UNIVERSITY OF LINCOLN

Investigative Development of 3D Printing Technologies, for the Production of Robotic Limbs

Final Year Project: CMP3060M: Item 2

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Family and friends, for their support over this long journey.

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Introduction

Biomimetics

The art of synthetic replication/ mimicry of biological systems. Here it will simply refer to replication of systems such as the human skeletal system, and other structural animal systems.

Stereolithography

Stereolithography (SLA), the metaphorical keystone that constitutes the future of biomimetics prototyping (BP). This project focuses on a single multi-layered outcome, to better universally enable BP. Let me begin by breaking down this outcome and the constraints that constitute it.

How would anyone make anything more accessible?

Clearly to make anything more accessible, making it easier to understand, attain, apply and use would be the most intuitive ways of doing this. In other words, by reducing the barriers that make it, in-accessible. These barriers can be abstracted as two types, knowledge, and ability barriers. These barriers, when examined in biomimetic robotics, would be:

1. Accessible and applicable knowledge of biomechanical systems.
2. *Broadly* the ability to produce these biomechanical systems.

This project will be principally concerned with the second of the prior barriers, as the first can be solved by other external resources which go beyond the scope of this paper.

From here on I will refer to overcoming the second barrier as, the *goal*. The *what* has now been established, what remains unanswered is, the *why*.

Why would, and why should, a computer science student undertake a project to improve the field of biomimetics? Surely biomimetics and biomechanics are fields of biology and engineering respectively?

Yes. Pure biomimetics and biomechanics are not true fields of computer science (CS). Achieving the goal however, is. To elaborate:

- Achieving this goal requires skills, abilities, and knowledge which are multidisciplinary. But the control structures, algorithms, methodologies, and optimizations which are the main constituents of the later proposed solution, are firmly in the field of CS, and further CS techniques and understandings.
- The outcome of this goal, would also see the field of biomimetic-robotics grow, robotics being itself a field of CS. Enabling a new paradigm in algorithms, being that of mimicking biological systems, such as responses, reflexes, and hopefully further down the line whole humans indistinguishably.

What solution(s) could be used to improve peoples' ability to produce biomechanical systems?

Simply, additive manufacturing. In more detail increasing accessibility to additive Stereolithography to better enable biomimetic robotics. Cutting through the jargon, a simpler, cheaper, and as-high-precision as required, 3D printer. Which leads on to the project aim.

Aim

Aim: Development of an SLA 3D printer, for prototyping biomimetic anthropomorphic skeletal systems; minimising cost, while maintaining similar model quality.

Literature Review

Since this project is made up of several different fields, this review will be grouped by topics/ fields. This is to help comprehension, and to aid in succinct discussion.

Current 3D printing & how this will affect the final artefact

Currently there are many different types of 3D printing:

1. FDM (Fused Deposition Modelling)
2. SLA (Stereolithography)
3. DLP (Digital Light Processing)
4. SLS (Selective Laser Sintering)
5. SLM (Selective Laser Melting)
6. EBM (Electrong Beam Melting)
7. LOM (Laminated Object Manufacturing)
8. BJ (Binder Jetting)
9. MJ (Material Jetting) (ALL3DP, 2016)
10. … (Esoteric)

For conciseness, only the top 4 will be considered, as the rest are either in early stages of development and/or are far more prohibitively expensive than would be reasonable to attempt. These 4 will be considered as the 3D printer solutions to facilitate biomimetic prototyping.

Short summary on 3D printer types (ALL3DP, 2016)

Type	*Advantages*	*Disadvantages*
FDM	Low Build Size Cost Fast Large Community Many & Varied Materials Large Build Size Expandability/ Hackability	Warping Jamming Medium Quality (Relative) Temperature Volatility Calibration Noise High Internal Impulses Permeability
SLA	High Quality Energy Efficient High Initial Cost Sound Low Internal Impulses Selective Permeability	Light Volatility Moderate Post-Processing Slow Radial Resolution High Build Size Cost
DLP	Fastest Low Internal Impulses Selective Permeability	Light Volatility Moderate Post-Processing Little Expandability
SLS	Selective Permeability No supports required Low Internal Impulses Manageable material Moderat-High Quality	Slow Radial Resolution Moderate Post-Processing High Build Size Cost

Current Biomimetics Robotics & considerations to accommodate it

To find an appropriate solution of these 4, which also complements the requirements of biomimetics. The requirements must first be analysed. This is what this following section attempts.

Looking at current biomimetics papers

In current significant biomimetic-robotics research such as Todorovs (2015) paper. They use a relativele high resolution 3D printers, of 0.025mm. Todorov (2015), also states that the robotic arm could be printed on a "tray" of 200 -200mm. It is important to note however, that this is specifically the arm, and speaks nothing of more demanding human components such as femurs or the three ossciles. Although not explicitly stated, the timeframe, size and wording would suggest that they used either a DLP, SLA, or SLS type 3D printer. As in 2015 or earlier few commercialy availiable FDM 3D printers could achieve 0.025mm resolution, and consistency. The term tray, is also primarily used to refer to resin trays, wheras in FDM they are called (heated) beds or plates, as they have no need to hold a substance, and therefore do not have edge lips which are constituents of trays. This use of resin based 3D printers or more specifically stereolithography, is also present in other similar papers such as Stanton (2015), and Peele (2015). Cummilativeley these papers suggest that they used stereolithography, to improve on their respective systems degrees of freedom (DOF), because of stereolithographic abilities to produce accurate biomechanical models and soft actuators, which they propose to be key. As such this will need to be accomodated in the final solution by it being a resin type 3D printer itself.

There are problems/ gaps not dealt with by these papers however. Cost. To elaborate all these biomimetics-robotics papers mentioned prior, speak passibly or not at all, about the cost of these systems, or how they attained/ accessed them. The reason why this is important, is this is a direct barrier to biomimetic-robotics prototyping, which is the root of the problem this project seeks to solve. This gap could have been made irrelevant, if there were already open source/ readily availiable, solutions that can match or exceed the requirements of biomimetic-robotics, but curentley, there are no wholistic, accessible resources that facilitate Stereolithography on this scale, and cost. This means that not only will it be necessary to reduce cost in these systems, but new systems will need to be deseighned and implemented, since no fit-for-purpose solution is accessable. This effects the project as it will need to tackle both gaps/ problems of, cost and development.

There are two possible avenues to solve this development problem, to use similar/ conceptual desighns to create an SLA 3d printer from pure understanding of the underlying mechanics, and/ or using the original, expired SLA 3D printer patent, Vinson's (1993) "US 5610824 A". Both of these avenues, have problems. Firstly the patent avenue; This patent is written to make it difficult to replicate the invention, while still being explicit enough to be patentable E.G.

> "directing said beam at said working surface of said medium for forming said successive cross-sectional laminae of said object including scanning…" (Vinson, 1993)

This makes this patent a very difficult schematic to follow or adapt for our purposes, and unsuitable on its own. The second avenue; conceptual apparatus and expand upon them, such as the apparatus described in Bethany C. Gross's (2014) paper examining and describing stereolithographic and other 3D printing apparatus, along with file formats such as STL and GCode, which are the current standards in most desktop 3d printers. Between the two avenues, the latter is intended to be clearer and with less jargon, making it more suitable for this projects needs.

What Software is Currently Available?

Currently, there are few SLA 3D printer specific software packages, and of those packages many confuse DLP with SLA, which are incompatibly different methods. To discern what falls into the SLA category the original patent for 3D systems can be used. An example of the available software on GitHub, can be seen in appendix figure 12. In this figure, there are five results, of those five the last one is this projects repository. Excluding this fifth result, only two are true SLA software packages, the rest being wrongly labelled, as they use projection systems instead of point/ laser polymerisation. This lack of relevant software, would suggest that there is little open community in the field, which would make this project harder, as there are less support materials, but also make it more necessary to fill the gap. As such this effects the project outcomes, such that the schematics and software needed to create this apparatus will upon completion be made public, to fill this void, and further the goal of making biomimetic-robotics *more accessible*.

Aim & Objectives

As discussed in the literature review, there are aspects that are currently missing from academic papers or the public domain. An accessible (in this instance being low cost), 3D printing apparatus suited for biomimetic robotics. As such the aim, should be to solve this problem. To formalize this:

Aim: Development of an SLA 3D printer, for prototyping biomimetic anthropomorphic skeletal systems; minimising cost, while maintaining similar model quality.

The objectives to achieve this end, should be split into the constituents that are required to make this aim true, since these topics have all been discussed within this paper, they will simply be listed:

- SDLC development of SLA hardware
    - Cost effective
    - Appropriate for biomimetic-robotics
    - Safe (alaRA)
- SDLC development of SLA software
    - Efficient algorithms
    - Interfaces with hardware effectively
    - Capable of accurate representation of models
    - Capable of handling large bone STL files which is 3D printer as discussed prior
- Comparison of apparatus capability to other professional apparatus.
- Publication of this projects knowledge, to improve upon accessibility of biomimetic-robotics prototyping, as proposed in literature review.

Methodologies

This methodologies section will be split into conceptual and practical requirements of the project, and evaluate what methodology is most suitable for this project. The reason this topic comes as two parts is that, each part comes to differing conclusions and that showing how a decision is formulated is important, to understanding how the project was undertaken.

Conceptual Requirements of Methodologies

Conceptually, this project has certain restrictions/ considerations that must be assessed to decide on a suitable methodology model:

1. Time restrictive, an artifact must be delivered by a certain date.
2. Safety conscious, as it is a physical artifact that can come with its own concerns.
3. Limited resources, since this project is focused on cost reduction and availability.
4. Complex and large multi-part system, with physical interfacing and real-world phenomenon.
5. Stable Requirements.
6. Enthusiast/ expert end users
7. Only one single member in the project.

