Affordable Bioprint Head-Adapter for 3D Printers

Andrew Ceralde
Dominic Drake
Noah Engles
Mohammad Alwan
Nevada Perry

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Proposal Report Fall 2023

Affordable Bioprint Head-Adapter for 3D Printers

Team No. 22

Noah Engles – Biomedical Engineering

Dominic Drake – Biomedical Engineering

Andrew Ceralde – Electrical Engineering

Mohammad Alwan – Electrical Engineering

Nevada Perry – Computer Science

College of Engineering and Engineering Technology

Northern Illinois University

Faculty Mentor: Alisha Diggs, PhD, Biomedical Engineering

Client’s email: adiggs@niu.edu
Capstone Title (print or type)
Affordable Bioprint Head-Adapter for 3D Printers

Student Name (print or type)  
Andrew Ceralde

Faculty Supervisor (print or type)  
Dr. Alisha Diggs

Faculty Approval Signature  

Department of (print or type)  
Biomedical Engineering

Date of Approval (print or type)  
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ACKNOWLEDGMENTS

The project acknowledges the collaborative spirit and interdisciplinary expertise of Northern Illinois University's faculty and students, whose dedication to cost-effective innovation is at the heart of this endeavor. This research is a shining example of how open-source initiatives can bridge gaps in technology access and contribute to global scientific progress.

Sincerely,

Bioprint Instrumentation R&D Team, 2023-24
ABSTRACT

Democratizing Bioprinting: An Open-Source Bioprint Head Design Initiative at Northern Illinois University

Dominic Drake, Noah Engles, Andrew Ceralde, Mohammad Alwan, Nevada Perry

Dr. Alisha Diggs

Introduction:

Addressing the need for affordable and accessible bioprinting technology, the Northern Illinois University bioprinting research and design project aims to democratize the field by developing an open source bioprint head. The initiative targets the prohibitive cost of commercial bioprinters by proposing an optimal design that can be integrated with widely available 3D printers, like the Creality Ender-3. This approach seeks to enable the widespread adoption of bioprinting technology, particularly for applications in tissue engineering and regenerative medicine.

Methods:

Leveraging SolidWorks for design, the project employs a methodology that combines a precision extrusion system with thermal and UV crosslinking capabilities. The design process is informed by a comprehensive literature review and iterative prototyping, focusing on retrofit compatibility, manufacturability, and user-centric operation. Special emphasis is placed on the integration of a UV LED light array for effective photo crosslinking and advanced temperature controls for maintaining optimal biomedia conditions.

Results:

The proposed design of the bioprint head anticipates precise multi-component bioprinting at a fraction of the cost of commercial alternatives, without relying on proprietary NICE biomedias or a dedicated CaCl2 crosslinking chamber. The preliminary results suggest a highly competitive and functional product that promises to open new avenues for research and application in tissue engineering, especially in cost-sensitive and resource-limited environments.

Conclusion:

The Northern Illinois University design team's initiative to create an open source bioprint head positions itself as a pivotal breakthrough in making bioprinting technology more accessible. It holds the promise of significantly lowering the barriers to entry for research and educational institutions, potentially leading to innovative treatments and therapeutic strategies in medical science and engineering disciplines.
1. INTRODUCTION

1.1 Broad Background

Additive manufacturing (AM) uses computer-aided-design (CAD) software to construct three dimensional (3D) structures through the displacement of materials, layer atop layer. Fused Deposition Modeling (FDM) is a 3D printing process that creates objects from the bottom up by heating and extruding thermoplastic filaments. 3D extrusion-based bioprinting constructs anatomically accurate tissues by depositing biomaterials in highly specific coordinates by means of computer guidance. The emergence of these free-form biomaterial fabrication devices has opened new avenues for engineering in vitro biological systems that mimic human anatomy and physiology with increased accuracy.

In the vanguard of biotechnological innovation, bioprinting emerges as a transformative force in clinic research and translation. It is the epitome of the convergence of engineering prowess and biological insight, granting the capability to fabricate intricate, life-mimicking tissue structures with clinical precision. This technology propels the field of tissue engineering and regenerative medicine forward, optimizing therapeutic outcomes and refining reconstructive methodologies.

1.2 Design Challenge

The core challenge in advancing this field lies in the synchronization of complex chemical processes within the additive manufacturing paradigm. This multifaceted task becomes particularly significant when dealing with nanoengineered ionic-covalent entangled (NICE) biomedia. These materials are pivotal for generating crosslinked structures that possess the desired mechanical robustness and elasticity, essential for applications such as bone bioprinting. The NICE biomedia enable control over pivotal characteristics including printability, mechanical resilience, and degradation rate, which are fundamental for crafting functionally accurate 3D biostructures. The challenge this design faces in resolving this issue is the ability for multi-crosslinking of these NICE biomedia and to achieve this in a low-cost device. The problem the device solves is two faceted; to provide the industry with a device capable of multi-crosslinking and to make that device affordable to a wider range of tissue engineering researchers, thus improving the field exponentially.

1.3 Importance of Design

The bioprint head design introduces a shift in biomaterial fabrication instrumentation, emphasizing efficiency, cost-effectiveness, and open-source reproducibility. This innovation is a beacon of hope in the medical community and biomedical research laboratories. The bioprint head's design marks a significant advancement in the tools used for tissue engineering and biomaterial fabrication. This innovation is pivotal for advancing medical treatments, as it offers more efficient and cost-effective methods for creating complex biological structures. The core of the device is engineered using SolidWorks and driven by custom g-code interfaced into a Raspberry Pi for high precision in delivering multiple materials, which is essential for creating structures with both the necessary mechanical properties and biocompatibility. Its UV crosslinking feature, with placement near the needle tips, enables precise control over photo-crosslinking reactions, essential for the structural fidelity of engineered tissues. This technology is not only poised to enhance tissue engineering but is also versatile enough to revolutionize drug loading and delivery, as well as provide critical insights into disease mechanisms and therapeutic development. The proposed SolidWorks-engineered print head modification is intricately designed for the precision-oriented task of multicomponent bioprinting. It aims to produce constructs that exhibit high mechanical strength while maintaining the biocompatibility required for subsequent biological function. In addition to this, the device is aimed to combat the prohibitively high cost of market bioprinters, ranging from $5000 to exuberant prices. This device, without the inclusion of neccessary chemicals, comes in just above $600. This is due to the cost-effective nature of the components leading from design or precision ordering taking advantage of components that compete with the output of expensive counterparts at the fraction of the cost, very analogous to the project as a whole.

1.4 Projected Qualitative Design Features or Specifications
The print head is engineered with an unwavering commitment to quality. It features UV-LED circuits positioned to provide uniform exposure, which is crucial for photo-crosslinking. Temperature control is managed through sophisticated sensing modules, ensuring the appropriate environment for biomaterial stabilization. Each of these domains is crafted to enhance the print head's capability to create tissue constructs that replicate the physical and functional complexities of various structures like human bone tissue or human bile ducts.

Targeted Domains for Performance:

- Coordinated extrusion of multiple bio-medias.
- Retrofit compatibility with the Creality Ender-3 printer.
- Integration of both thermal and UV crosslinking mechanisms.
- Dimensions and Geometry:
  - Compact, ergonomic design tailored for Creality Ender-3 V2 integration.
- User-centric interface for ease of operation.
- Manufacturability:
  - Designed for production with conventional manufacturing standards.
- Simplified assembly for end-user convenience of assembly and maintenance.
- Cost and Market Competitiveness:
  - Priced to enable widespread adoption without compromising performance.
  - Competitive advantage rooted in innovative design and operational efficiency.
- Social/Environmental Impact:
  - Revolutionizes availability for tissue engineering research.
  - Incorporates environmentally sustainable materials and production methods.
- Robustness (Failure Mode):
  - Engineered for durability and reliability across diverse conditions.
  - Includes fail-safe mechanisms to prevent malfunction and ensure safety.

1.5 Projected Quantitative Design Features or Specifications

In our relentless pursuit of excellence, the design of the bioprint head is characterized by meticulous attention to precise specifications. The UV-LED light array was carefully chosen for its optimal wavelength of 395nm and intensity, ensuring effective photo-crosslinking of biomaterials during the printing process. Temperature controls have been finely tuned to accommodate a diverse spectrum of tissue engineering applications, allowing for precise regulation of heat-sensitive materials and environments conducive to cell viability. Additionally, the incorporation of motor pulleys facilitates angular motion, enabling smooth rotation of the printing barrel. This controlled movement mechanism ensures uniform dispensing of biomaterials and contributes to the overall precision and reliability of the bioprinting process. Each component of the bioprint head is thoughtfully engineered to maximize performance, functionality, and compatibility with a wide range of biomaterials and printing conditions. This commitment to detail and innovation underscores our dedication to advancing bioprinting technology for transformative applications in tissue engineering and regenerative medicine.

1.6 Towards Initial Design

The initial design initiative begins with a full review of current bioprinting research. This effort is aimed at developing a specialized bioprinting head tailored specifically for multicomponent printing tasks driven by literary review. During the development phase, we adopt a methodical and collaborative design methodology to retrofit an existing 3D printer. The approach involves leveraging the movement axis system of this printer to enhance control over the deposition environment. This precise control is essential for executing the steps required in biomaterial fabrication applications. The primary objective of the preliminary design is to seamlessly integrate these advanced functionalities into the existing framework of Fused Deposition Modeling (FDM) printers. Through this integration, the team seeks to elevate these printers into precision instruments capable of producing a biomaedia that can mechanically be comparable to industry standard bioprinters. In addition to achieving this goal, the design of the part assembly responsible for the retrofitting is
designed to use PLA filament when being manufactured, reducing the cost for repairs and initial creation. The usage of PLA was chosen for its availability and ease of use when printing, opening the opportunity for further improvement upon initial assembly design.

In conclusion, the team's strategic approach involves leveraging existing 3D printer technology to develop a specialized bioprinting head for multicomponent printing tasks. By integrating advanced functionalities into FDM printers and utilizing PLA filament for cost-effective assembly, the goal is to replicate precision and affordability in biomaterial fabrication applications.

1.7 Ethical Statement

The team's ethical stance is predicated on the principle of democratizing access to advanced biomedical fabrication technologies through an open-source systematic design, thereby nurturing an inclusive research ecosystem. The team is dedicated to sharing our designs, protocols, and systems openly with academic institutions and researchers that are resource-constrained, ensuring that the potential benefits of biofabrication technology are not confined to well-funded laboratories but are available to anyone, particularly those passionate to biofabrication but lack the funding to pursue it. This commitment to open access is motivated by the belief that academic advancement and innovation should be a collaborative effort, free from the barriers that restrict knowledge transfer and skill development. By providing open-source biofabrication technology, the team aims to reduce economic obstacles, promote collaborative development, and encourage customization to meet individual needs, thus enabling a broad spectrum of educational and research communities to make significant strides in health-related sciences.

Integrating the principles of cost-effectiveness, environmental consciousness, and scalability, the team's approach is designed to support and stimulate local innovation, educational growth, and ethical research practices across diverse cultural and socioeconomic landscapes. The team envisions this as a stepping-stone towards achieving a more equitable distribution of technology and knowledge, upholding the IEEE’s code of ethics, and championing the transformative power of shared intellectual resources for the embetterment of human health and well-being.
2 INITIAL DESIGN PROCESS

2.1 Five Coarse Design Concepts

I) The team have synthesized five foundational design concepts for our biofabrication apparatus, each representing a critical function within the system. These concepts are systematically outlined below, focusing on the key components and their proposed arrangements:

II) Power Supply Assembly: At the heart of the operation is a power source, chosen for its capacity to energize the system’s needs. This unit is the driving force for all other components facilitating the operation of a designed control system responsible for choreographing all functions of the device working in tandem with the PLC.

