TCP/IP, Ethercat and PROFINET communication. For this project TCP/IP was used.

The integrated controller features a web-based interface called the MecaPortal, the files for which reside in the robot’s controller. This interface allows the writing for short scripts and control over individual joints or axis. Although it does not support any variables, it is a useful tool to directly control the robot.

For this project, the mecadmicpy API [X] has been used. It features a range of commands that work very similarly to the web interface. Once sent, the robot will use its own controller to fulfil the command, such as reaching a certain location and orientation, also called a pose.

Starting the robot requires the following procedure:

1. Confirm that the emergency stop is not activated.
2. Connect the power cables and turn on the power.
3. Press the Reset button on the robot’s power supply and wait for approximately 30 seconds. The lights on the base will flash until the robot is ready. Only then will the mecaportal be ready. To access it one needs to open a web browser and type in the IP address 192.168.0.100. The connecting computer needs to be setup correctly to be able to connect. A screenshot of a computer

   Description automatically generated
4. Activate and Home the robot (either via the Mecaportal or the API).

Robot Arm Singularities and stuff

2.2 Bioink and UV-LED

In order for the material to be able to solidify after a short curing process, but still be printable we used a highly viscous ink. The material used for the prints was acrylate mixed with a photoinitiator that is mixed in a ratio of 1g of TEGDMA to 1 mg of photo initiator. This was first preheated to just below 100° C and then mixed in a magnetic stirrer at 500 rotations per minute at 100° C. After that it was cooled slightly and then filled up into the syringe from above. It is important to reduce bubbles as much as possible because they greatly disturb the printing process.

2.3 Printhead

A custom designed fixture that attaches to the print head by clamping holds 6 UV lamps [UV reference and specs]. They are all attached to a potentiometer (ohmage) and connected to the 5V power pin of an Arduino.

MORE INFO IN PRINTHEAD

2.4 Rotating Base

Because of the very limited reach and workspace of the Meca500 with a long endeffector and the flexibility requirements to the printing process so that the full capabilities of this multi-axis approach can be utilized, the printbed is not fixed in space but mounted on a FDM 3D-printed rotating bed. This is attached to a Nema 13 Stepper motor and can be spun around. To make sure the bed is level in all position, the mount features 4 bearing mounted rollers that stabilize the base in all directions. This is necessary so that the base plate is perfectly level. If that would not be the case, then not only bed adhesion for the first layer would be impossible but also, if the bed would rotate, then alignment of the parts would not be proper and it might crash into the printed structures.

The Rotating Base is controlled by an Arduino (model?) with a stepper shield (model) and stepper drivers with micro-stepping (how) enabled (1/16) and the 5V to [blabla] shorted. The Arduino receives position data via a serial connection from the main controller, which in this case it a windows laptop. The instruction message is always attached to an index, which will be in turn be replied to once the position has been reached.

2.5 Extrusion

Extrusion is done by a Nema 13 motor connected to a custom linear mechanism using a lead screw. The stepper is also connected to the previously mentioned Arduino and is controlled in unison with the base.

Attached to the end of the rig is a 3Dprinted mount and a PTFE Tube that then leads into a silicone tube of higher diameter. This is then lead into the printhead where its attached using a reverse chamfer and the flows entered the 3D printed head. In the other hand there is a needle of 0.4 mm diameter that is attached using a Luer lock connection. The entire length is UV shielded using aluminium tape, so that the curing process does not start before the ink reaches the end needle tip.

2.5 Slicer Settings

Ultimaker Cura was used as a slicer. As the only relevant part of the print is the extrusion information and the print path, there are some relevant settings.

* The base printer settings were the Cura default for the Creality CR10 printer
* Layer height of 0.3 mm with a nozzle size of 0.6mm
* The wall layers were set to 9999 so that there would be no infill. The reason for that is that the infill is printed differently to wall layers, especially in regards to extrusion.
* The top layers were set to 9999 because Cura tends to make the top layer of a higher quality. By setting every Layer to a top layer, the detail of the print should be higher
* Retraction and z-hop when retracted is enabled. The retraction distance is 0.1mm and z-hop height is 0.4mm
* The ‘skin overlap’ setting is set to -0.1mm. This will make it so that the needle tip does not collide into other already printed structures and potentially get stuck. This setting might need some tweaking depending on the extrusion.
* The ‘wall ordering setting’ was set to ‘Inside to Outside’

03 Project work and results

3.1 Meca500 handling

3.1.1 Robot Workspace and Singularities

A common description of 6-axis robots is the reach and some sort of working area. The reach is the the maximum distance between the robot’s wrist center, which is defined as the intersection point between the axis of the last three joints of the robot and the first, also called base, joint. Figure [X] displays the area of attainable poses for the robot wrist center. The workspace itself, which is the actually space of reachable poses however is highly non-linear and highly dependent on the end effector configuration. The actual description of the workspace is 6 dimensional and generally impossible to display graphically.