Now that the main SDLC considerations have been outlined, these must be evaluated against the different SDLC models, to find the best candidate model. When these requirements are evaluated against Balalji & Murugaiyan's (2012) comparative study on SDLC models, it would suggest that waterfall is the most applicable for this use case. As:

1. Time restrictive – waterfall phases are completed in a specified period, then is frozen, and the next phase begins. This means that with waterfall sticking to time restrictions is simpler, when compared to something like V or agile models. Agile models can instead be more difficult to judge time required for the development.
2. Safety conscious - Requirements in waterfall are set and do not allow for creep/ changes that would compromise prior planning/ safety considerations, unlike that of Agile.
3. Limited resources – Waterfall takes minimal amount of resources to implement, and allocation of resources is understood and can be planned for.
4. Complex system – Waterfall allows for a simplification, through use of a step by step process, allowing for little concern for what is outside of current phase.
5. Stable requirements – Waterfall relies on stable requirements, which is facilitated in this project, while also reducing the theoretical benefit of using an agile model, since no changes in the requirements are to be expected.
6. Enthusiast/ specialist end users – Who can adapt the project to their needs, meaning only the most core functionality is needed to help them create this apparatus effectively, since they will likely create their own adapted versions to their needs. This also means no feature creep since a set core functionality is needed, therefore no gains in using a more complicated agile model, to handle this feature creep.
7. Single project member – Meaning only one thing can be worked on at any given time, and attention splitting could be harmful to the end artifact, making waterfall a better suited solution.

In conceptual conclusion, this project would appear to be well suited for waterfall, as many of its restrictions/ considerations are handled better by a simpler and more controllable SDLC model. The issue highlighted in the next section, are the implications of how impractical/ unrealistic waterfall is, even under well suited circumstances.

Practicality of Methodologies

As discussed previously, this project conceptually fits a waterfall style model. Waterfall was as such the original method used. After some time into the project, it became increasingly apparent how there was a requirement to go back and adjust previous work, as bugs or unforeseen obstacles, need to be accounted for. A common example, would be small details that were not included in prior plans, such as specific bolts being overlooked or having the wrong size thread/ length for their application, or for the software having to adjust code already completed and functional. An example is the packet manager (packman), with each iteration using different protocols, such as raw, TCP and UDP packets. The reason these iterations were necessary is that they allowed for more reliable/ faster communication more suitable for communicating to and receiving on an ESP8266 chip.

Final Methodology Conclusion

While in theory the most well suited methodology is waterfall. The reality of such a project stands in opposition, being more well suited to a more practical agile model, as no project can follow a plan without adaptations, while still having a successful outcome.

Evolution

As noted previously, this project follows an evolutionary framework. To make the evolution more succinct and comprehensible, this section will present this development as if it were waterfall, and outline iterations in their respective sections, E.G any iterations or changes made to the design will be outlined in design rather than using a chronological system.

Requirements Analysis

Keyword	*Meaning*
SLA / SL	Stereolithography apparatus; 3D printing, via photopolymerisation.
QoL	Quality of Life; In the following context, means ease of use / operation, usually separate from the functional requirements of something.
FWHM	Full-Width Half-Maximum; Is a method of measurement to find the width of an object, of uncertain edges. Whereby the edges are deemed to be where the intensity falls to half of its highest value. This method is usually used in astronomy.
PB	Push button.
VOC	Volatile organic compound; volatility of organic compounds, and their ability to vaporize, diffusing in air.

Section Introduction

This section aims to briefly gather requirements for SL apparatus, as outlined in the "project: Pygmalion" proposal. To this end, this section will break requirements, into one of two categories, functional requirements and QoL requirements. This is to separate requirements that are key to the success of the project (functional), but also to consider and possibly include requirements that are key to achieving this success easily (QoL). This allows for better prioritization, while still allowing, *if time permits*, the inclusion of these QoL features.

The following is presented as tables/ matrixes, for better organization, and visual recognition. The features are later filtered, through evaluation of appropriateness, to separate features that should and should not be present in the final artifact. This also allows for more dynamic scoping, depending on the requirements found. On investigation, there were no set universal standards, so this section arbitrarily selects the most notable features, based on prior understanding of 3D printing systems.

Please note: the difference *here* between a feature and a specification, is that a feature is considered to be only a reworded version of a specification, so they have been included together. Also, all measurements are in millimeters, unless otherwise specified.

E.G

Feature: SL apparatus can print [moderately] sized models up to x . y . z (mm).

Specification: volume = x . y . z (mm) <- preferred, for conciseness.

Desktop SLA 3D Prtinter Requirements

SLA	**Price**	**Functional Features / Specifications (mm)**		**QoL Features**
Form 1 (FormLabs, n.d.) 	$1,999	SLA Volume: 300 . 280 . 450 Build Volume: 125 . 125 . 165 Axis Resolution: 0.025 . 0.050 . 0.100 Power Supply: 100-240V, 1.5A, 60W	Laser: 405nm 120mW Laser FWHM: 0.155 Weight: 8kg Control: USB	Basic PB control. Auto-generated supports. Auto-orientation. Translucent UV-reducing cover.
Form 2 (FormLabs, n.d.) 	$3,499	SLA Volume: 350 . 330 . 520 Build Volume: 145 . 145 . 175 Axis Resolution: 0.025 . 0.050 . 0.100 Power Supply: 100-240V, 1.5A, 65W	Laser: 405nm 250mW Laser FWHM: 0.140 Weight: 13kg Control: USB, Ethernet, Wi-Fi	Interactive touch screen + PB. Auto-generated supports. Auto-orientation. Translucent UV-reducing cover. Auto-fill resin tank. Swappable resin cartridges. Protected optics. Multiple control methods. Self-heating tank (auto 35◦ C).
XFAB (DWSLAB,  *n.d.)*	€5,000	SLA Volume: 400 . 606 . 642 Build Volume: Ø 180 . 180 Axis Resolution: 0.25 . 0.25 . 0.01 Power Supply: 24V DC (External)	Laser: 360-480 nm 25-250mW Laser FWHM: Weight: Control: USB, Ethernet	"Intelligent" resin cartridges. Translucent UV-reducing cover.
ProJet 1200 (3D Systems, n.d.) 	$4,900	SLA Volume: 229 . 229 . 356 Build Volume: 43 . 27 . 150 Axis Resolution: . . 0.030 Power Supply: V, A, W	Laser: nm mW Laser FWHM: Weight: 13kg Control: Ethernet	Nothing of serious note
Nobel 1.0 (XYZ printing, n.d.) 	$1,499	SLA Volume: 280 . 337 . 590 Build Volume: 128 . 128 . 200 Axis Resolution: 0.30 . 0.30 . 0.025 Power Supply: V, A, W	Laser: 405nm mW Laser FWHM: 0.140 Weight: kg Control: USB	Translucent UV-reducing cover. PB operation. Auto-fill resin tank. Standalone functionality.

Photopolymer Analysis

Brief overview of research, excluding cheaper, and possibly more dangerous unknown resellers.

Photopolymer	*Price*	*Amount*	*Shrinkage*	*Wavelength*	*Fumes / VOC*	*Warnings*	*Notes*
MakerJuice G+ (IMakr, n.d.)	£39	500mL	<3.5%	~420nm	None	Mild irritant	Polydimethylsiloxane friendly, low viscosity.
Functional Prototyping oo-kuma resin (oo-kooma, n.d.)	$125	1kg		385-405nm			Suggested layer height: 25-50 µm
PhotoCentric 3D UV resin (PhotoCentric 3D, n.d.)	£45	1kg	~5%	350-405nm		Irritant	Explicitly, water resistant.
XYZ nobel resin (XYZ printing, n.d.)	$83.99	500 + 500 mL		~405nm	Vapors present, but little specific information.	Irritant, discomfort.	Operating temperature: 18-35°C
Formlabs Clear Resin (FormLabs, n.d.)	$149	1L	~2%	~405nm	Acrylates/ methacrylates, when exposed to high temperatures.	Irritant (cat: 3). Sensitization (cat: 1). Target organ systemic toxicity (cat: 3).	Capable of >25µm resolution. Operating temperatures: 18-28°C

Conclusions

Lack of standardization. Little to no available information. Limited choice, if excluding unknown resellers, selling questionable goods, with high VOCs. Safety information for many is difficult to find. Difficult to determine overall safety, as compounds have little available information, making it difficult to draw meaningful comparisons.

Biomechanics

The purpose of carrying out this section of research, is to both formalize and characterize, the main effects of, biomechanical requirements, on the 3D printing system. As such the principle concerns are that of implementation, namely, what is needed of the 3D printer, to achieve biomechanically representative, and functional prints. This means that this section should focus on physical requirements and capabilities of biomechanics and 3D printing respectively, thus the focus will be on replicating bones.

Bone(s)	*Bone Type (Long, Short, Flat, Irregular, Sesamoid)*	*Replication Difficulties/ Reason for inclusion*	*3D Printer requirements to achieve replication.*	*Difficulty to implement*
Femur (Taylor, 2012)	Long	Longest continuous bone. Smooth rounded femur head. Greater & lesser Trochanters complexity. Intertrochanteric line & crest overhang.	Bed size capable of continuously printing a solid femur. 3D printer of resolving capability to create "smooth" rounded femur head and trochanter sites.	Moderate – attaining accuracy is dictated purely by scanning galvo, and is related to cost, an extremely limited resource in this project.
Sphenoid (Taylor, 2012)	Irregular	Most complex bone in the human body. Difficult to recreate articulation sites, sphenoidal sinuses, and general feature intricacies.	Seamless support structure capabilities, "smooth" and regular form resolution. High repeatability.	Low – Many of these requirements are standard nature of SLA 3D printing, including seamless support structures, if they are even required, because of resin suspension support.
Carpals/ Carpus (Taylor, 2012)	Short	Small feature sizes, high strength, complex intra-carpus sites and mechanisms.	High resolving power, seamless supports and simultaneous carpal printing to ensure mechanization can occur smoothly.	Low – As above.
Pelvis	Flat	Periosteum formation, of compact and spongy bone. Large volume.	High enough volume to encompass pelvis. Supports.	Moderate – Resin change mechanism or alternative to achieve periosteum.
Patellar (Taylor, 2012)	Sesamoid	Included for completion of bone types. Has to be extremely smooth.	Resolving power enough to print small smooth structures.	Low – as previous "lows"

Conclusions

Apparatus requires a large printing area, to be able to print large bones such as pelvis and femur. A high resolution to be able to support printing the carpus, and mimic smoothness of the trochanter and femur head.