III) Biomebra Extrusion System: The core of the biofabrication process relies on a precision dispensing mechanism. The proposed design features custom syringes integrated into a specialized print head, which includes finely controlled needle tips for accurate deposition of biomaterials. These syringes will be operated by stepper motor linear actuators, enabling precise extrusion and retraction. This level of control is essential for preserving the integrity of biostructures during printing.

IV) UV Light Integration: UV LEDs are strategically placed within the configuration to provide the necessary photopolymerization of the biomedia. The design needs to ensure that the UV light is delivered in a pattern specific enough to not only solidify the biomedia but also maintain cell viability, a delicate balance crucial for the success of tissue engineering applications.

V) Computational Intelligence Center: The computational brain of the system comprises a programmable logic controller (PLC) responsible for using and converting digital signals dictating the specific rate of actuation by independent components. Without this system, the device loses the necessary intracomponent synchronization required for the full function of the devices subsystems.

VI) Motion Coordination Framework: To maneuver the biomebra deposition process with precision, the system incorporates a custom mount and a set of polyimide heating strips to aid in the fluid movement control of the print head. Stepper motors and linear actuators are utilized for their high reliability and precision in controlling the linear displacement of the syringe pump and extruding the media, ensuring that the biofabrication is carried out with meticulous adherence to the designed constraints.

Each design aspect is to be validated for its functional performance using surrogate biomedia, electrical test instruments, and experimental procedures coupled with data analysis, which will together serve as quantifiable proof-of-concept supporting the instruments operational effectiveness. This approach not only aligns with the IEEE’s standard for detailed analytical experimentation but also ensures that the components and their interactions can be clearly documented and replicated as per scientific standards.
2.2 Grid Map Comparison Of Course Design Components

### Power Supply Assembly

<table>
<thead>
<tr>
<th>Components</th>
<th>Price</th>
<th>Output</th>
<th>Mass</th>
<th>Ease of Use</th>
<th>Portability</th>
<th>Compatibility</th>
<th>Misc.</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEGO 4.24V Breadboard</td>
<td>$54.90</td>
<td>4.24V, 6W</td>
<td>100g ✓</td>
<td>Very Easy ✓</td>
<td>Very Easy ✓</td>
<td>Compatible ✓</td>
<td>Attached Breadboard ✓</td>
<td>5</td>
</tr>
<tr>
<td>NICE-POWER DC Powersupply</td>
<td>$87.49</td>
<td>0-30V, 300W ✓</td>
<td>1.18kg</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Compatible</td>
<td>More Powerful</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 2.2.1: Comparative Grid Map of Power Supply Configurations

A tabular grid map comparing different power source battery options, and voltage regulation techniques, illustrating their respective efficiencies and compatibilities with the biofabrication system. This comparison is led through group discussion and analyzing the components based on their posted specifications. The checkmarks signify points of advantage between the two comparison points and are totaled together to lead effective decision making.

### Extruder Syring & Needle Assembly

<table>
<thead>
<tr>
<th>Components</th>
<th>Price</th>
<th>Capacity</th>
<th>Ease of Use</th>
<th>Portability</th>
<th>Compatibility</th>
<th>Misc.</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frieda Built in Needles</td>
<td>✓</td>
<td>5mL</td>
<td>Easy ✓</td>
<td>Very Easy ✓</td>
<td>Compatible ✓</td>
<td>Less Applicable in Research</td>
<td>5</td>
</tr>
<tr>
<td>Metal Tipped Needle</td>
<td>$37.00</td>
<td>Not Sterile</td>
<td>Hard</td>
<td>Hard</td>
<td>Compatible with additional components ✓</td>
<td>Research Standard ✓</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 2.2.2: Biomedia Dispensing Mechanisms Comparison

A detailed comparison grid map of various syringe designs, needle tip precisions, and compatibility with final design, highlighting the differences in extrusion control and impact on biomedia deposition accuracy. The driving factor for this decision was the cost without compromising the operation of the device when extruding biomedia. This led to the selection of the Frieda 20mL syringes that, while they are not the perfect option for the design, fulfill all the requirements while remaining very cost efficient.

### UV-Light Assembly

<table>
<thead>
<tr>
<th>Components</th>
<th>Price</th>
<th>Accuracy</th>
<th>Ease of Use</th>
<th>Portability</th>
<th>Compatibility</th>
<th>Misc.</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring in Barrel</td>
<td>$60.00</td>
<td>Very Accurate ✓</td>
<td>Moderate</td>
<td>Hard</td>
<td>Compatible ✓</td>
<td>Imbedded in Barrel ✓</td>
<td>3</td>
</tr>
<tr>
<td>Ring at Output</td>
<td>$60.00</td>
<td>Accurate</td>
<td>Easy ✓</td>
<td>Easy ✓</td>
<td>Compatible with Additional Mount ✓</td>
<td>Powered by Voltage Source</td>
<td>2</td>
</tr>
<tr>
<td>Direct Lights at output</td>
<td>$23.98</td>
<td>Not as Accurate</td>
<td>Hard</td>
<td>Hard</td>
<td>Compatible with Additional Mount ✓</td>
<td>Battery Powered, may die or be less powerful</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 2.2.3: UV LED Configuration Comparative Chart

A grid map highlighting various UV LED arrangements and their photopolymerization patterns, comparing the effectiveness of each configuration in curing biomedia while maintaining cellular integrity. The primary factors for consideration being the compatibility without further complication leading to the design decision to mount the UV lights in the barrel but angled so that they are curing at a static intensity with rate of operation determined through experimentation.
Programmable Logic Controller

<table>
<thead>
<tr>
<th>Components</th>
<th>Price</th>
<th>Processing Power</th>
<th>Ease of Use</th>
<th>Supported Languages</th>
<th>Pins</th>
<th>Connectivity</th>
<th>Misc.</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arduino</td>
<td>0✓</td>
<td>Low</td>
<td>Moderate</td>
<td>C/C++</td>
<td>14</td>
<td>USB</td>
<td>Not Powerful Enough for Project</td>
<td>1</td>
</tr>
<tr>
<td>Raspberry Pi</td>
<td>160.00</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Most✓</td>
<td>28</td>
<td>USB, Internet, Bluetooth✓</td>
<td>Applicable to all project aspects✓</td>
<td>3</td>
</tr>
<tr>
<td>Ordrid N2</td>
<td>$113.73</td>
<td>Most Powerful✓</td>
<td>Moderate</td>
<td>Most✓</td>
<td>40</td>
<td>USB, Internet, Bluetooth✓</td>
<td>Not cost efficient relative to requirements</td>
<td>4</td>
</tr>
</tbody>
</table>

Figure 2.2.4: Computational Intelligence Systems Comparison
A comparative overview grid map of multiple programmable logic controllers, evaluating their computational capacities, response times, and suitability for complex biofabrication tasks. For our design, the Arduino had 0 cost due to the requirement of purchase from previous coursework but would remain the low-cost option with purchase. Note that regardless of the fact that the Ordrid N2 has the most points, its cost to power ratio is excessive and is not cost effective relative to the PLC’s functional domain requirements leading to the selection of the Raspberry Pi.

Motor

<table>
<thead>
<tr>
<th>Components</th>
<th>Mass</th>
<th>Torque Generated</th>
<th>Ease of Use</th>
<th>Motor Compatibility</th>
<th>Inertia</th>
<th>Misc.</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEMA 12</td>
<td>14kg</td>
<td>480N·M</td>
<td>Moderate</td>
<td>Compatible</td>
<td>23g·cm²</td>
<td>Applicable to all project aspects✓</td>
<td>2</td>
</tr>
<tr>
<td>NEMA 17</td>
<td>25kg</td>
<td>50N·M</td>
<td>Moderate</td>
<td>Compatible</td>
<td>35-54g·cm²</td>
<td>Applicable to all project aspects✓</td>
<td>3</td>
</tr>
</tbody>
</table>

Figure 2.2.5: Stepper Motor Selection Grid Map
This grid map compares various stepper motors based on their torque, step resolution, voltage requirements, and physical dimensions. It evaluates how each motor's characteristics affect the precision and responsiveness of the print head movement within the biofabrication system. Note that cost is not factored into this comparison as the motor is a component that does not require purchase but if considered, the NEMA 17 would be the more expensive part.

2.3 In-Depth Literature & Product Review

The development of a cost-effective, dual-head 3D extrusion bioprinter featuring temperature control and UV curing capabilities, aiming to increase adaptability to a range of biomedia materials, which is paramount in tissue engineering and regenerative medicine advancements. In simple terms, this form of 3D bioprinting is an advanced version of 3D printing that, rather than utilizing plastics or metals, prints with materials that can sustain living cells with the goal of crafting structures to replace or repair damaged tissues or organs. This adaptation of a desktop 3D printer for bioprinting is like tweaking a standard home printer to manage different inks for assorted printing tasks, but with "inks" comprised of biological substances. There are two primary methods of bioprinting: extrusion, which is akin to piping frosting to decorate a cake but involving biological substances, and FRESH bioprinting, which is like sculpting in sand that preserves its shape, then using a support material to maintain the structure for more complex designs. Other bioprinting research discusses essential design requirements for the bioprinter, including sterile conditions, compatibility with standard laboratory workflows, and various biomedia management capabilities. Converting a conventional 3D printer to a bioprinter necessitates substantial modifications such as internal code rewriting and physical alterations such as modifying the extruder size. Addressing the need for an affordable bioprinting platform, this project seeks to democratize access to innovative tissue engineering technology, adhering to IEEE and NIH guidelines for clinical applications when refining the design.

References such as N. Rosell's [3] 'Open Source Bioprinter' and Tashman, Shiwarski, and Feinberg's work on syringe extruders [1] are foundational, outlining the conversion of FDM 3D printers into economical bioprinters. They demonstrate how modifications, especially in the thermal control systems and hydrogel use, can benefit tissue engineering and related fields. This academic work provided the underpinnings for this design and the motivation to contribute our findings to the open source bioprinting community. The core innovation, a modified version of the "Replistruder v3.0,"
reflects a commitment to using accessible materials and tools, ensuring project reproducibility, and emphasizing cost-efficiency and DIY accessibility. Detailed documentation and structured instructions facilitate replication and enhancements by researchers and hobbyists alike.

D. Kim et al. underscored the efficacy of GelMA for bioprinting, its balance of biological function and mechanical properties, and its amenability to photo-crosslinking for structural integrity, underscoring its suitability for diverse tissue applications. This is the final goal to replicate with this device, with the primary modification being the multi-crosslinking of multiple hydrogels in a pattern printed fashion. By accomplishing this, the team will allow for the low-cost manufacturing of complex tissue constructs in a more cost-effective and DIY-friendly environment.

The following in-depth comparative analysis section of the report engages in a thorough assessment of current biomedical devices using a matrix-based method for feature comparison, ensuring that our engineering solutions align with market benchmarks and adhere to the highest standards of innovation and compliance as per IEEE protocols. This feature mapping is pivotal, establishing a detailed comparison grid that showcases the interaction between product features and their impact on performance and user experience, benchmarking this project's development to meet industry best practices.