A drawing of a mechanical arm

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When handling the robot, one needs to make the distinction between the base reference frame (BRF) and the tool reference frame (TRF). The BRF is the static global coordinate system with origin in the base. The TRF however the coordinate system associated with the actual endeffector and origin in the tool reference point (TCP). It moves with the end effector and the software allows for it to be set up dynamically.

[Different configurations]

In every six-axis robot, there exist certain points where the robot end-effector loses certain degrees of freedom, for example it can’t move in a certain direction. They are critical in the utilization of robot arms. They are not a mathematical construct but the real physical restriction of certain configurations [example sketch]. The existence of singularities can lead to a loss of control, theoretical infinite velocities and therefore unpredictable behaviours. These considerations must be taken into account when doing the path planning and need to be included in control algorithms. Theoretically they can be combatted by introducing further actuators to create redundancy.

Because the Meca500 is a small robot with limited reach and the setup required for the print of structures is large in comparison, it is clear that it would not be possible to print very large structures and reach all the poses necessary.

To tackle this challenge, it was necessary to determine the limits of operation and gain an intuitive understanding by trying to reach the extreme positions necessary for the 5D printing process. Because this was done in the early stages of the project, there were a various uncertainties which had to be taken into account such as the size and length of the printhead, the available space in the chassis, the mounting and position of the base in relation to the print bed. For this reason, a modular printhead was designed and produced with the goal of gaining a higher intuitive understanding. The following description are by no means a complete discussion but a best-effort analysis of the various approaches considering uncertain conditions.

3.1.2 Vertical arrangement

This arrangement is the most employed arrangement for 5D printing which has already been used in previous research and was the most straight forward approach. However, the problem, especially with longer printheads, is that the available print size shrinks to zero, or even becomes negative as soon as the length of the printhead reaches half of the reach of the Meca500. And even if it would only approach the length of the reach, it would mean that the size and height is severely limited. The main problem with the Meca 500 is that the robot size and reach is very small compared to the necessary size of the printhead as well as the limited joint angles. The joints are not continuously turnable and are also mechanically limited by the arm structure. One cause for headache was also the often-occurring collision with the base when trying to reach poses with high angles. Because of these reasons, this arrangement was deemed infeasible.

3.1.3 Perpendicular arrangement

The next arrangement that was tested is one where the nozzle is oriented perpendicular to the axis of joint 6. In this case collision with the base would be very marginal, when printing with high angle poses. For these kinds of poses it would work well and the reach of the robot would not pose a big restriction. However, the most concerning problem in this arrangement was in fact the low angle poses, meaning the poses that would be printing close to planar layers. In these cases, it was necessary to double-twist the arm to get into the right positions. This is not necessarily an issue. However, the configurations that allow the robot to reach these poses from different sides are in different configurations so that to move from one of them to the next, it needs to move through a singularity. While this is generally possible with the Meca500, it is still unreliable and not possible from every start to target position. Therefore, this arrangement was discarded.

3.1.4 Tilted needle arrangement

As an option in between the vertical and perpendicular arrangement, tests have been made to find out if tilted needles would perform better. Three needle angles were explored at 60°, 45° and 30°. However, none of those arrangements performed satisfactorily, enhancing or diminishing problems with the previously explored options. Collision with the base would be one of the biggest problems.

3.1.5 Rotating base

Inspired by the paper of [] reinfocedFDM, this approach was developed. Their system utilized two rotation axis around one horizontal rotation axis and one vertical axis relative to the previous rotation. Due to the flexibility of the Meca500 the decision was made to simulate one of the rotation axis by keeping the arm tilting movement in one axis and then rotating the base in a way that the real orientation plane would coincide with the robot tilting plane. This design went through a few iterations but in the end this concept seems feasibile to print all kinds of poses up 80° rotation from the vertical axis and therefore selected. [more explanation and sketches] and math…………

3.1.6 Varied base mounting

Other options including the mounting of the robot on the wall or the ceiling of the chassis were also explored. Even though not selected due to structural and vibrational reasons, the wall-mounted robot might also work. The ceiling-mounted robot will not work because of the joint limitations of the robot. As can be seen in [previous sketch], the reachable points for the wrist are severely limited in the space above the robot and behind, which makes it infeasible.

3.2 Plotting

The first step in order to start the project was to be able to control the robot using the mecademicpy API and a custom program to read .gcode files and translate it into positions that the robot should follow. To test this out, a custom designed pen holder end effector was designed to plot a single planar layer using a white board and marker. These tests were successful, and this was the basis for the subsequent layers of code that were integrated into the system.