Design

For clarity, this design will be split between hardware and software.

Hardware

The requirements analysis completed prior, meant that the specification of the printer is known. By using 3D MRI models of the most significant human bones, it would make it possible to work backwards and create a system around these models, to ensure the design meets specification.

To accomplish this however it was necessary to find accurate 3D models of human bones, which as was quickly apparent, are difficult to find. After persistent attempts, an appropriate solution was found, namely Okubo's (et al, 2013) anatomical dictionary. This dictionary contains all human bones, by ethnicity, gender, age, location, and types, along with having other highly relevant vascular, muscular, and other internal systems mapped in the same way. This dictionary has many versions, such as 'heart5.0i' or 'brain5.0i' which specialize on different human constituents. For our purposes, 4.3i was used as it has the most relevant bone dictionary. This paper will not go into further detail about this dictionary, but it is an important resource for this project, and is highly recommended.

As planned the models from Okubo's (et al 2013) anatomical dictionary, were used importing them into 3D modeling software to form the size requirements of the 3D printer which can be seen below figure.

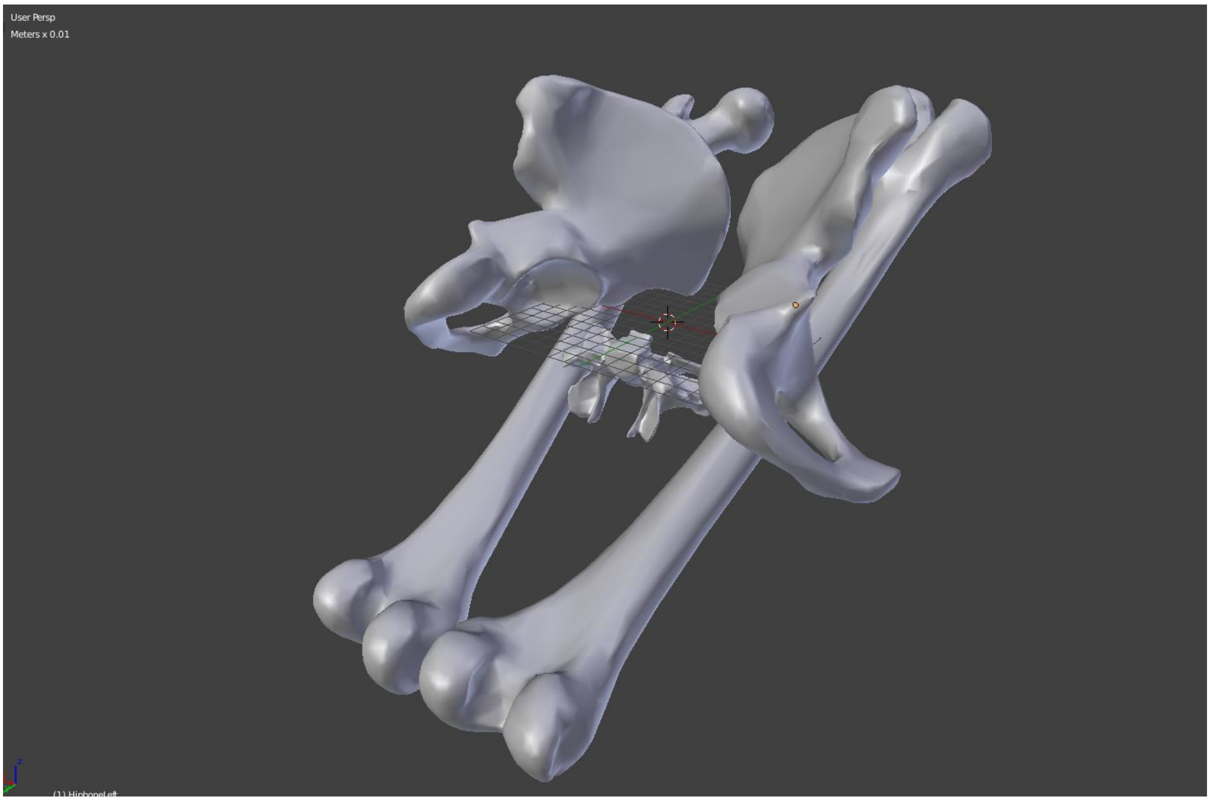

Figure 1: Image of Blender imported, dictionary models.

The 3D modeling software used was Blender, because its open source, real-world scalable, powerful, and because I as the investigator, had many years of experience with this software, making it an appropriate fit for the resources available (both monetary and skill).

Now that 1-1 models of the significant human bones are present; it is possible to build up a simple design based off of the requirements analysis. That being a bottom-to-top SLA style printer (figure 2), based on current, commercially available 3D printers, and available materials.

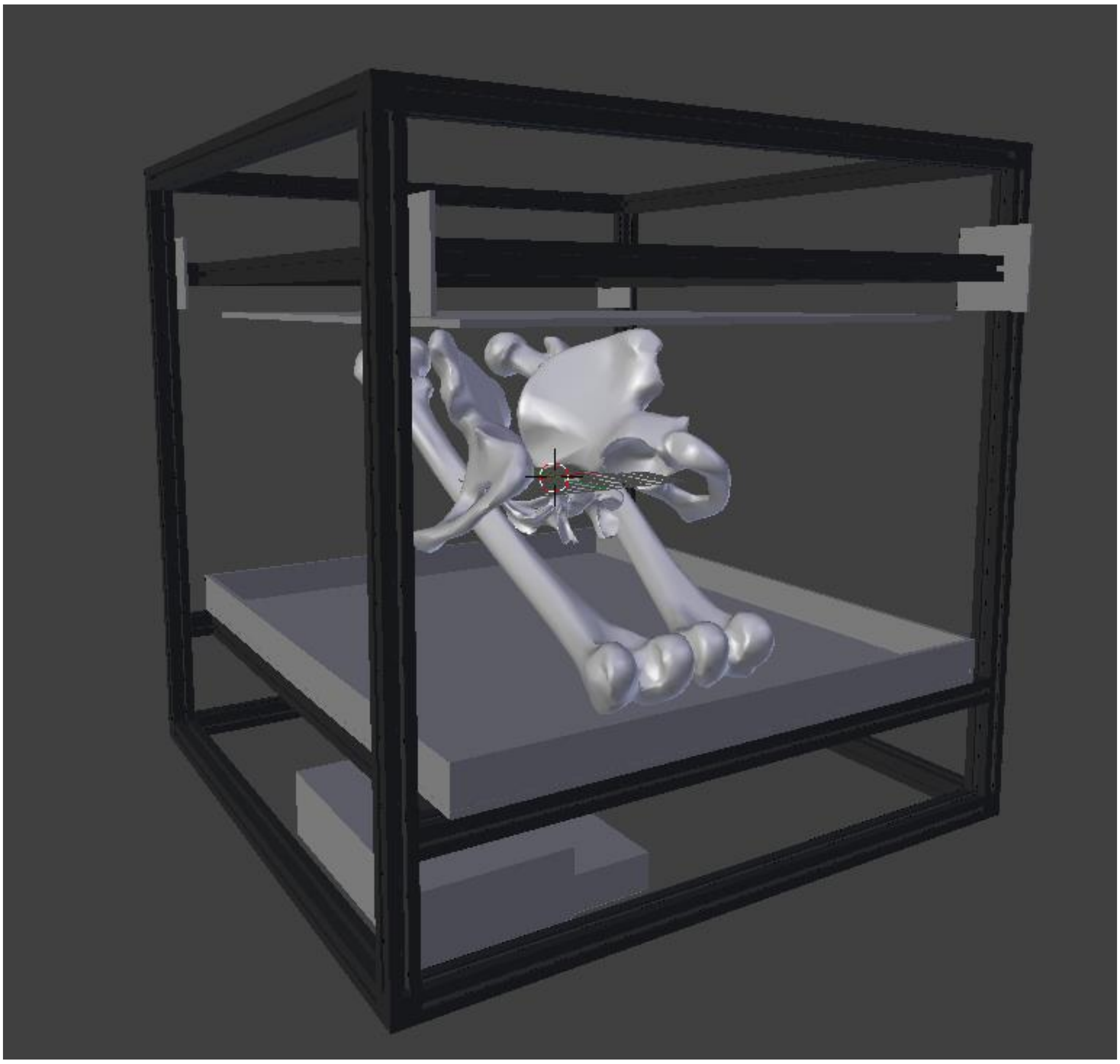

Figure 2: Basic bottom-up 3D printer with no actuators.

The principle difference between this frame and standard frames, are that:

- Each different type of piece, is self-similar. E.G, every frame section (black in the images) are exactly 500mm long, meaning no unique pieces are required, and this makes it easier to manage and construct since any frame piece can be used in any slot.
- The print tank/ tray and plate, are separable by significantly larger volumes than is currently available for the same price (see requirements analysis).
- The apparatus frame is also the actuator system, saving cost and complexity since one piece fulfils both roles, for an overall reduced cost.
- The large print volume has much larger distortion that needs to be accommodated, since galvanometers have arc segment accuracy, and increasing the distance to the galvanometer (arc radius) means any degree change results in a larger arc length change than one of smaller arc radius.

The following figure shows the initial apparatus design, after adding the final actuator mechanisms, which are necessary to animate the system.