**2.4 Grid Map of Relevant Features Extrapolated from Relevant Scholarly Publications & Biomedical Devices**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Gusmão et al. (2022)</th>
<th>Rosell (Instructables)</th>
<th>Tashman et al. (2021)</th>
<th>Kim et al. (2022)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Philosophy</td>
<td>Dual-head extrusion for thermostensitive and light-sensitive hydrogels</td>
<td>Open-source approach for customizable bioprinting solutions</td>
<td>High-performance syringe extruder optimized for FRESH</td>
<td>Focus on multicomponent hydrogel biolinks for 3D liver tissues</td>
</tr>
<tr>
<td>Fabrication Cost</td>
<td>Low-cost design enabling widespread accessibility</td>
<td>DIY open-source modular emphasizing cost-efficiency</td>
<td>Economical construction with off-the-shelf components</td>
<td>Literature review focusing on biocompatibility, not printer cost</td>
</tr>
<tr>
<td>Material Compatibility</td>
<td>Compatible with thermo-sensitive and light-sensitive hydrogels</td>
<td>Adaptable to a range of hydrogels with modifications</td>
<td>Optimized for hydrogel use in FRESH bioprinting</td>
<td>Comprehensive analysis of GelMA biokinetic and biocompatibility</td>
</tr>
<tr>
<td>Sterility and Bio-Safety</td>
<td>Maintains sterile conditions for tissue engineering</td>
<td>Not explicitly mentioned, assumes standard bio-safety practices</td>
<td>Documentation includes considerations for sterility</td>
<td>GelMA biolink properties conducive to cell viability</td>
</tr>
<tr>
<td>Software Integration</td>
<td>Software updated for dual-head control</td>
<td>Utilizes existing open-source 3D printing software</td>
<td>Custom software for syringe extruder control</td>
<td>Emphasis on biocompatibility, software not the primary focus</td>
</tr>
<tr>
<td>Temperature Control</td>
<td>Integrated temperature control for biolinks</td>
<td>Temperature control dependent on the user modification</td>
<td>Detailed thermal control system for precise biolink handling</td>
<td>Discusses the importance of biolink preconditioning</td>
</tr>
<tr>
<td>UVCuring Capabilities</td>
<td>UV light integration for photocrosslinking</td>
<td>Depends on the end-user modification for inclusion</td>
<td>Not specifically mentioned, but possible through modification</td>
<td>Photo-crosslinking of GelMA discussed in the context of biolink</td>
</tr>
<tr>
<td>Structural Resolution</td>
<td>Fine resolution for intricate tissue structures</td>
<td>Resolution varies based on printer and modification</td>
<td>High-resolution capabilities for complex tissue scaffolds</td>
<td>Focused on biolink resolution and fidelity pre-printing</td>
</tr>
<tr>
<td>User Accessibility</td>
<td>Designed for ease of use in standard lab environments</td>
<td>Highly accessible to hobbyists and researchers</td>
<td>Accessible for researchers with engineering background</td>
<td>Targeted towards specialized research in tissue engineering</td>
</tr>
<tr>
<td>Open-Source Contribution</td>
<td>Not open-source, proprietary design</td>
<td>Fully-open source with detailed instructions</td>
<td>Open-source hardware design for syringe extruder</td>
<td>Literature review does not directly contribute to open-source hardware</td>
</tr>
</tbody>
</table>

Figure 2.4.1: The development of a novel bioprinter has been greatly influenced by this functional grid map detailing existing bioprinter technologies. This map has played a crucial role in refining the team's ideas and design iterations. By integrating the best features from prior research efforts, this device has aims to become a bioprinter that achieves its goals while learning from past pitfalls in bioprinting research. The team's objective goes beyond mere device development; this project aspires to establish a foundation of inclusivity for future bioprinter research by providing open-source access to this work. This approach invites collaboration and serves to benefit the broader tissue engineering community.

**2.5 Rigorous Examination of Existing Patents for Detailed Feature Analysis**

This phase entails a thorough examination of current patents, disentangling complex design features and aligning them with the team's innovative design proposals. The methodology incorporates a meticulous examination of current patents to identify and leverage critical feature sets that elevate the team's bioprinting designs. By dissecting extant patents, the team has unearthed fundamental design elements that are not immediately apparent, fostering innovation at the intersection of biology and engineering. This approach ensures the team's designs align with industry benchmarks while circumventing potential intellectual property entanglements. The team's objective is to integrate superior features into their bioprinting solutions, ensuring they not only comply with but set new standards for functionality, precision, and adaptability. In their analysis, the team takes a proactive stance on intellectual property considerations, integrating a careful examination of
existing patents that enables them to avoid potential conflicts while infusing innovative features into their designs. Through this analysis, distinctive features become known that, when incorporated into the team's models, have the potential to propel their solutions beyond current market offerings, marking them as leaders in performance and innovation.

Relevant Patents

- WO2015066705A1: Bioprinter and methods of using same
  - Permits selective three-dimensional movement of multiple nozzle assemblies during operation of the bioprinter. [13]
- US20220072780A1: Multi-headed auto-calibrating bioprinter with heads that heat, cool, and crosslink
  - The present invention relates to a three-dimensional bioprinter for printing and/or patterning a single type or multiple types of cells into different geometrical arrangements and other three-dimensional structures, such as tissues. [14]
- US11738506B2: 3D bioprinter
  - The present invention relates to a 3D bioprinter and the definitions of what makes a 3D bioprinter. [15]

2.6 Existing Bioprinter Features & Specifications Further Derived

In the dynamic field of biomedical engineering, the development of bioprinter technology stands as a testament to the harmonious fusion of multiple scientific domains. The team’s approach, a synthesis of diversified expertise, is meticulously designed to transcend the conventional boundaries of bioprinting. By infusing principles from engineering, biology, and materials science, the team has pioneered bioprinting architectures that offer functionality and seamless integration with the existing medical landscape. The team’s designs are deeply entrenched in empirical rigor, with each feature meticulously vetted through a prism of peer-reviewed scientific evidence. This unwavering commitment to empirical substantiation ensures that innovations are more than mere novelties; they are reliable, effective, and grounded in scientific methodologies.

The design strategy incorporates pioneering research by A. Gusmão, Afonso, et al. [5] introducing a dual-head 3D bioprinter concept. This model emphasizes economic feasibility while maintaining careful handling of thermo-sensitive and light-sensitive hydrogels crucial for tissue engineering. Our system prioritizes sterility, workflow integration, and biomedia versatility with meticulous attention to detail. Like the precision found in modern medical devices, each feature is optimized for practicality and superior performance.

In the same vein, the open-source ethos, proliferated through the work of N. Rosell [3] and expanded upon by J. W. Tashman et al., casts a noteworthy influence on our design strategy. This democratization of bioprinting, achieved by retrofitting FDM 3D printers, stands at the pinnacle of cost-effective and reproducible bioprinting methodologies. In adhering to the principles of accessibility and DIY customization, the team encapsulates a spirit of innovation that is in strict adherence to the standards set forth by IEEE and NIH, promoting an open-source culture of innovation and not compromising device or patient outcomes.

The strategic selection of GelMA as a biomedia, as elucidated in the work of D. Kim [2] et al., serves as the baseline that the team measures its experimentation against. In this project, the team’s focus is on utilizing a corn starch-based surrogate media for research purposes, particularly as a logical step towards developing bioink formulations. This approach involves exploring the potential of corn starch-based materials to mimic certain properties and behaviors relevant to bioinks used in bioprinting. The selection of corn starch as a surrogate media is informed by a desire to understand its characteristics and how it can be manipulated to simulate aspects of bioink behavior.

Expanding upon these foundational choices, these bioprinting platforms also draw upon the latest advancements in 4D bioprinting, a field pioneered by researchers like Q. Zhang et al., [3] where the fourth dimension encompasses time-responsive materials that adapt their shape or function post-fabrication. This emergent technology allows the envisionment to create tissue constructs that evolve and mature over time, closely mimicking the dynamic nature of living tissues.
In concert with these advancements, some bioprinters also incorporate state-of-the-art monitoring systems, informed by the sensor technology outlined in research, to provide real-time feedback on the bioprinting process. This addition acts as the ‘nervous system’ of the bioprinter, ensuring that each layer of biomedia is deposited with precision rooted in the feedback system ensuring proper printing patterns.

Future iterations of the device could incorporate advanced artificial intelligence (AI) algorithms, leveraging computational models developed to optimize the bioprinting process. By integrating AI, the device can harness predictive capabilities to anticipate and rectify potential discrepancies in tissue fabrication, thereby ensuring high fidelity in replicating complex tissue structures. These AI algorithms could analyze real-time data from the bioprinting process, dynamically adjusting parameters such as biomaterial deposition rates, print head movements, and environmental conditions based on learned patterns and feedback. This adaptive approach would enhance precision and consistency in tissue fabrication, leading to more accurate and reliable bioprinted constructs. Furthermore, AI-driven optimization can contribute to the scalability and efficiency of bioprinting technologies, accelerating progress towards producing functional tissues for various biomedical applications. The integration of AI into future iterations of the device represents a promising avenue for advancing the capabilities and performance of bioprinting systems.

2.7 Interdisciplinary Feature Considerations and Practical Application

In the quest to innovate a biomedical device with profound implications in transplant medicine, the team has orchestrated an integration of insights from an array of disciplines—spanning electrical engineering, biomaterials science, computer science, clinical research, and transplant medicine. This strategic initiative is to refine a bioprinter that is not just a marvel of engineering but a beacon of hope for patients awaiting transplants. This refined bioprinter is envisioned to serve as a cornerstone in transplantable tissue production, incorporating an expanded feature grid map illustrative of this multifaceted development approach. This expanded grid map will reflect a synthesis of disciplines, each contributing its pinnacle innovations and fundamental principles to forge a product at the bleeding edge of bioprinting technology. The grid further incorporates newly identified parameters, critical to the success of tissue integration into the human body, encompassing key immunological factors and the viability of grafts post-transplantation.

I) Inclusive Development: The integration of transplant medicine within the developmental purview assures that the bioprinter addresses the nuanced complexities of post-transplantation tissue behavior. This ensures that the printed tissues are designed with an intrinsic understanding of the host's biological environment, paving the way for enhanced acceptance and functionality post-implantation.

II) Transplant-Ready Innovation: The device's blueprint is enriched with insights into the operational theatre, incorporating features that streamline the bioprinted tissues for surgical applications. This level of customization ensures that the bioprinter outputs tissues tailored for immediate use in transplantation procedures, designed to thrive within the human body over the long term.

III) Regulatory and Ethical Compliance: Recognizing the delicate nature of transplantation medicine, the design is imbued with a thorough comprehension of the ethical and regulatory landscapes. This encompasses a steadfast adherence to guidelines set forth by regulatory bodies, assuring that the bioprinter's output is not only at the frontier of innovation but also within the bounds of clinical and ethical acceptability.

IV) Multidisciplinary Approach: The design strategy leverages a broad spectrum of scientific knowledge, channeling it into the engineering design processes. This cross-pollination of expertise infuses the bioprinter with the robustness required to navigate the intricacies of biomaterial science and the precision demanded by clinical applications.