3.3 GUI

The next step was to create a graphical user interface that could be used to control the robot. It consists of a few general robot control operations such as initialization and calibration as well as real time control options for the print such as the z-offset and speed control. Additionally there is a terminal, that displays relevant information and a status bar that displays the current printing state.

Idle operation and deactivation of buttons, How slicer work, motion queue, checkpoints

* Initialization: This button connects the controlling PC to the robot arm via TCP/IP as well as the Arduino via a COM port. The program itself searches for the correct COM port to use. Both of those need to be synchronized and respond with a confirmation for the program to proceed. The Arduino makes the rotating base turn in quick succession and command the robot arm to reach a starting position. A Remark shall be made that Ultimaker Cura can interfere with the connection to the Arduino. If there is an error in the connection, then it might be because of that. To mitigate one needs to close cura and retry.
* Select File: By pressing this button, the file explorer window opens, allowing the user to select a file to be printed.
* Start printing: This will start the printing process. Firstly it reads the .gcode file line by line to extract the relevant information about the model. Then it will activate the ‘preview print’ button and start the main printing loop. Only then will the robot arm move to start printing.
* Pause Printing: When trying to pause the printing loop, the robot will not react immediately but finish the commands stored in the motion queue and then turn into a position that presents the print until further input. The button itself will change label into “resume printing”. If clicked again, the robot will recommence printing at the same point in the print as it has been stopped before.
* Stop Printing: This button stops the print and slowly moves the printhead back into the starting position. After this, one can reselect a file and start printing again.
* Calibrate: This calibration pose is used to determine the z-position. In order not to collide with the base, if it is slightly too high, the calibrate button moves the robot arm into a position 10mm above the print surface. One can the use the z-offset buttons to correct the orientation and then stop the calibration again by repressing the same button.
* Status: The status field shows relevant information about the printing state such as the file that has been selected, the print progress and the printed structure.
* Print info: This works similarly to a terminal and displays some information about the system and helps the user keep track of what happened.
* Z-offset: The two arrow buttons allow the user to control the z-offset in increments and decrements of 0.1mm. For more control, the field that displays this offset is writable. By writing a number and pressing enter, a finer control is possible.
* Speed: This modifies the printing speed at a percentage of a base speed in increments of 5%. The field is writable in the same way as the Z-offset. Note that even though the system theoretically allows very high speed modifiers, there is a physical limit to what the system can achieve. Note also that with the pressurized extruder setup in place, there is no way to control the extrusion speed so the user should refrain from modifying carelessly
* Extrusion: This allows the user to modify the amount of extrusion that is done. The program takes the extrusion information from the .gcode instructions and multiplies it with a constant, which can be modified by using this button. Note also here, that with the pressurized valve, one cannot control the extrusion amount. In this case, this button has no effect.
* Reset System: This button aims to reduce errors that might happen with the robot arm. By pressing this button it send error resetting commands to the robot. This is by no means a complete reset. For a complete reset the user should restart the software.
* Preview print: This button gets activated once the printing process is started and plots the extracted coordinates from the .gcode file and plots it in a separate window.

While this system is not perfect by any means, it allows the user to use the SonoBone setup without diving into the code.

sssA screen shot of a computer

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3.4 Acrylate printing with lead screw extruder

To create 3-dimensional structures we collaborated in the SonoBone team to create a setup that is able to print and cure acrylate. The main component of the extruder and print head were provided from a previous setup and adapted for the robot arm. The addition needed for curing acrylate consists of six UV lights in a fixture designed for the robot arm. This design was also shared with other team members for their setups. The methodology has been described previously. The code used in this setup was solely planar.

The results with this setup have been very inconsistent. The main challenges were the lack of control of the extrusion flow. Even though the program is able to send precise position commands to the stepper motor controlling extrusion, the real flow is dependent more on the pressure in the fluid channel. In some cases, the flow would continue to print multiple layers without the motor even being connected to the power supply. Under these conditions it was hard to adjust the flow to not over-extrude. Both under- and over-extrusion are significant problems. If the printer extrudes too much ink in a short amount of time, a puddle of ink forms, not only destroying the print structure and precision but also trap the needle in a well after curing. Because the curing process was done continuously, the needle would get stuck either shortly after overextruding, or if it continued the print and printed the next layer, it would get stuck.

Another issue was an inconsistent curing. In some cases, the ink would cure very shortly after leaving the nozzle and then form a blob that would stick to the nozzle and attach more ink to it. Once it received enough weight to fall off or some collision made it detach, it would drop into the previously printed part and adhere to the previous layers. This would have a similar effect as the previously described challenge. In some rare cases the ink would cure even faster and lead to a clogged nozzle. In all three cases the print is unusable and needs to be aborted.

05 Discussions and Conclusions

Acknowledgements