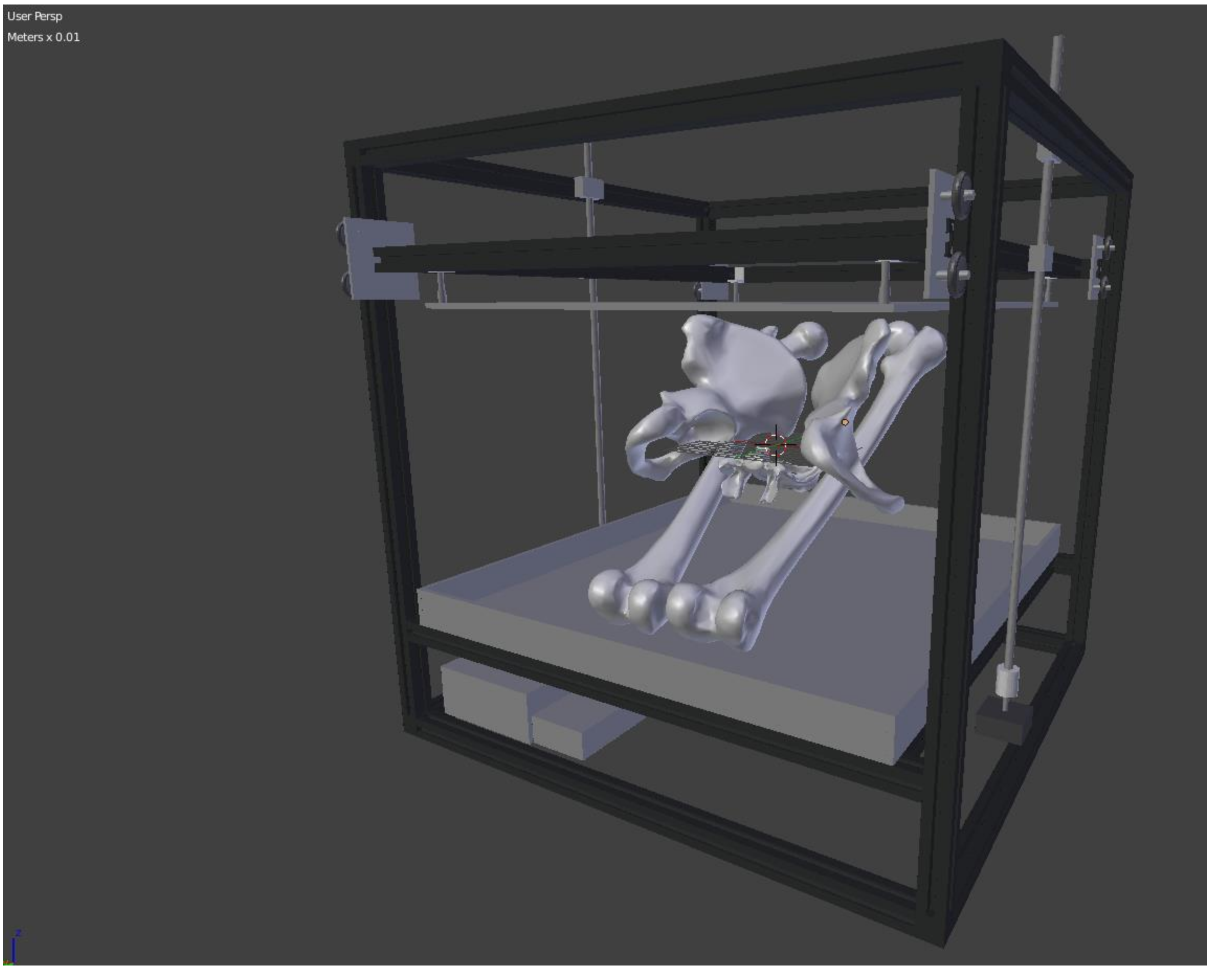

Figure 3: SL apparatus initial design

The main non-circuitry problem remaining are the available galvanometers. The available options:

- Off-the-shelf galvanometers
- Create a galvanometer system

Both options have their own advantages and disadvantages. Off-the-shelf galvanometers:

- Reliable/ blameable if something should go wrong.
- Cost more than their parts, since it is a product, although bulk company production could reduce cost difference.
- Not necessarily easily interfaceable.
- Trust, both advantage and disadvantage.
- May not match specification exactly.

Created galvanometers:

- Created to specification.
- Cheap since no 3rd party.
- Trust implicitly.
- Interface can be made to suit system.

- Risk of low reliability.

After investigating available off-the-shelf systems, and considering the advantages of both prior approaches, creating a galvanometer system, was concluded to be the most suitable, since cost is one of the main constraints of the system, and since creating a galvanometer would result in significantly more control over the system and its functionality.

When creating the galvanometer, there were several considerations that were taken to make the system as fit for purpose as possible:

- Radial accuracy of motor, e.g 200 steps per 360◦
- Controllability of motor, such as deciding between stepper motor and others.
- Driving the motor.
- Reliability of motor.
- Cost of motor.
- Energy consumption.

The most applicable type of motor that is both cheap, controllable and reliable are stepper motors. This allows for a checkless system, since any one whole step can be almost guaranteed, assuming the initial state is known. The drawback of using stepper motors are that they must be continually provided a set voltage to prevent the motor from slipping, which increases the power consumption. Since electrical power is relatively cheap in the short term, this power consumption should not be of much significance, when compared to implementing more specialised and costly motors. Secondly the accuracy of the stepper motor is dictated by the steps per rotation. In our case 200 step, stepper motors are used. This results in $\frac{360}{200} = 1.8^0$. This on its own would be too large of an angle but combined with solutions like the A4988 driver boards, the steps can be reduced to $1/16^{th}$ their original size. The drawback however is that only the full step can be guaranteed, but the intermediary steps are dependable enough in this application to be minor inaccuracies for the cost. This results in an angular change per step of $\frac{360}{200*16} = 0.1125^0$. A significant increase in the steps per rotation and accuracy of the galvanometer, namely 16^{th} fold reduction.

Originally planetary gears pictured below, were intended to reduce this angle even further resulting in higher accuracy. But after calculating the accuracy of the galvanometer system with just A4988 drivers and steppers alone, this would have just added more mechanical complexity (and thus more places for the printer to go wrong), than was necessary for the application. Furthermore, the design was later updated to not include these planetary gears, due to the previous considerations.

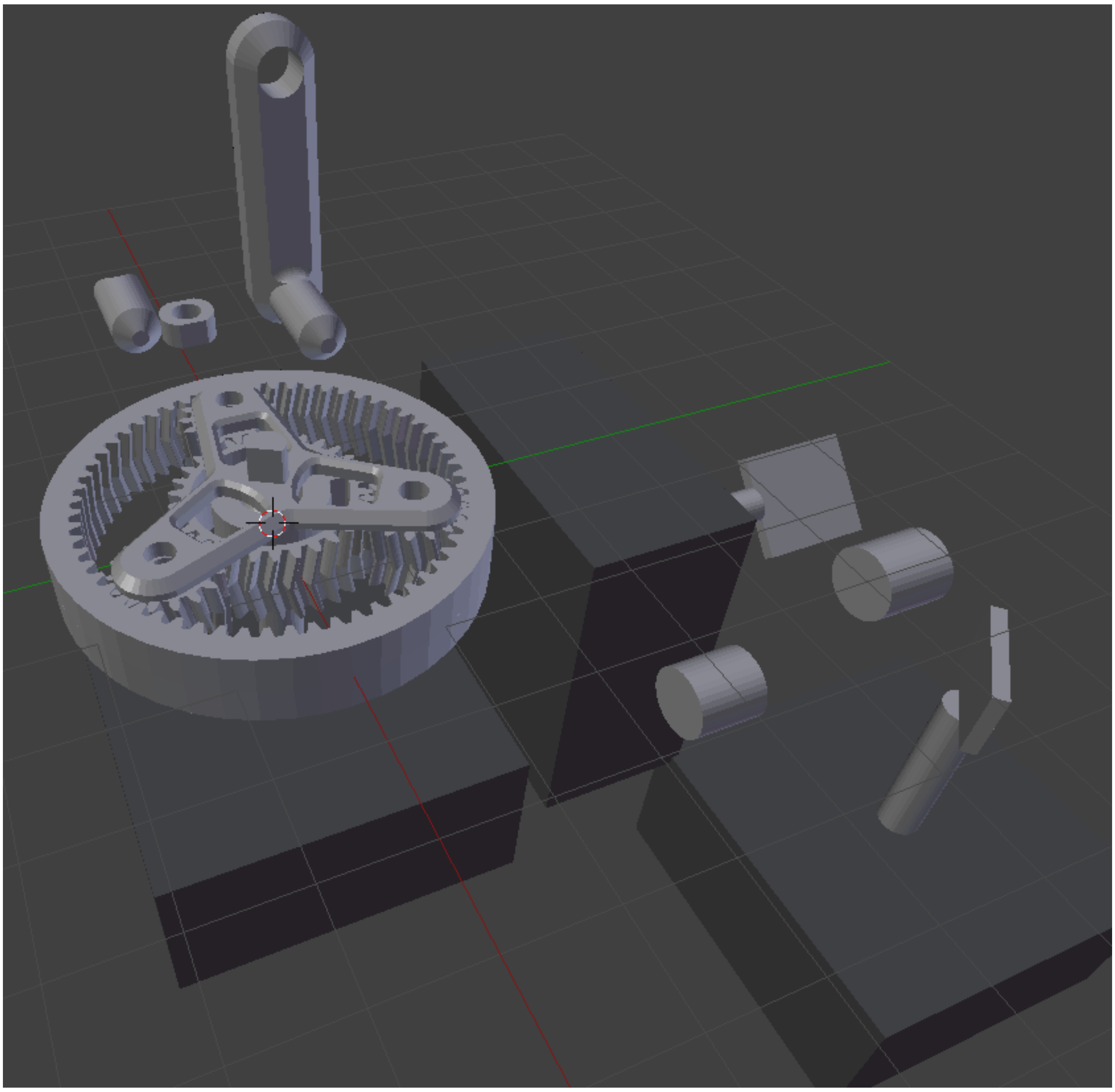

Figure 4: Planetary gear and stepper motor galvanometer conceptualisation.

Lastly circuitry design. The circuitry is abstracted into 3 different constituents, the laser, motor and huzzah circuits, as can be seen in the following figure. To keep this quite large design step from being unnecessarily long, only the rationalisation of the circuit will be discussed, since the specific implementation can be seen in the circuit diagram figure, following.