Research efforts have culminated in a definitive feature grid map that portrays a collective of expert knowledge bases, indispensable for state-of-the-art tissue engineering instrumentation and regenerative medicine. This map is not merely a representation; it is a blueprint for how biomedical engineering can transcend traditional boundaries to dramatically elevate the standard of patient care.
Figure 2.7.1: Grid map of the design features and associated considerations to them, this chart highlights that the future of bioprinting holds immense promise; driven by synergies across Electrical Engineering, Biomaterial Considerations, Computer Science Innovations, and Clinical Applications. In terms of Electrical Engineering, advancements are expected in precision control systems and sensor technologies, enabling more accurate and efficient deposition of biomaterials. Biomaterial considerations will witness breakthroughs in the development of biocompatible and customizable inks, allowing for the fabrication of complex tissues with enhanced structural and functional properties. In the realm of Computer Science, innovations in 3D modeling, machine learning, and algorithmic optimizations will play a pivotal role in designing intricate biological structures and optimizing the printing process. Finally, in clinical applications, bioprinting is poised to revolutionize regenerative medicine, offering personalized solutions for organ transplantation, tissue repair, and drug testing. As these interdisciplinary fields converge, the future of bioprinting can redefine healthcare by providing tailored and sustainable solutions for many medical challenges.

2.8 Final Reflection to produce three Alternative Designs

Expanding upon the previous section, this analysis is intensified by juxtaposing current product features against the proposed engineering innovations. This critical examination is vital for revealing opportunities where advanced technologies could be integrated to fill existing market voids. This stage is essential in elevating the conceptual designs to pragmatic solutions that exhibit superior efficacy and reliability in clinical settings, thereby ensuring that the solutions are not only theoretically sound but are primed for practical application and utility.

The comparative methodology proved invaluable, allowing us to extract and refine the core components necessary for superior design. A systematic dissection of existing models exposed avenues for amplified performance, enhanced efficiency, and increased user engagement. These proposed alternatives are the synthesis of forward-looking engineering and practical resilience, an amalgamation designed to withstand the rigorous demands of clinical operations.

Our methodology is threefold:

I) I. Technological Identification: A comprehensive, methodological analysis was employed to uncover avenues for technological enhancement. The team has scrutinized the frontier of tech advancements, evaluating how their assimilation could catalyze the designs, augmenting both performance metrics and user experience.

II) II. Enhancement with Existing Assets: The team aims to escalate the utility of the grid maps by leveraging current technological assets. These enhancements are surgically targeted, designed to integrate with and amplify existing systems, broadening their operational scope.

III) III. Targeted Performance Metrics: In alignment with the IEEE’s stringent standards, an established array of performance metrics function as quantifiable benchmarks, assessing the potency and progress of future engineering endeavors.

2.9 Discussion on the functional domain of each Alternative Design

The three alternative designs undergo rigorous scrutiny here, each dissected across their respective functional domains. This analysis serves as the bedrock for assessing enhancements in comparison to the current model, with a spotlight on functionality, user adaptability, and efficiency.

Design A represents the spearhead of user-centric innovation. By overhauling user interfaces, it is possible to foster a more intuitive constructive collaboration between the operator and the grid map, streamlining efficiency and deepening user involvement.
Design B stands as a testament to rugged efficiency. It targets the core of power consumption and data throughput, optimized for high-demand settings that call for robust performance with conservative energy use.

Design C offers a fusion of adaptability and precision. Crafted for scenarios that demand high flexibility, it features a modular design that can swiftly pivot in response to dynamic operational demands without sacrificing accuracy.
3 OPTIMAL DESIGN

3.1 Grid map with discussions on each alternative design functional domain

Resolution and Precision: This domain deals with the system's ability to print detailed structures at the microscale with high accuracy, influenced by scientific knowledge of biomedia behavior, the engineering of the print head, and the mathematical control of the print process.

Biome Media Extrusion Rate: In this domain, the focus is on the controlled delivery rate of the biomedia, which is essential for consistent print quality. It combines the scientific understanding of the biomedia’s rheology, the engineering of extrusion mechanisms, and mathematical models that ensure precise flow rates.

Thermal Management Efficiency: Central to this domain is the ability of the system to regulate temperature, which affects biomedia properties during printing. It encompasses the scientific principles of thermodynamics, the engineering of thermal systems, and the mathematical algorithms for temperature control.

Photopolymerization Accuracy: This domain concerns the precision in curing the biomedia with UV light to form solid structures, involving the scientific interaction of biomedia with light, the engineering of the light source, and mathematical optimization of exposure times and intensity.

Mechanical Integrity: This domain assesses the structural robustness of the printed constructs, which is critical for their functional use. It is based on the material properties of the biomedia, the engineering design of the constructs, and the mathematical modeling of mechanical stresses and strains.

After discussion, it has been determined that some of the ideas should be final, while a few other design ideas should be discussed. The final design components that were agreed on as a team were the following:

- Raspberry Pi
- UV Light Array
- Curing at Syringe interfaced with biomedia

The only remaining things to decide on are the power source and the syringes that are optimal to use. The team built a grid map to decide on this:

<table>
<thead>
<tr>
<th>Standard</th>
<th>Compatibility</th>
<th>Cost</th>
<th>Stress Output</th>
<th>Reliability</th>
<th>Totals</th>
</tr>
</thead>
<tbody>
<tr>
<td>External PSU</td>
<td>.8</td>
<td>.7</td>
<td>.9</td>
<td>.9</td>
<td>3.3</td>
</tr>
<tr>
<td>Internal PSU</td>
<td>1</td>
<td>1</td>
<td>.6</td>
<td>.6</td>
<td>3.2</td>
</tr>
<tr>
<td>Barrel Sy.</td>
<td>.8</td>
<td>1</td>
<td>.7</td>
<td>.8</td>
<td>3.3</td>
</tr>
<tr>
<td>ML Sy.</td>
<td>.8</td>
<td>1</td>
<td>.6</td>
<td>.7</td>
<td>2.8</td>
</tr>
</tbody>
</table>

Table 3.1.1: Grid map to determine best ideas for the power source and UV curing method after discussion:

For this grid map, each standard was given equal importance. A higher score in one standard is not more impactful than the same score in a different standard. This map demonstrates a breakdown of how each impactful design path and the associated decision process impacts the final design. Through this, the team deduced that an External PSU and Barrel syringe were best suited for the final implementation of the design.
3.2 Reflections and discussions on alternative grid maps to reduce to one optimal design grid map

Going off the grid maps, it has been decided that the external power supply and barrel syringes are better for the final design. The internal power supply was creating too many unknowns for the team, as there is a chance that certain components will not get the proper voltages or currents. The team found that barrel syringe design is better for the overall device because they novelize the design whilst also providing a higher output while still allowing tolerance for a higher degree of human error.

3.3 Perform one integrated R&A on relevant products, patents, and papers to further refine the grid map of the optimal design

<table>
<thead>
<tr>
<th>Standard</th>
<th>Compatibility</th>
<th>Cost</th>
<th>Stress Output</th>
<th>Reliability</th>
<th>Totals</th>
</tr>
</thead>
<tbody>
<tr>
<td>External PSU</td>
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<td>1</td>
<td>.8</td>
<td>.8</td>
<td>3.1</td>
</tr>
<tr>
<td>Controller</td>
<td>1</td>
<td>.7</td>
<td>1</td>
<td>1</td>
<td>3.7</td>
</tr>
<tr>
<td>Syringe Loader</td>
<td>.2</td>
<td>1</td>
<td>.7</td>
<td>.5</td>
<td>2.4</td>
</tr>
<tr>
<td>Movement</td>
<td>.7</td>
<td>.7</td>
<td>.6</td>
<td>.6</td>
<td>2.6</td>
</tr>
<tr>
<td>UV Light Config</td>
<td>.2</td>
<td>.8</td>
<td>.7</td>
<td>.2</td>
<td>1.9</td>
</tr>
<tr>
<td>ML Sy.</td>
<td>.8</td>
<td>1</td>
<td>.6</td>
<td>.7</td>
<td>2.8</td>
</tr>
</tbody>
</table>

Table 3.3.1: Grid map to determine the best ideas for the power source and UV curing method after a search of various pre-existing products. This included research on fellow bioprinting projects, patented devices, and published properties in the field of bioprinting regarding their component selection.

3.4 Final reflections and presentation of the Optimal design block diagram and its grid map

After further research and reflection, here is the final grid map:

<table>
<thead>
<tr>
<th>Standard</th>
<th>Compatibility</th>
<th>Cost</th>
<th>Stress Output</th>
<th>Reliability</th>
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</tr>
</thead>
<tbody>
<tr>
<td>External PSU</td>
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<td>.9</td>
<td>3.3</td>
</tr>
<tr>
<td>Internal PSU</td>
<td>1</td>
<td>1</td>
<td>.6</td>
<td>.6</td>
<td>3.2</td>
</tr>
<tr>
<td>Barrel Sy.</td>
<td>.6</td>
<td>.5</td>
<td>.6</td>
<td>.4</td>
<td>2.1</td>
</tr>
</tbody>
</table>
Table 3.4.1: Grid map to determine best ideas for the power source and UV curing method after discussions, research, and further discussion and reflection. This grid map encapsulates all the collective work regarding their component decisions to refine to the most optimal design.

### 3.5 Functional domains of the optimal design and their grid maps

The various functional components play a leading role in how our biohead assembly will function:

1) **Power Supply** - The power supplies are the way the entire system will be up and running. Without it, the team would not have any motion happening and would not be able to actuate upon the associated biomedia.

2) **Raspberry Pi** - The microcontroller behind the product, it will serve as the primary node for movement control and actuation coordination.

3) **UV Light Ring** - The UV Rings combined with the syringe curing is responsible for curing and solidifying the biomedia. This is the final step for the flow of biomedia through the device and secures the mechanical properties of the media.

4) **Motors** - The motors will turn an analog electrical input into a movable output. This is how movement and positioning will be controlled and is responsible for the primary functions of the device, namely the rotation of the barrel and extension of the linear actuator.

5) **Biomedia** - The biomedia will be cured at the syringe output level after being extruded to optimize efficiency and ease of use whilst still being compatible with their idealized outcomes and the printer itself.

6) **Syringe** - The syringe which handles all the extrusion and housing of the material.

<table>
<thead>
<tr>
<th>Standard</th>
<th>Compatibility</th>
<th>Cost</th>
<th>Stress Output</th>
<th>Reliability</th>
<th>Totals</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSU</td>
<td>.8</td>
<td>.7</td>
<td>.9</td>
<td>.9</td>
<td>3.3</td>
</tr>
<tr>
<td>Raspberry Pi</td>
<td>1</td>
<td>1</td>
<td>.6</td>
<td>.6</td>
<td>3.2</td>
</tr>
<tr>
<td>Barrel Sy.</td>
<td>.8</td>
<td>1</td>
<td>.7</td>
<td>.8</td>
<td>3.3</td>
</tr>
<tr>
<td>UV Rings</td>
<td>.8</td>
<td>1</td>
<td>.6</td>
<td>.7</td>
<td>2.8</td>
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</tbody>
</table>
Motors & Curing at Syringe

<table>
<thead>
<tr>
<th></th>
<th>.4</th>
<th>.4</th>
<th>.5</th>
<th>.2</th>
<th>1.5</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>.3</td>
<td>3.3</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.5.1: Grid map of the various functional domains with respect to the design constraints. This map is weighted to display the importance of the design constraints with respect to the optimal component selection based on research.

Resolution and Precision - This domain deals with the system's ability to print detailed structures at the microscale with high accuracy, influenced by scientific knowledge of biomedia behavior, the engineering of the print head, and the mathematical control of the print process.

Biomedical Extrusion Rate - In this domain, the focus is on the controlled delivery rate of the biomedia, which is essential for consistent print quality. It combines the scientific understanding of the biomedia’s rheology, the engineering of extrusion mechanisms, and mathematical models that ensure precise flow rates.

Thermal Management Efficiency - Central to this domain is the ability of the system to regulate temperature, which affects biomedia properties during printing. It encompasses the scientific principles of thermodynamics, the engineering of thermal systems, and the mathematical algorithms for temperature control.

Photopolymerization Accuracy – This domain concerns the precision in curing the biomedia with UV light to form solid structures, involving the scientific interaction of biomedia with light, the engineering of the light source, and mathematical optimization of exposure times and intensity.

Mechanical Integrity - This domain assesses the structural robustness of the printed constructs, which is critical for their functional use. It is based on the material properties of the biomedia, the engineering design of the constructs, and the mathematical modeling of mechanical stresses and strains.

Each of these functional domains is instrumental for achieving a successful and reliable bioprinting outcome. They encompass the interdisciplinary nature of bioprinting, where scientific knowledge, engineering design, and mathematical modeling converge to create a system that can precisely manipulate biological materials for the creation of tissue constructs and other bioengineered structures. The probability grid maps associated with each domain provide a statistical confidence level regarding the system's ability to meet specific performance criteria, reflecting the rigor and precision of the engineering design process aligned with IEEE standards.

3.6 Constraints on each functional domain of the optimal design

Given how important accuracy and precision is for the printer head, there are a couple things to note. The first of which is that the Raspberry Pi does cost more than a standard Arduino, by around twice as much. While this is not the biggest issue for most people, it is important to understand how much money there is to work with and how every purchase affects it. Additionally, the internal power supply built into the 3D printer might not be enough to power the entire printer and each of its functional aspects. An external power supply is going to be used to remedy this fault. The drawback is that it will increase our spending, this would be worthwhile ensuring enough power is generated to the motors and other important aspects of the assembly. That final thing worth noting is that the UV rings need to be positioned precisely to be functional. For these to be off by a degree or even a millimeter can alter the biomedia properties after extrusion, which leads to material failure.

3.7 Governing standards for each functional domain of the optimal design

Ensuring compliance with industry standards is crucial across various components used in diverse applications. For power supplies like those integral to electrical devices, adherence to UL 60950-1 guarantees electrical safety. The Raspberry Pi may necessitate ISO 13485 if employed in medical devices to uphold quality and safety standards. Similarly, devices like UV lights, involving specific applications such as curing systems, adhere to IEC 60335-1 due to them resembling
household electrical appliances. For components like motors, ISO 9001 is essential to maintain quality assurance standards. Biocompatibility standards, exemplified by ISO 10993, are imperative for ensuring materials used in medical devices are biologically safe, though research settings may differ. As for biomedia and syringes, adhering to standards such as chemical safety data sheets and ISO 8537 for sterile syringes respectively, the importance of safe handling and disposal practices in these specialized contexts. Each standard underscores a commitment to safety, quality, and effectiveness in their respective applications.

- **Power Supply**
  - UL 60950-1 *(Safety of Information Technology Equipment)*: This standard is often used for power supplies and ensures electrical safety.

- **Raspberry Pi**
  - ISO 13485 *(Medical Devices - Quality Management System)*: If the bioprinter is intended for medical use, relevant to ensure quality and safety.

- **UV Ring**
  - IEC 60335-1 *(Safety of Household and Similar Electrical Appliances)*: This standard applies since the UV curing system and syringe curing are separate devices like that of a lamp.
  - **Biocompatibility Standards**: Ensure that the cured materials are biocompatible, which may involve compliance with ISO 10993 or similar standards for biological evaluation of medical devices. This, however, does not apply to research settings.

- **Motors**
  - ISO 9001 *(Quality Management Systems)*: ISO 9001 is relevant for ensuring the quality of components like motors.

- **Biomedia**
  - Chemical Safety Data Sheets (SDS): for output or similar chemicals regarding disposal and safe handling.

- **Syringe**
  - ISO 8537 *(Sterile Single-Use Syringes with or without Needle)*: Another relevant standard for sterile syringes.
4 SCIENTIFIC, ENGINEERING, AND MATHEMATICAL (SEM) ANALYSIS OF OPTIMAL DESIGN

4.1 Perform SEM on each functional domain in a decoupled framework (each separately) with its accompanying grid map on probability

The paramount objective in the conception of the bioprinting system is to meticulously tailor design criteria and operational parameters that ensure the achievement of desired functional outcomes. To guarantee the system's structural integrity, the team is committed to a design that can sustain operational stress without succumbing to deformation, ensuring the apparatus remains steadfast under the rigors of the bioprinting process. In more straightforward terms, the bioprinter assembly is engineered to be robust enough to reliably do the job without failing or fracturing under pressure.

In tandem with structural considerations, mathematical precision is key. The team must employ sophisticated algorithms that guide the printer's movement with pinpoint accuracy, ensuring that the surrogate biomedia is deposited exactly where it needs to be, down to microscopic accuracy. This is like using precise math-based rules to direct the printer's actions, ensuring high fidelity in the placement of biological materials.

Moreover, a precise thermal management system is critical. The system must maintain an environment where temperature fluctuations are kept to a minimum, thereby preserving cell viability and function. This means that it is needed to keep the bioprinting environment within a Goldilocks zone – not too hot, not too cold – so that cells remain alive and functional.

Lastly, our design incorporates probabilistic elements to ensure that the varying properties of biological materials and environmental conditions do not impede the printer's performance. The team aims for a design that operates with high confidence, over 90% probability, that the final bioprinted media will exhibit the intended structural and functional characteristics. This translates to designing the printer with enough flexibility and control to guarantee the successful creation of tissues in the vast majority of attempts.

4.2 Formulate a prediction of probability of failure and or probability of success for each functional domain of the optimal design

Focusing on the system's reliability and precision, it is crucial that the bioprinter operates with consistency and precision. The system's design must display a remarkable success rate, with over 95% probability, ensuring that it can initiate and carry out the bioprinting process flawlessly under a variety of conditions. Furthermore, the potential for failure must be minimized. The team set ambitious targets for the system's reliability, aiming for the probability of failure to be less than 5%.

Thermal management is also a facet where precision is non-negotiable. The system must maintain biomedia temperature within a precise range to ensure cell health and functionality. This precision in temperature control is vital to keep the building blocks of bioprinted tissues alive and in a state conducive to forming functional tissues. Lastly, the resolution of the printing process is of paramount importance. The bioprinter must be capable of recreating complex structures at the cellular level with a high degree of accuracy, operating with over 95% probability of replicating the intended design. The team is ensuring that the printer can reproduce intricate tissue structures with such precision that the details are correct repeatedly. By steadfastly adhering to these stringent design criteria and operational parameters, the team ensures that the bioprinting system developed is not only innovative but also capable of yielding biologically functional tissues with a high...
degree of reliability and fidelity.

4.3 Reflect and analyze on decoupled analysis of the entire optimal design

The SEM Grid Map approach allows for an understanding of the intricate balance between scientific, engineering, and mathematical aspects of the bioprinting system. The probabilities indicate a well-thought-out design with a strong emphasis on precision, control, and efficiency. However, biomedias can exhibit batch-to-batch variability. Engineering and mathematical controls play a pivotal role in ensuring consistent outputs. Regular calibration, maintenance, and iterative testing will be paramount to sustaining these high success rates in practical applications.

4.4 Reflect and analyze on integrated analysis of the entire optimal design

The SEM Grid Map approach provides a comprehensive framework for comprehending and optimizing the complex interplay between scientific principles, engineering practices, and mathematical algorithms within the bioprinting system. Through this method, the probabilities highlighted underscore a meticulously planned design that prioritizes precision, control, and efficiency. However, it's important to acknowledge that biomedias can display batch-to-batch variability, which poses a challenge in maintaining consistent outputs. To address this variability, rigorous engineering and mathematical controls are essential components of the system. These controls enable fine-tuning of parameters and algorithms to mitigate the impact of batch differences, ensuring reliable and reproducible results. Moreover, the success and reliability of the bioprinting system hinge on regular calibration, proactive maintenance, and iterative testing. By implementing these practices, the system can sustain its high success rates over time and across practical applications. This iterative approach not only supports continuous improvement but also reinforces the system's robustness and adaptability to evolving demands in bioprinting technology. In essence, the SEM Grid Map approach, bolstered by meticulous engineering and mathematical controls, coupled with diligent maintenance and testing, forms the cornerstone of achieving consistent and dependable outcomes in bioprinting.

Integrated SEM Analysis of the Bioprinting Extrusion Process:

Scientific Consideration: The scientific analysis of a bioprinter extrusion process involves a meticulous examination of the intricate interplay between various parameters and components crucial for the fabrication of three-dimensional biological structures. The extrusion system itself, comprising nozzles and pressure controls, undergoes evaluation to ensure precise deposition of biomaterials. Also, environmental influence such as temperature and humidity on the printing process is fully investigated. Cellular viability and functionality post-printing are critical endpoints, prompting assessments of cell
survival rates, differentiation potential, and overall tissue integrity. Advancements in the scientific understanding of bioprinter extrusion processes not only contribute to the refinement of current techniques but also pave the way for innovative applications in tissue engineering, regenerative medicine, and pharmaceutical research.

Engineering Consideration: The engineering considerations in a bioprinter extrusion process revolve around the intricate design and optimization of the printing system to achieve precision, repeatability, and scalability. Nozzle geometry, material compatibility, and extrusion pressure must be meticulously calibrated to accommodate the rheological nuances of various biomedias. Engineers focus on developing robust and controllable extrusion mechanisms, ensuring a consistent flow of biomaterials. The mechanical aspects of the bioprinter, such as frame stability and motion control, are critical to achieving high-resolution prints. Cost-efficient materials for the printer components are carefully selected to avoid adverse effects on cell viability. Moreover, considerations extend to automation and software control for precise spatial deposition of biomedias, enabling the creation of complex, multi-material structures. Balancing these engineering parameters is essential for the successful integration of bioprinting technologies into practical applications, from personalized medicine to organ-on-a-chip systems.

Layer Integrity: Ensuring each layer adheres well to the previous layer, preventing delamination or voids. This is a common process fine-tuned by 3D printers in standard processes. For the team’s design, refinement of such has not been achieved and as such requires independent attention to detail from operators to ensure smooth and integrated layer printing.

Mathematical Consideration: In the realm of mathematical considerations for a bioprinter extrusion process, several key parameters and models play a pivotal role in optimizing the fabrication of complex biological structures. Rheological models, such as the power-law model or Bingham plastic model, are employed to describe the flow behavior of biomedias and predict their response to varying shear rates during extrusion. Computational fluid dynamics (CFD) simulations are utilized to analyze the fluid flow patterns within the nozzle and optimize the design for uniform deposition. Mathematical models also aid in predicting the impact of nozzle diameter, extrusion speed, and layer height on the resolution and fidelity of the printed structures. Kinetic models for gelation and cross-linking reactions in biomedias help determine the optimal conditions for maintaining the structural integrity of printed constructs. Additionally, mathematical algorithms for path planning and trajectory optimization are essential for precise and efficient spatial deposition of biomaterials. Integration of these mathematical models enables a systematic approach to fine-tuning the bioprinting process, ensuring accuracy and reproducibility in the creation of intricate tissue constructs.

Algorithmic Control: Advanced algorithms need to dictate the timing, sequence, and rate of each biomedia deposition, ensuring even layering and optimal crosslinking. These algorithms are incorporated into custom g-code, specifically for the pattern printing through the device, and actuated by the connectivity between the Raspberry Pi and Ender 3 V2 printer.

Feedback Systems: Continuous monitoring of the process parameters, adjusting in real-time to ensure consistency and quality. These feedback systems are an integral part of the control system, allowing for the PLC to continuously monitor conditions and adjust in accordance with the g-code.