Rationalisation of:

- PWM; Adafruit Huzzah ESP8266 – cost effective for task, pinouts, ease of interface, debug, wireless capability, real time, does not require high clock rates, as offloading of program to WiFi connected computer system.
- PSU; 24V 200W Power Supply (Non-branded) – Sufficient Voltage to cover motors laser and ESP8266 simultaneously, ease of interface, speed of use under time restrictions, safety.
- Voltage Regulator; LM317 T – Variable, current limiting (necessary with diodes due to increased diode pull over time), cheap, multipurpose, mostly heat efficient.
- Transistor; NPN – heat efficient, cheap, multipurpose, ease of use, fast (compared to say relays)

- Laser; 405nm laser diode – resin most effective cure at 405nm, diodes are cheaper, ease of use and interfacing, but requires good heat dissipation.
- Stepper Motors; NEMA 17 – self similar slotting, high power not required for this application if holding force is sufficient, ease of interface, common in industry.
- Stepper Motor Driver; A4988 – common in industry, ease of use, safety, reduction of pins needed, no need to drive motor using complex aping circuits, all in one solution for speed.

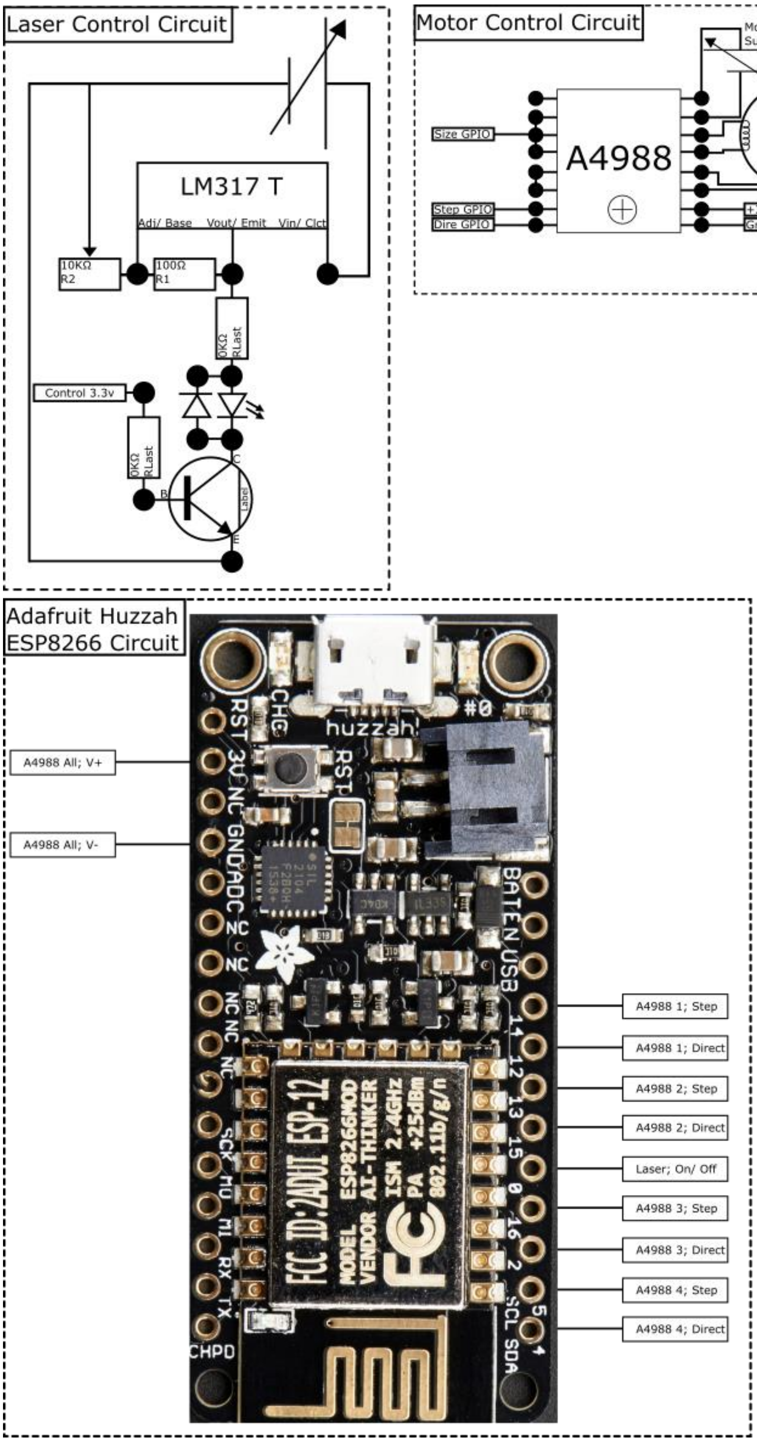

Figure 5: Circuit Diagram.

Software

Language of choice C++, since Arduino is most effective with C/C++ and since I as the investigator, am most proficient with C++ including its standards. C++ also offers the power to create efficient solutions, including individual bit encoding which is the intention initially in the design phase. This C++ program will aim to have as few dependencies as possible to maintain as much cross platform capabilities as possible. This C++ program should also use CMake since CMake is industry standard, and this allows others to configure the build of this program easily. The C++ programs will use tail-end Hungarian notation, to ensure naming conventions are consistent. The only difficulty with this C++ program will be maintaining Sockets for both windows and Unix environments. But cross platform is not a pillar of this project, so will only be maintained within reason, possible solutions could be to use operating system mapping tools such as Cygwin, enabling the program to run on windows platforms if it can run on Unix platforms, by remapping Unix calls to windows variants.

IDE of choice, CLion, since CLion is an environment I am familiar with and use regularly, enabling me as the investigator to work more efficiently. CLion is also a strict environment that enforces CMake on all platforms and Cygwin/ MinGw compatibility on windows, ensuring that cross platform compatibility can be maintained.

Conceptual Abstraction of program done simply to express attributes of agile manifesto; “Working Software, over, comprehensive documentation” (Murray, 2016), and subsequently work on software faster:

- File Class (Host) – handling the file functions, e.g reading and writing files, and storing the data for the rest of the program to use.
- Parser Class (Host) – handling the parsing of GCode directly into compressed/ encoded, executable commands.
- Listener (Arduino) – enable ESP8266 to listen and acknowledge on specific ports and execute specific related commands.
- *Ptr Class (Host) – handling the smart pointer implementation. Discontinued as unnecessary*
- *Slicer Class (Host) – handling conversion of STL file class data, into paths. Discontinued as a plethora of resources do this already and are far more advanced at it.*
- *Packman Class (Host) – packet manager class, using TCP protocol. Discontinued as superseded by RawPackman.*
- *Serial (Host & Arduino) – class dealing with serial connections to and from Arduino. Discontinued as WiFi communication is more suitable for remote operation, and allows for greater flexibility of use.*

Later Iteration additions:

- *RawPackman Class (Host) – packet manager class, using raw packets to send data. Discontinued as does not follow standards, difficult to manage on Arduino, and subsequently superseded by Packman2.*
- Packman2 Class (Host) – Final implementation of the packet manager class, using UDP packets to send and receive data, error checking done by host and Arduino applications and MD5 checksums.
- A4988 Class (Arduino) – Abstraction of motors, so that control can be single A4988 calls to do complex routines. This class also handles the duration of inoperability of a motor between steps, since motor is a physical medium and generates momentum, which cannot be changed as rapidly as the Arduinos pinouts.

Implementation

Hardware Implementation

Following the original hardware design, all the respective pieces need to be ordered. There are problems however sourcing certain components such as the laser diode and photopolymer resin. With both the former and latter requiring significantly longer than any of the other components to be delivered. Secondly the laser class; to elaborate 3D printers used in industry such as the form 1 and form 2, both use 250mW lasers. The issue here is that 250mW laser come under the class of 3B, which causes issues with importing such lasers. The solution, is to use a much less powerful laser of class 3R <5mW. The drawback of this however, is that the print times will be increased as it takes longer to polymerize any single section, and that the penetration depth to which this laser reaches in the resin is shallower. Although this last shallower aspect could be used to increase the z-axis resolution, it forces all models to have more layers, which is a drawback if speed instead of quality is of principle concern. But since this project is primarily concerned with quality for biomimetic-robotics, this should not be a concern.

Creating the frame, cutting and attaching the acrylic, is a simple process, so only images shall be used to describe the process. For the sake of formatting these images will be included in the appendix, figures 13 - 22.

Implementing the circuitry was first prototyped in a breadboard, then in a later iteration soldered into a proto-perm Vero board. This is to allow at least in the early stages, to rapidly prototype the circuits, and allow continuous testing of each constituent circuit. Soldering the circuit was only necessary, to allow the system to be more reliable, and to allow the system to be transported.

Software Implementation

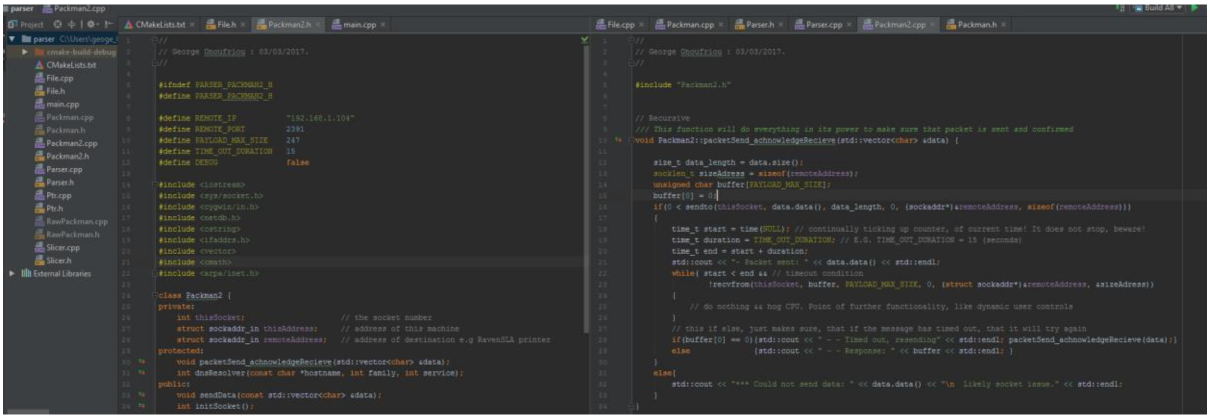

Figure 6: CLion IDE while implementing host code

There was not much deviation of significance, from the original plan, while implementing the host or Arduino code. Getting the two to communicate in an encoded manner was however an obstacle see above figure for example. Parsing GCode into operable commands was also an obstacle.

Software communication

As stated in design, early on in the project, wireless packets were a more fit for purpose solution, since the bottleneck of this system is never the software but instead the rate at which the stepper motors could operate. A major consideration is the activity of the ESP8266 chip and what protocols it can support. This was one of the main reasons why the design had to be iterated away from TCP, as the activity was unnecessarily high, and risked sapping too much power from the Arduino board it was a constituent of, since the Arduino board operated on 3.3V logic and could only handle short burst operations of 5V to operate the ESP8266. After versions shown in the design section, UDP was the best solution, since it was the only one that could be sustained and was maintainable, which TCP and raw packets respectively could not match UDP.

Parsing GCode, into a further quantised state

Firstly, the problem can be visually characterised in the following 4 figures, of when the GCode does not match the stepper motors possible scanner states, which is a common case due to non-relation:

Figure A - Under Pathing

Figure B - Significance pathing

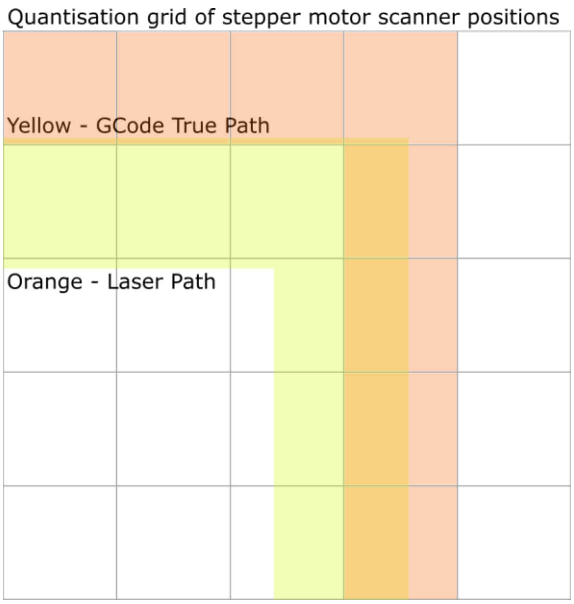

Figure C - Over pathing

Figure D – Compound case of diagonal pathing

Figures A, B ,C and D; show the methods of quantization available at each layer, depending on the instructions of the GCode and how they align with the galvanometers possible positions. A, B and C represent the different possible methods of approaching a quantization boundary, excluding every boundary that is touched by the GCode line. Intuitively including all the squares, that are more than 50% covered by the GCodes yellow path would appear to be the best method. The problem however is for what application. To elaborate, depending on the application of the apparatus, dictates which of A, B, or C is used, E.G if the application was key making, then over printing the boundary would be significantly more impactful than under printing, since it is required to fit within a boundary as it goes in to the lock, and another to attempt to turn the tumbler, and only any excess would prevent it from doing so. This means that depending on the application any excess or any less material could be unacceptable, eliminating two of the three methods if either case is true. For biomimetic-robotics however, accurately representing the biomechanics as closely as possible is the goal. Take the example of a human joint. The focus of a joint is the smoothness of the bone-bone boundary. Which of these 3 methods achieves this best? Under printing the boundary. Take the example of opening and closing in a binary image. If you close the image, you are including all the noise of this image, which could originate from the MRI images readings, which originally dictated the shape of these models. In the opposite case, if you open the binary image, you will be eliminating noise, at the cost of some (in the 3d model case) depth. This latter case is far more acceptable in our example of a human joint, because it:

- Must be as smooth as possible (as little noise as possible)
- Must fit inside a joint (just like the key must be able to fit the lock to work at all)
- Small surface details that of the tubular portion of the femur aren’t critical to the operation of the hip or knee joint.

A formalization of this implementation in the parser class can be seen in the following sub section, and figure, which visually aids the understanding of single component (x or y) movement, in the galvanometer.

Parser Class Abstract Data Type

Distance from galvanometer to bed, $s, (s \in \mathbb{Q} \wedge s \geq 0)$

Minimum step distance, $d, (d \in \mathbb{Q} \wedge d \geq 0)$

Minimum step angle, $a, (a \in \mathbb{Q} \wedge a \geq 0)$

Width of bed, $w, (w \in \mathbb{Q} \wedge w \geq 0)$

Length of bed, $l, \ (l \in \mathbb{Q} \wedge l \geq 0)$

Printable height, $h, \ (h \in \mathbb{Q} \wedge h \geq 0)$

Position tuple, $P = (x, y, z)$

Goal tuple, $G = (x_g, y_g, z_g)$

Laser tuple, $L = (x_l, y_l, z_l)$

Where:

$$x \in (\mathbb{Q} < w) \bigwedge (\mathbb{Q} > 0)$$

$$y \in (\mathbb{Q} < l) \bigwedge (\mathbb{Q} > 0)$$

$$z \in (\mathbb{Q} < h) \bigwedge (\mathbb{Q} > 0)$$

$$xSteps\big((x, \_, \_), (x_g, \_, \_), (x_l, \_, \_), a, s; r\big) :: r = DIV\Big(\big(theta2(x, x_g, x_l, s)\big), a\Big)$$

$$ySteps\big((\_, y, \_), (\_, y_g, \_)(\_, y_l, \_), a, s; r\big) :: r = DIV\Big(\big(theta2(y, y_g, y_l, s)\big), a\Big)$$

$$zSteps\big((\_, \_, z), (\_, \_, z_g), d; r\big) :: r = DIV\big((z_g - z), (d)\big)$$

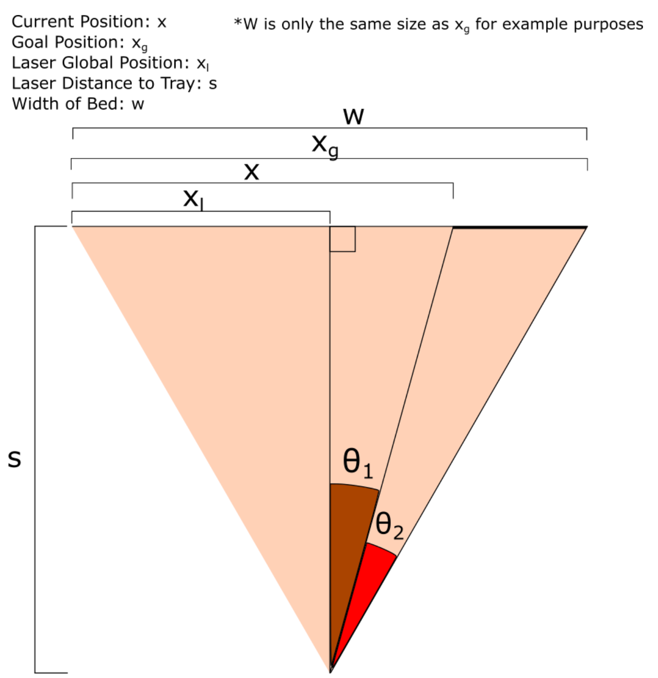

Figure 7: theta2 operation visual

Where:

$$theta2(n, n_g, n_l, s; r) :: r =$$

$$tan^{-1}\left(\frac{n_g - n_l}{s}\right) - tan^{-1}\left(\frac{n - n_l}{s}\right)$$

Testing

Over the many iterations of this project, software and hardware had to be tested thoroughly to ensure safe, reliable and expected operation. Since this artifact is software and hardware, both had to be tested. The problem with testing this system however, is the complex nature of the interactions, especially since all instructions are encoded to increase the amount of transmittable instructions at any given time.

Hardware

The only hardware testable without the software, are circuit connections, visual frame checks, manual frame stress checks. Such as the ability/ smoothness of the actuation moved by hand. Circuit connections were tested using a multimeter, to discern if output is expected. These sorts of checks happened thought the project to prevent compound problems that would almost certainly be non-trivial to solve. An example of this can be seen in the appendix figure 23, of a simple circuit check using a bread board in the early stages.

Figure 8: single test circuit

Software

Software tests were primarily unit tests, ensuring each class and function had expected input outputs and functionality per specification. The main difficulties as described briefly are the encoding blocks used, which make it harder to intuitively harder. E.G using Wireshark to test packets are being sent on the correct network, and with the correct payload. An image of this example can be seen below.

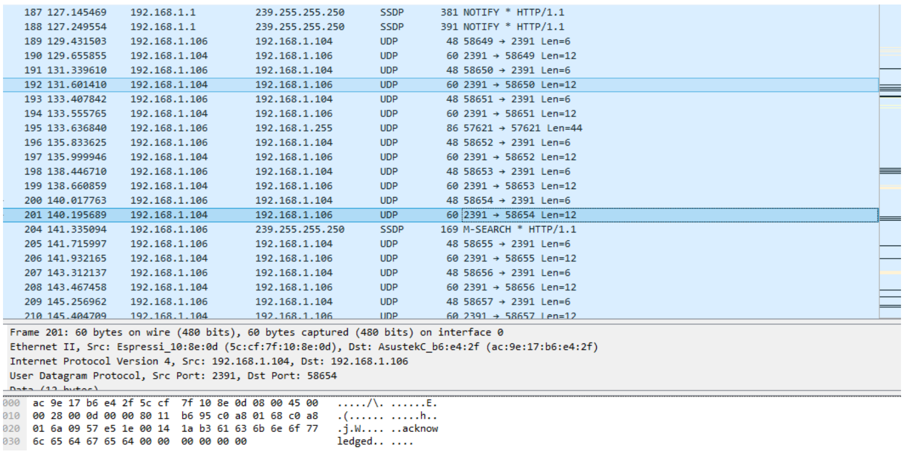

Figure 9: image of Wireshark showing packet acknowledgement

Simultaneous hardware and software

Testing the software or hardware independently would be insufficient, since both comprise the wanted system. This is arguably the hardest part of the process since, problems of all facets of the system could arise. One of the biggest problems solved by whole start to finish printing attempts are, scale. The scale in this system is dictated by many things that are difficult to account for purely in software or purely in hardware. Subsequently getting a model to be 1-1 scale with a physical medium is a difficult task to get correct. Primarily the errors originated from ‘s’ the variable that is the distance from galvanometer to bed, since this area is difficult to take measurements in, and must be tweaked between tests to adjust for inaccuracies. Another difficulty with the whole system testing, is time. This system being a 3D printer, can take large amounts of time to produce viewable results and longer still to get meaningful test results in the form of models. Meaning the rate at which new iterations can be made is significantly slower, than most non-hardware systems.