Integrated Probability Analysis: Integrated probability analysis in the context of bioprinter extrusion processes involves a multifaceted examination of various probabilistic factors that influence the overall success and reliability of the bioprinting operation. One crucial aspect is the probabilistic assessment of material properties, considering the variability in rheological characteristics, viscosity, and gelation kinetics of biomedias. Another critical consideration is the probabilistic evaluation of mechanical components and system reliability within the bioprinter. This includes assessing the failure probabilities of components such as nozzles, pumps, and motors, which can impact the overall system performance. Probabilistic risk analysis can help identify potential weak points in the system and guide engineering efforts to enhance robustness. Cell viability and functionality post-printing are inherently uncertain due to biological variability and as such, a surrogate biomedia is used for testing process. This probabilistic approach provides a comprehensive understanding of the potential variations in the biological response to the printing process. Moreover, considering the nature of environmental conditions, such as temperature and humidity, in the working environment, probability analysis aids in predicting how these variations might affect the printing process. This information is crucial
for implementing real-time adjustments or developing adaptive control strategies to mitigate the impact of environmental fluctuations. By integrating probability analysis across material properties, system components, biological responses, and environmental conditions, researchers and engineers can understand the uncertainties inherent in bioprinter extrusion processes. This insight is invaluable for optimizing protocols, enhancing system reliability, and advancing the overall reproducibility and predictability of bioprinting technologies.

Integration of Quantifiable Areas

Resolution and Precision: Assuming a high individual success rate, the integrated probability for maintaining resolution and precision throughout the multi-layer printing is slightly reduced to around 85%. This accounts for potential misalignments or inconsistencies during layer transitions.

Biopedia Extrusion Rate: As each biopedia may have distinct properties, the overall probability of maintaining a consistent extrusion rate through all layers drops to approximately 85%, considering potential hiccups during transition.

Thermal Management Efficiency: The integrated probability remains high at >90% as temperature control should be consistent throughout the printing process after validation experimentation and calibration is complete.

Photopolymerization Accuracy: Given the multiple layers and varying biopedia properties, the integrated probability for achieving uniform curing across the entire structure is approximately 85%. This is due to the validation testing for UV output and potential application of the lights being able to fault from human error during operation.

Mechanical Integrity: With the complexity of multi-layered structures, ensuring mechanical stability becomes challenging. The integrated probability is estimated to be around 80%. This stems from the compatibility and stress resistance of mechanical parts responsible for device operation.

In summary, the SEM Grid Map approach offers a systematic framework for optimizing the complexities of bioprinting systems. This method prioritizes precision, control, and efficiency in design, despite challenges like batch-to-batch variability in biopedias. Rigorous engineering and mathematical controls are crucial for maintaining consistent outputs, requiring regular calibration, maintenance, and iterative testing for sustained success in practical applications. Probability analysis across material properties, system reliability, and environmental conditions provides critical insights for protocol optimization and system enhancement. Addressing uncertainties proactively is key to advancing the reliability and predictability of bioprinting technologies. The SEM Grid Map approach, underpinned by meticulous controls, represents a fundamental strategy for achieving dependable outcomes in bioprinting.

4.5 Market Analysis for the demand and cost-competitiveness of optimal design

1. Demand Analysis:

a. Universities, Research Institutions, & Hospitals: There is a growing interest in bioprinting in academic and clinical sectors. A cost-effective bioprinter will make it feasible for institutions, even those with budget constraints, to integrate bioprinting into their curriculum and research projects.

b. DIY Bio-enthusiasts & Makerspaces: The open-source community thrives on affordable, modifiable designs. A bioprinter in this price range is a momentous change for DIY enthusiasts and makerspaces looking to explore the realm of bioprinting without heavy capital investments.

c. Small Biotech Start-ups: For budding biotech companies, initial capital can be a constraint. A sub-$750 bioprinter offers them an affordable entry point to kickstart their R&D.

d. Developing Nations: In areas where budgetary constraints are paramount, an affordable bioprinter can bolster research capabilities and attract talent.

2. Cost Competitiveness Analysis:
a. Hardware Costs: Compared to commercial bioprinters priced over $2000, the proposed bioprinter presents a significant cost advantage. The sub-$750 price point translates to potential savings of over 60%, which is a strong value proposition for cost-conscious buyers.

b. Customizability: Being open-source means users can modify and adapt the printer to specific needs without the constraints often found in commercial systems. This flexibility might lead to further cost savings overall, as users can implement low-cost, localized solutions for upgrades or maintenance.

c. Running & Maintenance Costs: Assuming the design ensures durability and ease of maintenance with readily available parts, the long-term running costs would be reduced. However, if failure occurs, the key failure points lie in the 3D printed parts which due to their availability, would lead to relatively cheap repair processes.

d. ROI (Return on Investment): For organizations and individuals, the ROI is not just in monetary terms. The accessibility and affordability of this bioprinter can accelerate research, foster innovation, and provide educational value, making the ROI substantial both in direct financial terms and broader societal impacts.

3. Market Position:

The bioprinter, at its proposed price point, occupies a unique niche in the market. It fills the gap between high-end commercial bioprinters and rudimentary DIY setups, potentially appealing to a broad spectrum of users.

Figure 4.5.1: Market analysis with preexisting bioprinters and highlights the cost efficiency of the proposed bioprinter design. This figure gives a visual representation of the bioprinter cost efficiency.

4.6 Environmental and policy and regulatory analysis of optimal design

- FDA Regulations:
  - In the United States, the Food and Drug Administration (FDA) regulates medical devices, which can include bioprinters. Regulations will depend on the intended use and classification of the bioprinted product. These regulations, however, should not impact the overall scope of the project due to it being a
research setting. This is merely an assumption due to the FDA as of 10/22/2023 not publishing any regulations for bioprinters in research setting nor for the biomedia. If this device were applied to clinical standards, the FDA does have regulations that would need to be met in that instance.

- **Biocompatibility Standards:**
  - Bioprinted materials must meet biocompatibility standards to ensure they are safe for use in the human body. ISO 10993 is a standard procedure for all medical devices to test biocompatibility and avoid any physiological harm to patients. They are not necessitated in research setting but similarly to the FDA regulations should be considered if this device is to be used clinically.

- **Good Manufacturing Practices (GMP):**
  - If bioprinted tissues are intended for clinical use, the team will need to adhere to GMP standards to ensure product quality, consistency, and safety. GMP, however, does not have any documentation regarding research settings but is a crucial framework to ensure product quality and reproducibility.

- **Ethical and Legal Considerations:**
  - If cells are to be cultured or any biomaterial is developed, the printer would have to adhere to review and approval from the Institutional Review Board (IRB). Biomedia and other non-biological printed substances should be free from IRB jurisdiction if cell culturing or testing remains outside of the product's scope. If however, there is an application where cell testing or culturing needs to be performed, the cells must have approval from the IRB or come from an approved vendor.

- **Environmental Impact:**
  - Considerations for the environmental impact of bioprinting processes, such as waste management and energy consumption, may become more significant as technology advances. At the current state of the product, the team must only worry about the SDS of any chemicals used in the printing process to ensure the proper safety and disposal procedures are followed.

- **FDA Approval Pathways:**
  - Depending on the nature of the bioprinted product and its application, different FDA approval pathways exist including the following: such as the 510(k) clearance, De Novo classification, or Pre-Market Approval (PMA) process.

### 4.7 Ethical Considerations for each functional domain of the optimal design

- **Power Supply**
  - **Safety:** Ensure that the power supply is designed and maintained to prevent electrical hazards, reducing the risk of accidents or harm to researchers or users.
  - **Energy Efficiency:** Minimize energy consumption to reduce the environmental impact and promote sustainability.

- **Raspberry Pi**
  - **Data Privacy:** When collecting data using the microcontroller, data should be secure and only related to the project. Data should be handled responsibly and with consent if applicable.

- **UV Ring**
  - **Safety:** UV curing systems can emit harmful UV radiation. Ensure that safety measures are in place to protect those around and prevent unintended exposure.
  - **Environmental Impact:** Consider the environmental impact of UV curing systems, including the disposal of consumables like UV bulbs.

- **Syringes**
  - **Material Compatibility:** Ensure that the syringes used are compatible with the bioprinting materials and do not leach harmful substances into the printed structures.
- Waste Management: Properly dispose of syringes and related materials to prevent environmental contamination.

- Barrel Loading Mechanism
  - Safety: Ensure that the power supply is designed and maintained to prevent electrical hazards, reducing the risk of accidents or harm to researchers or users.

- Motors
  - Safety: Motors used for movement and positioning should have safety features to prevent accidents. Researchers should be trained in their proper use to avoid injuries.
  - Resource Use: Consider the energy efficiency of motorized components to minimize resource consumption and reduce environmental impact.

4.8 Ethical Considerations for the entire optimal design

- Environmental Impact: Consider the environmental impact of the project, including the disposal of biological waste, materials used, and energy consumption. Strive to minimize any negative environmental consequences.
- Safety: Ensure the safety of both group members and any potential end-users. This includes working with potentially hazardous biological materials and ensuring the safety of the final product. Implement proper safety protocols and risk assessments.
- Dual-Use Concerns: Be aware of the dual-use nature of bioprinting technology, which could be used for both beneficial and harmful purposes. Consider taking steps to prevent misuse, such as sharing findings responsibly and working in collaboration with appropriate regulatory bodies.
- Compliance with Regulations: Ensure that the project complies with all relevant local, national, and international regulations and ethical standards. This may include obtaining the necessary permits, licenses, or ethical approvals.
- Transparency: Maintain transparency in your research, including the methods, results, and any conflicts of interest.
- Responsible Innovation: Consider the broader ethical implications of your project. Strive for responsible innovation, where you actively think about the potential impacts of your work and how to mitigate any negative social and environmental consequences.

5 DESIGN PROTOTYPING

5.1 Reflect on your optimal design to do a rough listing of components needed for each functional area and sub functional area to build a design prototype

The project consists of four functional areas: The 3D printer itself, a power supply for the additional components, the components themselves, and the measurement of the output. Of these functional areas, all of them have sub functional areas that cover specific aspects of the respective areas.

- 3D Printer
  - The 3-D Printer is an Ender-3 V3.

- Power Supply
  - Battery: MEGO 4-24V Breadboard DC Rechargeable Power Supply
  - Wires, terminals, insulative shrink wrap, crimp on terminals, solder, and flux.

- Components:
  - Motor – Stepper Motor STEPPERONLINE 1A 22.6oz*in/16N*cm
    - A4988 Driver Module Compatible, A4988 Stepper Motor Drive modules with Heat Sink
- Timing Belt
- Drive Shaft Gear
- Linear Actuator - Compact Stepper Motor Actuator, NEMA 17, 50 lb. Pull/Push Load, 1.25 in./Sec Speed
  - Motor Frame Size, NEMA 17
  - Travel Distance per Full Step, 0.000625"
  - Stroke Length, 2"
  - Stroke Protection Type, None
  - Dynamic Load Capacity, lbs.,
  - Pull, 50
  - Push, 50
  - Static Load Capacity, 50 lbs.
  - Maximum Speed, 1.25 in./sec.
  - Accuracy, ±0.0006" per in.
  - Maximum Current per Phase, 1.5 A
  - Resistance per Phase, 1.56 ohms
  - Inductance per Phase, 1.9 mH
  - Full Step Increment, 1.8°
  - Rotor Inertia, 0.2 oz-in.^2
  - Duty Cycle, Continuous
  - Motor Type, Hybrid Stepper
  - Polarity, Bipolar
  - Electrical Phase, Two
  - Overload Protection Type, None
  - Electrical Connection Type, Hardwire
  - Wire Connection Type, Wire Leads
  - Number of Wire Leads, 4
  - Wire Lead Color, Green, Green/White, Red, Red/White
  - Wire Lead Length, 12"
  - Wire Lead Gauge, 26
  - Extension Rod Type, Nonrotating
- UV Lights
  - 4 (1=3 series by 3 parallel) UV Light Modules rated at 395nm
  - Stage of Circuit Powered by +15V Terminal on DC/DC Converter
  - Logic Gate Using MOSFET (IRF540N)
  - 4.7 Ohm Current Limiting Resistors (parallel with diode module) & 1 Kohm Gate Resistors
- Raspberry Pi Model 4 B
  - 24 GPIO Terminal Pins
  - Broadcom BCM2711, quad-core Cortex-A72 (ARM v8) 64-bit SoC @ 1. 5GHz---4GB LPDDR4-2400 SDRAM
  - 2.4 GHz and 5.0 GHz IEEE 802.11B/g/n/ac Wireless LAN, Bluetooth 5.0, double-true Gigabit Ethernet
  - 2 × USB 3.0 ports, 2 × USB 2.0 Ports---2 × micro-HDMI ports supporting up to 4Kp60 video resolution
  - 2-lane MIPI DSI/CSI ports for camera and display--4-pole stereo audio and composite video port--Micro SD card slot for loading operating system and data storage
  - Requires 5.1V, 3a power via USB Type C or gpio-poep (power over Ethernet) enabled (requires PoE hat-not included)
- Thermal Control Stage of Circuit
  - 4 PCS Film Heater Plate Adhesive Pad, ICstation PI Heating Elements Film 12V 12W Strip Heater Adhesive Polymide Heater Plate 10mmx93mm
- DS18B20
- Solid State Relay Model: SSR-25DD
  - Specifications:
    - Control Voltage: 3-32V DC
    - Load Voltage: 5-60V DC
    - Load Current: 25A
    - Control Current: Typically, around 5-20mA which is suitable for a Raspberry Pi GPIO.
    - Zero Voltage Turn-On or Instant-On depending on the model for DC control.
    - This SSR is a small, breadboard-compatible module that typically comes with a built-in input resistor to limit the current from the control signal. It would have pins or screw terminals for easy connection to a breadboard and your circuit.
    - When connecting the SSR to a breadboard and Raspberry Pi, the wiring would be as follows:
      - Input Side (Control Signal):
        - One input terminal connected to the GPIO pin on the Raspberry Pi.
        - The other input terminal connected to a ground (GND) pin on the Raspberry Pi.
      - Output Side (Load):
        - One output terminal connected to one end of the heating strip.
        - The other output terminal connected to the positive terminal of the power supply.
        - The negative terminal of the power supply should be connected to the other end of the heating strip.
  - Output Measurement
    - W1209 12V DC Digital Temperature Controller Board
5.2 Coarse component selection in a grid map for each functional area

![Component selection table]

Figure 5.2.1: Component selection table. This is the foundation for our optimal design and the development of an innovative bioprinting prototype as it shows all components per functional domain.

Figure 5.2.2: Extra components spent in the prototype process. These were independent purchases from the team and were instrumental to the prototyping steps and some components made it into the final design. Components such as the temperature control board, linear actuator, and mounting hardware made it into the final design and without their interaction, would severely detract from the performance of the device.

5.3 Refinement of the grid map for each functional area to produce a refined grid map for each functional area

<table>
<thead>
<tr>
<th>Component</th>
<th>Quantity</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D Printer</td>
<td>1</td>
<td>Creality Ender V3.</td>
</tr>
<tr>
<td>Power Supply</td>
<td></td>
<td>Power supply in addition to breadboards and various resistors to divide up 1 input voltage as well as voltage regulators to maintain voltages</td>
</tr>
<tr>
<td>Motors</td>
<td></td>
<td>Stepper Motor STEPPERONLINE 1A 22.6oz<em>in/16N</em>cm</td>
</tr>
<tr>
<td>UV Lights</td>
<td></td>
<td>4 Lights with wavelength of 395 nm.</td>
</tr>
<tr>
<td>Raspberry Pi</td>
<td></td>
<td>Raspberry Pi and wires</td>
</tr>
</tbody>
</table>
Temperature Sensor

In addition to the various resistors and components, it also needs to be able to connect the power supply to the sensor and its output to various points.

Figure 5.3.1: Grid map of the finalized description of the functional areas for this bioprinter. It has been refined after rigorous research and simulation completed to optimize each aspect and functional domain thoroughly.

5.4 Come up with a paper design with components in place

With temperature control being such a pivotal element in the circuitry, a temperature control board is selected to keep the temperature of the calibration bio media in its proper range. The temperature control board must be linked to power, which enables it to heat up. Should the temperature outputted by the sensor be outside the 25-30°C as required for mass biomedia, the temperature must heat up or shut down to get into range, outputting a logical low. When in range, the temperature sensor outputs a logical high, allowing the bio media inside to stay within the proper temperature range.

Figure 5.4.1: Temperature control board.
Figure 5.4.2: Final design paper schematic for the electrical control system in the device.

5.6 Carry out a computer simulation to further validate the process
Figure 5.6.1: The final design simulated in KiCAD. This simulation was done to verify voltage connections and observe waveform responses to validate wiring connections.

5.7 List potential components by approximate price, ease of use, price, and lead time

Schematic 2 (Figure 5.4.2) Component List:
Figure 5.7.1: Table outlining the necessary components needed for the schematic discussed in figure 5.4.2.

Tables 5.1 and 5.2: Individual budget table and combined budget totals

<table>
<thead>
<tr>
<th>Component</th>
<th>Price</th>
<th>Ease of Use</th>
<th>Lead Time</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ender-3 V3 3D Printer</td>
<td>$179</td>
<td>Moderate</td>
<td>1 Week</td>
<td>Base Printer</td>
</tr>
<tr>
<td>MEGO 4-24V DC Power Supply</td>
<td>$0</td>
<td>Easy</td>
<td>N/A</td>
<td>In-kind from NIU</td>
</tr>
<tr>
<td>DC/DC Converter (DC2-185-4007)</td>
<td>$29.98</td>
<td>Easy</td>
<td>1 Week</td>
<td>8-36VDC</td>
</tr>
<tr>
<td>Wiring and Terminals</td>
<td>$30</td>
<td>Easy</td>
<td>N/A</td>
<td>Internal Components</td>
</tr>
<tr>
<td>Solder and Flux</td>
<td>$30</td>
<td>Moderate</td>
<td>N/A</td>
<td>Internal Components</td>
</tr>
<tr>
<td>STEPPERONLINE Stepper Motor</td>
<td>$50</td>
<td>Moderate</td>
<td>N/A</td>
<td>Internal Components</td>
</tr>
<tr>
<td>A4988 Driver Module</td>
<td>$10.19</td>
<td>Easy</td>
<td>1 Week</td>
<td>Motor Driver Module with Heat Sink for 3D Printer</td>
</tr>
<tr>
<td>Timing Belt</td>
<td>$20.49</td>
<td>Easy</td>
<td>1 Week</td>
<td>Compatible with Gear to turn Barrel</td>
</tr>
<tr>
<td>Drive Shaft Gear</td>
<td>$0</td>
<td>Easy</td>
<td>N/A</td>
<td>3D Printed, Compatible with timing belt</td>
</tr>
<tr>
<td>Linear Actuator</td>
<td>$38</td>
<td>Moderate</td>
<td>2 Weeks</td>
<td>110mm</td>
</tr>
<tr>
<td>UV Light Modules</td>
<td>$60</td>
<td>Hard</td>
<td>1 Week</td>
<td>UV 395nm / 900mA / DC 9V - 11V / 10 Watt</td>
</tr>
<tr>
<td>MOSFET (IRF540N)</td>
<td>$11.23</td>
<td>Easy</td>
<td>1 Week</td>
<td>MOSFET N-CH 100V 36A TO220AB</td>
</tr>
<tr>
<td>Raspberry Pi Model 4 B</td>
<td>$55</td>
<td>Moderate</td>
<td>1 Week</td>
<td>Central control unit</td>
</tr>
<tr>
<td>Polyimide Heating Pad</td>
<td>$30.17</td>
<td>Easy</td>
<td>1 Week</td>
<td>ICstation PI heating elements, 12V 12W</td>
</tr>
</tbody>
</table>

*Figures valued in US dollars.*

### Printing Components

<table>
<thead>
<tr>
<th>Component</th>
<th>Source</th>
<th>Cost</th>
<th>Quantity</th>
<th>Final Cost</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D Printer</td>
<td>store.creality.com</td>
<td>$179</td>
<td>1</td>
<td>$179</td>
<td>Ender-3 V3 SE</td>
</tr>
<tr>
<td>Raspberry Pi</td>
<td>Digikei.com</td>
<td>$53</td>
<td>1</td>
<td>$53</td>
<td>PI 4 Model B</td>
</tr>
<tr>
<td>ABS Filament 1.75mm</td>
<td>Amazon.com</td>
<td>$12</td>
<td>1</td>
<td>$12</td>
<td>Red</td>
</tr>
<tr>
<td>ABS Filament 1.75mm</td>
<td>Amazon.com</td>
<td>$12</td>
<td>1</td>
<td>$12</td>
<td>Red</td>
</tr>
<tr>
<td>PLA Filament 1.75mm</td>
<td>Amazon.com</td>
<td>$12</td>
<td>1</td>
<td>$12</td>
<td>Black</td>
</tr>
<tr>
<td>IN HOUSE COMPONENT</td>
<td>cellink.com</td>
<td>$15</td>
<td>5</td>
<td>$75</td>
<td>PSU for external components</td>
</tr>
</tbody>
</table>

### Chemical Components

<table>
<thead>
<tr>
<th>Component</th>
<th>Source</th>
<th>Cost</th>
<th>Quantity</th>
<th>Final Cost</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>GelMA</td>
<td>sigmaaldrich.com</td>
<td>$179</td>
<td>300g</td>
<td>$535</td>
<td>Degree of substitution 60%</td>
</tr>
<tr>
<td>PEGDA</td>
<td>polysciences.com</td>
<td>$97</td>
<td>250g</td>
<td>$194</td>
<td>Polystyrene glycol diacrylate (PEGDA 400)</td>
</tr>
<tr>
<td>Carboxylic acid</td>
<td>Amazon.com</td>
<td>$14.99</td>
<td>907g</td>
<td>$14.99</td>
<td>&quot;Pure&quot; Brand</td>
</tr>
<tr>
<td>Photo initiator</td>
<td>cellink.com</td>
<td>$15</td>
<td>5g</td>
<td>$75</td>
<td>IRGACURE 2950 STORES AT 36-46 Deg F</td>
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### Electrical Components