Evaluation

Cost

Since cost is one of the biggest constituents of the aim in this project, the cost of the system should be the first evaluated.

Name of Item	Unit Cost (£)	Quantity	Total Cost (£)	Total Cumulative (£)
Three Way Cube Corner	3.10	8	24.80	24.80
V-Slot Rail 500mm	4.50	20	90.00	114.80
8mm Lead Screws	23.00	2	46.00	160.80
V-Slot Gantry Set	24.15	4	96.60	257.40
M5 Bolts 25mm (5)	1.25	1	1.25	258.65
Nyloc Nuts M5 (5)	0.44	1	0.44	259.09
Inner V-Slot corner	3.00	12	36.00	295.09
Nema17 Stepper 114oz	15.95	2	31.90	326.99
L Bracket	1.00	4	4.00	330.99
Nut Block	8.00	2	16.00	346.99
Motor Coupler	3.60	2	7.20	354.19
24W 200W Power Supply	19.80	1	19.80	373.99
Nema17 Stepper 21oz	9.90	2	19.80	393.79
Right Angled Stepper Mount	4.00	2	8.00	401.79
Self-Tapping Screws (25)	5.50	1	5.50	407.29
M3 Socket Bolts 6mm (25)	2.48	1	2.48	409.77
Drop in Tee Nuts M3 (5)	1.25	1	1.25	411.02
M5 Bolts 15mm (5)	1.13	1	1.13	412.15
Drop in Tee Nuts M5 (5)	1.25	1	1.25	413.40
Self-Tapping Screws (5)	1.38	1	1.38	414.78
M5 Bolts 6mm (5)	1.00	1	1.00	415.78
Drop in Tee Nuts M5 (5)	1.25	1	1.25	417.08
M5 Bolts 50mm (5)	1.88	1	1.88	418.91
M5 Bolts 55mm (5)	2.00	1	2.00	420.91
2N2222 NPN (100)	8.86	1	8.86	429.77
Laser Goggles (405nm)	9.26	1	9.26	439.03
Acrylic cutter	14.44	1	14.44	453.47
LM317 Regulator (10)	1.44	1	1.44	454.91
Mains Power Lead	5.49	1	5.49	460.40
405nm Laser Diode Module	12.10	1	12.10	472.5
500x750mm Acrylic Sheet (2)	15.98	1	15.98	488.48
A4988 Stepper Driver	3.95	5	19.75	508.23
Gorilla 25ml Epoxy	5.29	1	5.29	513.52
Si CO2 mirror	9.79	2	19.58	533.10
ESP8266 Feather	12.50	1	12.50	545.60

*note: this does not include common tools, of which acrylic cutter is not counted as, but a soldering iron is. This also does not include delivery fees.

This puts the material cost of the apparatus to £545.60, but this will be rounded up to £600, to cover the cost of tools and delivery fees, giving a better indicator of the likely cost for most individuals. Comparing this cost to the currently available SLA desktop printers, which can be seen in the requirements analysis, shows that this apparatus is significantly cheaper than any other major SLA 3D printers. This is however a barebones apparatus, whereas the commercially available ones, have more quality of life features. The difference in cost from those in the requirements analysis is $£1499 - £600 = £899$ when compared to the cheapest one at the time of conducting the requirements analysis. More than twice the cost of this projects apparatus, and a smaller printable area than this projects apparatus. This significant cost reduction is the biggest constituent of the project aim, and would in this regard be a success. When these plans are made available to the public, this would indeed make SLA 3D printing more accessible to everyone, as the cost barrier has been reduced by more than half, in the given examples, even excluding the industrial printers which have comparable print areas to the apparatus created here.

Usability

This apparatus could be improved with more quality of life functionality, such as an acrylic cover, so that safety goggles don't have to be worn. However, this apparatus is not aimed at being user friendly, and more at its capabilities, meaning this usability while still a concern is secondary to the aforementioned capabilities.

Performance

To facilitate this performance evaluation an A-B comparison shall be used, between a professionally printed model and a section printed on this projects apparatus. Since the results are significant enough to intuitively discern, and since no calipers of this precision are owned, a digital comparison using an object of known dimension, to calculate the precision of the 3D printer lines, and separation. Here a two pence coin shall be used, of diameter 25.9mm per the royal mint (2017), as the object of known dimensions.

Figure 10: Image comparison of models, left is this projects apparatus, right is professional apparatus

In the above figure, to calculate the inter-stroke distances, these images were imported into vector software called Inkscape. Per the Inkscape units, the left-hand coin is 2602.85 (arbitrary units) tall and wide, while the right-hand coin is 938.126 (arbitrary units). Taking one sample in these images, would be insufficient so instead the corresponding values are averaged between 5 different points each, which are the red lines in the images. The inter-stroke arbitrary units are averaged to be:

- 26.85 (au) – left average
- 42.386 (au) – right average

These averages can now be used to calculate the inter-stroke size in millimeters by converting these arbitrary units.

To convert the averages:

$$size = \frac{(au\_seperation)}{(au\_scale/mm\_scale)} = mm$$

$$left = \frac{26.85}{(2602.85/25.9)} = 0.267mm$$

$$right = \frac{42.386}{(938.126/25.9)} = 1.170mm$$

This would suggest that the left image has significantly lower separation in its inter-stroke lines. This test however is extremely limited, and could be improved by using finer measuring methods. This test could have been improved upon by having two equally flat or identical objects, since the true distance could be masked by image depth. Due to a short circuit, this was not possible at the time of writing. To minimize the effect image depth has on the calculations both images were taken as close to perpendicular to the surface of the model as was reasonably achievable. As an indicator however, this comparison is very efficient, as it is quick, cost effective, and intuitive.

Have the Aim and objectives been met?

Yes; A development of an SLA 3d printer for biomimetics, has taken place, minimizing cost and maintaining model quality, using efficient algorithms, and cost effective hardware solutions, as previously discussed in this evaluation. These designs will improve accessibility to biomimetic-robotics prototyping, as was the original intention. Some stretch quality of life goals have been implemented, such as adapter power supply connections and the capability to run the printer without having to tether it to a serial port. More quality of life features are still needed to make operation of the printer easier.

Critical Evaluation

This critical analysis will use the Gibbs' reflective cycle framework, to maintain consistency, and to aid readability.

Requirements Analysis

Description

The requirements analysis was straight forward, hindered only by the lack of standardization/ availability of information needed, such as laser width, or presence of VOC fumes.

Feelings

At the time of gathering the requirements in the requirements analysis, it was incredibly frustrating searching for meaningful information, on these proprietary machines, because every company/ manufacturer treated them very differently.

Evaluation

While there possibly could have been more information to find that could have affected the project, I felt that overall this section garnered the required important information, to base the 3D printer on.

Analysis

There is very little literature on the SLA apparatus itself (discussed in literature review), which forced the requirements to come from less significant sources such as company websites.

Conclusion

In conclusion, it would not have been reasonable to have delved deeper into this aspect of the project as, any further gains would likely have had little impact on the final artifact, and this section is more informative of what is currently available, and expected. Give the same scenario I likely would have used lower quality resources again, as there is little to be gained even if there was some information available in high quality literature.

Action Plan

Nothing of significance needs to change in this section, or would help in future other than continuing to develop writing style.

Design

Description

Designing the apparatus and software, so that it could work properly and safety, especially with such a multidisciplinary project is the most difficult part of the entire project. The wide-ranging fields of understanding required:

- Physics; mechanical properties, circuit & force calculations, mechanical understanding
- Chemistry; photopolymer properties, safety, initiation energy considerations and wavelength
- Biology; human anatomy, biomechanical understanding
- *Computer Science; Networking, OOP, algorithm efficiency, modeling, set theory, standards*
- Computer Engineering; circuit building, chip understanding, soldering
- Mathematics; Formal notation, angular change calculations, algebra

There were some small errors in the original plans, that cost time later in the project, due to any missing components needing to be ordered and waited on.

Feelings

I felt this section played to my strengths, because I am quite effective at cross domain problems. As such this is likely also one of the most enjoyable sections, because I can use my plethora of understanding.

Evaluation

Overall this section was very effective, as very little changed/ needed to be adapted. However, there were some things that did need to be changed, such as stepper motor mounting positions, which caused delays of ordering and receiving parts. This was mitigated thanks to a change from waterfall to iterative development, allowing time to be spent elsewhere during these periods (discussed prior).

Analysis

If I was more experienced in circuit design this section could have been completed in significantly less time and with fewer changes to design. Alleviating more time on the rest of the project. But this is a constant in all projects and people.

Conclusion

In conclusion, there was little that could have changed under the circumstances, nor should be changed. As no one is all knowing, and small changes to plans are inevitable. Given the same scenario again, I would design the apparatus in the same way. As such there is no action plan for this section.

Implementation

Description

Implementation is where the most obstacles occurred, due to unforeseen events/ changes. As examples, dead-on-arrival components, or lack of documentation caused making the artifact far more difficult than it should have been. This is also where faults in design came through, such as being unable to follow schematic exactly. Lastly human errors also had a significant effect here, such as wires in the wrong connections on breadboards, which cause other problems like surface mount capacitors being provided too much current.

Feelings

While implementing features, and of course immediately testing them, frustration due to miscalculation or human error ensued. Especially when the surface capacitor for the lasers circuit blew, since it was an important time to produce models for later comparison/ use. Thankfully these problems were solved using my resourcefulness and understanding of the circuits, but it was an extremely stressful experience. A point I like to remind myself, is that so few people could overcome the problems like I did, with an analytical and systematic approach to problems, especially of such a complex domain.

Evaluation

Please see the non-critical analysis, Implementation: evaluation section.

Analysis

Given more time, I would have created the printer with better calibration and quality of life systems, which were documented in the requirements analysis section, while investigating currently available SLA printers. One such addition would have been, a blue-violet wavelength blocking acrylic case, which could have been simply made with orange semi-transparent acrylic, like all the other desktop SLA printers discussed previously.

Conclusion

In conclusion, there were areas where I could have improved upon the implementation, such as better soldering connections, gluing certain bolts to prevent vibration loosening and cleaner acrylic cutting. As mentioned the artifact could also have been improved further if there was more time for stretch goals of quality of life features.

Action Plan

Accept that implementation will take far longer than any other stage of the SDLC cycle, and allocate more time to it. Take and apply newfound understanding of where problems arise to inform on the next set of implementation problems.

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Appendix

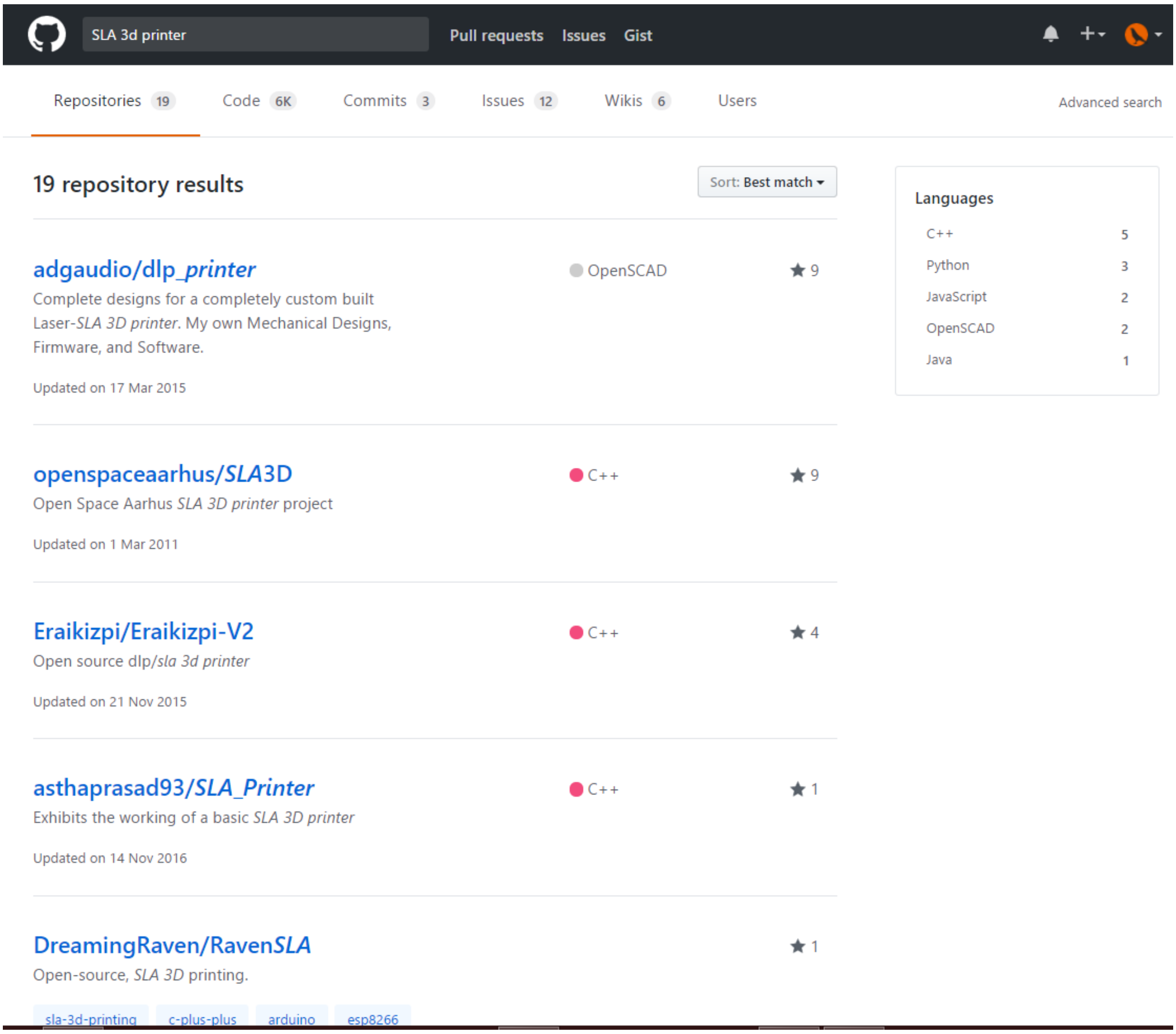

Figure 10: GitHub results page of SLA 3d printer (GitHub Press, 2008)

Figure 11: Frame, front

Figure 12: Frame, front and sides

Figure 13: Frame, gantry

Figure 14: Frame, outer

Figure 15: Frame, Shelf

Figure 16: Frame, Completed

Figure 17: Cutting bed and tray acrylic

Figure 18: Frame and tray

Figure 19: Sanded bed, creating a frosted/ obfuscating effect

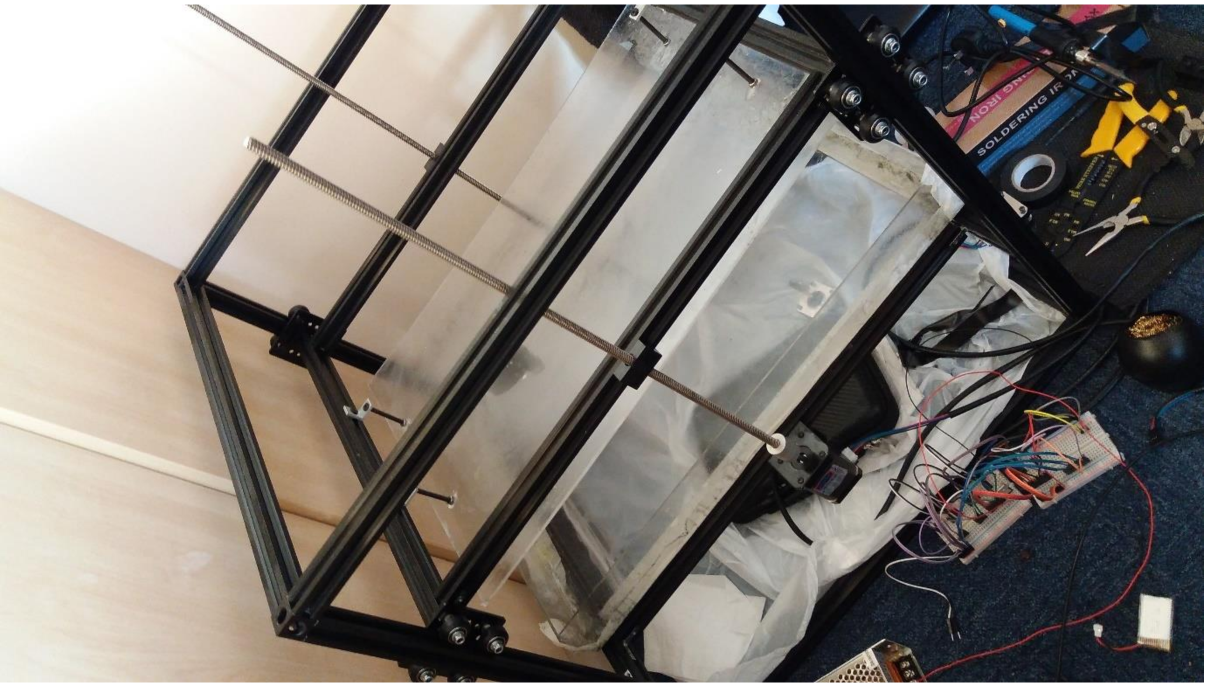

Figure 20: Functional prototype, using temporary connections

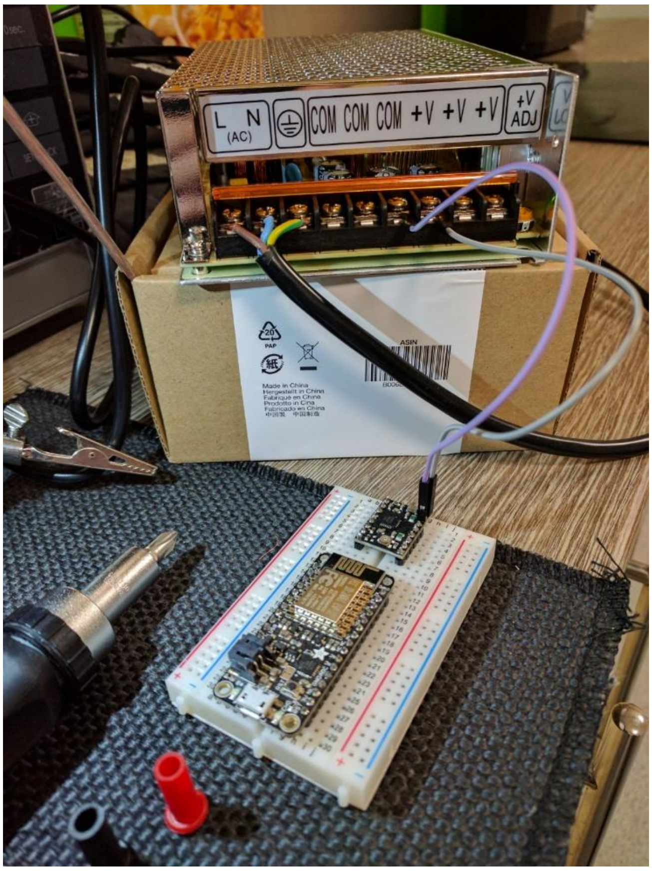

Figure 21: Single circuit, for hardware tests