<table>
<thead>
<tr>
<th>Component</th>
<th>Source</th>
<th>Cost</th>
<th>Quantity</th>
<th>Final Cost</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Sensor</td>
<td>Amazon.com</td>
<td>$8.99</td>
<td>1</td>
<td>$8.99</td>
<td>Custom Circuit</td>
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<tr>
<td>Polyimide Strips</td>
<td>Digikei.com</td>
<td>$8.02</td>
<td>10</td>
<td>$80.20</td>
<td>12V 12W Flexible Polyimide Heater Plate</td>
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<td>Linear Actuator</td>
<td>Amazon.com</td>
<td>$3.88</td>
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<td>$3.88</td>
<td>GP30 WYANHua</td>
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<td>Light Array 395nm</td>
<td>Amazon.com</td>
<td>$9.99</td>
<td>1</td>
<td>$9.99</td>
<td>Everlight 395nm 10W UV LED</td>
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<tr>
<td>Liquid Properties Sensor</td>
<td>Amazon.com</td>
<td>$26.50</td>
<td>1</td>
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<td>Solid State Relay</td>
<td>Amazon.com</td>
<td>$2.80</td>
<td>1</td>
<td>$2.80</td>
<td>TBD DC TO DC input 3-33VDC</td>
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<td>Motor Driver</td>
<td>Amazon.com</td>
<td>$10.19</td>
<td>1</td>
<td>$10.19</td>
<td>A4988 5 Pack</td>
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<td>Light Power Supply Diodes</td>
<td>Digikei.com</td>
<td>$0.38</td>
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<td>$3.84</td>
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<td>MOSFET</td>
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<td>$1.12</td>
<td>10</td>
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<td>Light Voltage Divider</td>
<td>Amazon.com</td>
<td>$14.99</td>
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<td>3511 XL1018 XL1018</td>
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### Extrusion Components

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<th>Final Cost</th>
<th>Description</th>
</tr>
</thead>
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<td>Syringe Housing (Barrel)</td>
<td>Printing</td>
<td>$0</td>
<td>0</td>
<td>0</td>
<td>Printed using Prexisting PLC</td>
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<td>Mini Thrust Bearings</td>
<td>Amazon.com</td>
<td>$8.49</td>
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<td>$8.49</td>
<td>ucell 51204</td>
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<td>Deep groove bearings</td>
<td>Amazon.com</td>
<td>$5.87</td>
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<td>ucell 5206-ZR5</td>
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<td>Timing Belt</td>
<td>McMaster.com</td>
<td>$6.83</td>
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<td>Belt Pulley</td>
<td>McMaster.com</td>
<td>$17.30</td>
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<td>$34.60</td>
<td>MXL Series Timing Belt Pulley</td>
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<tr>
<td>Extruder</td>
<td>Amazon.com</td>
<td>$6.99</td>
<td>2</td>
<td>$13.98</td>
<td>4 Pack with Needle</td>
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### Final Totals

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<tr>
<th>Component</th>
<th>Final Total</th>
<th>% Utilization</th>
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</thead>
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<tr>
<td>Printing</td>
<td>$500</td>
<td>16.64%</td>
</tr>
<tr>
<td>Chemical</td>
<td>$796.99</td>
<td>55.54%</td>
</tr>
<tr>
<td>Electrical</td>
<td>$215.24</td>
<td>24.63%</td>
</tr>
<tr>
<td>Extrusion</td>
<td>$93.05</td>
<td>3.08%</td>
</tr>
<tr>
<td>Total</td>
<td>$1,409.28</td>
<td>100%</td>
</tr>
<tr>
<td>Total W/O Chems</td>
<td>$608</td>
<td>44.68%</td>
</tr>
</tbody>
</table>
Figure 5.7.3: Complete parts list with the supplies, sources, cost, and quantities.

Figure 5.7.4: Totals added up for each individual design sector, additionally added together to show our final cost.

Our biggest budget issue is the prohibitive cost of the various chemicals the team wants to use. Removing the chemical aspects from our budget drops our costs to $609. Future iterations of this design would involve the incorporation of actual biochemicals and validate the design’s performance with the integration and testing versus commercial bioinks.

6 RESPONSIBILITY MATRIX, TIMELINE, AND GANTT CHART

6.1 Present each team member qualification

Dominic – As an aspiring biomedical engineer, Dominic brings the drive for innovation to the forefront of biomedical engineering. As well, Dominic has proficiency in leadership abilities and adaptability to rise to any challenge, with these skills he steps into a manager role for the group who works hard to fill in the gaps and keep the team motivated. He is certified to work on medical equipment and brings that knowledge to bring forward and design his own medical device. His experience in the workforce and courses lead him to be a proficient problem-solving leader determined to design and finalize a bioprinter.

Noah – As the principal investigator, Noah displays a blend of academic distinction and practical engineering acumen, underscored by experiences that demonstrate proficiency in innovative technologies. With a foundation in Biomedical Engineering from Northern Illinois University, his expertise extends to the automation of complex laboratory procedures. Their role in leadership positions, such as the President of the Biomedical Engineering Society and the R&D Lead within Engineering World Health, reflects a commitment to applying technical knowledge to societal challenges. Noah's practical skills as a Biomedical Engineering Technician at Project C.U.R.E. further highlight his technical prowess in medical instrumentation.

Andrew – An Electrical Engineering major and a Biomedical Engineering minor student, Andrew brings in a wide variety of knowledge on electrical circuitry to the table. Andrew has taken many circuitry classes here at NIU and will be immensely helpful in bringing everything together. His knowledge of various circuitry including voltage and current dividers, temperature sensors, and operational amplifiers will play a key role in the final product coming May 2024.

Mohammad - An Electrical Engineering major, Mohammad brings a wide range of knowledge like power control, control systems, and Raspberry Pi programming. Mohammad has taken many Electrical Engineering classes and knows his way around electrics as well as electrical components which would help make sure that the project is as design optimal as possible.

Nevada – A Computer Science major, Nevada brings experience with building data systems from CS classes as well as interning at a healthcare company from 2022.

6.2 Coverage on each team member for their assigned functional domain or sub domain

- Andrew, Dominic & Noah - Research and Report Writing
- Mohammad & Dominic - Budgeting
- Dominic- Organizational/Administrative duties and helping serve as the voice of the team
- Nevada- Software Research
- Mohammad & Andrew - Electrical Component Research
- Dominic & Noah – Biomedical Research
- Nevada, Mohammad, and Andrew - PowerPoints
- Dominic & Noah - Fill in gaps as needed and assist group members
- Dominic – Assembly Manager
- Noah – Assembly Director
• Andrew & Mohammad – Electrical Engineering Coleads
• Nevada – Assembly Software Lead

6.3 Timeline from the beginning to the end

**Week of 10/9/23 - 10/15/23: Research and Initial Budgeting**

- Review components and start developing a rough budget for the project.
- 3 Min Presentation.
- Gant Chart
- Prepare for the 10/13 meeting.

**Week of 10/16/23 - 10/22/23: Budget Refinement and Design Proposals**

- Review and revise the budget as needed based on initial research.
- Prepare for the 10/20 meeting.
- Work on refining the three best design options.
- Ensure that the "DESIGN PROPOSAL AND PRELIMINARY DESIGN IDEAS" is ready (by Friday, October 20th).

**Week of 10/23/23 - 10/29/23: Design Selection and Meeting Preparation**

- Finalize and select the best design option from the three.
- Prepare for the 10/27 meeting.

**Week of 10/30/23 - 11/5/23: Alternative Designs and Analysis**

- Finalize budget and work through any issues with final design
- Ensure that the "ALTERNATIVE DESIGNS AND ANALYSIS" report is ready by Friday, November 3rd.
- Prepare for 11/3 Meeting.

**Week of 11/6/23 - 11/12/23: Optimal Design Selection and Analysis**

- Select the optimal design and justify the selection with thorough analysis.
- Draft Final Presentation
- Prepare for the 11/17 meeting on.
- 11/10- Component Ordering


- Draft the "FINAL REPORT" with project details and findings.
- Finalize Final Presentation
- Work on team evaluations, which are due by Wednesday, December 1st.
- Prepare for 11/17 Meeting.

**Week of 11/20/23 - 11/26/23: Final Report and Thanksgiving Break**

- Finalize the "FINAL REPORT" and submit it by the deadline of Friday, December 8th.
- Prepare for meeting 11/23
- Hopefully Have parts, begin prototype assembly
- Test components for compliance
Week of 11/27/23 - 12/3/23: Post-Submission Follow-Up

- Address any post-submission requirements or revisions to the report.
- Prepare for meeting 12/2
- Prototype testing and refinement

Weeks Starting 12/4/23-1/6/24: Ongoing Development

- Continue the project's development, testing, and refinement.
- Work to finalize and test prototype

MILESTONE - By 1/1 Have Prototype Working

1/15/24-2/4/24 Component Testing

- Work on prototype refinement
- Test Component Compliance

2/4/24-2/11/24 Final Assembly

- Design and Assembly Finalized

2/11/24-4/28/24 Testing Phase

- Final design Testing and Validation

2/4/24-5/28/24 Final Preparation

- Prepare for Demo Day

MILESTONE - 5/5/24 Demo Day

6.4 Present and discuss Gantt Chart for implementation of your final design

Semester 1

This semester was focused on design iteration and refinement, with the primary focus being on research which is reflected upon in the breakdown of responsible tasks.

<table>
<thead>
<tr>
<th>Task</th>
<th>Duration</th>
<th>Start</th>
<th>End</th>
<th>9/1-9/15</th>
<th>9/15-10/1</th>
<th>10/15-11/1</th>
<th>11/15-12/1</th>
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<tr>
<td>Planning</td>
<td>5 Months</td>
<td>8/28</td>
<td>1/1</td>
<td></td>
<td></td>
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<tr>
<td>MILESTONE- 3 OPTIMAL DESIGNS</td>
<td></td>
<td></td>
<td></td>
<td>1/5</td>
<td>10-Oct</td>
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<td>20-Oct</td>
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<tr>
<td>MILESTONE- FINAL DESIGN DONE</td>
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<tr>
<td>Electrical Research</td>
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<td>1/1</td>
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<tr>
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<td>5/1</td>
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**Winter Break - Semester 2**

This semester prioritizes the development and refinement of the physical property and through the utilization of rigorous testing and validation, produces a fully functional optimal prototype.

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<td>1/1</td>
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<td>5/1</td>
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<td>1/1</td>
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<td>MILESTONE - Final</td>
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<td>3/1</td>
<td>5/1</td>
<td></td>
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Figure 6.4.1: Gantt chart outlining our responsibilities for the from 9/1-12/1.

Figure 6.4.2: Gantt chart outlining our responsibilities for the from 12/15-5/1
7 CONCURRENT ENGINEERING PART 1

7.1 Parallel prototyping of each sub-functional area

The project encompasses four core functional areas: printing, chemical, electrical, and extrusion. These functional areas are being prototypes parallel to one another with no more than two members per emphasized area. This was done to increase the proliferation of design diversity and create a better understanding of the interconnectivity of all aspects of the design. Parallel prototyping also has been correlated to increased final usability of ideas and the final project, as well as fostering a more collaborative team. Through utilizing this methodology, the team can prioritize their strengths and mitigate any weaknesses by focusing their tuned problem-solving abilities. Overall, this leads to a greater success rate for each functional area that combines with the realization of a more innovative final product.

Printing: This functional area includes any processes related to the printing of biomedia and project components that do not explicitly include the extrusion of the printed media. Printing in this project involves two sub functional areas that cover different aspects of the printing processes used throughout the project.

- Bioprinting: This subdomain is primarily focused on turning our standard 3D printer standardized to be utilizing plastic filament into a medical device capable of printing a biomedia that is usable in tissue engineering sectors. This subdomain is intrinsically tied to both the chemical and extrusion functional domains as they facilitate the proliferation of biomedia creation and eventual extrusion to be a usable product. This area is dominated and led by the primary biomedical engineering students with close assistance from Dr. Diggs. This combination allows the biomaterial familiar members to prioritize their prior knowledge.

- Parts Printing: This subdomain is linked solely to the printing of components to be used in the function of the final design. Included in this is the novel barrel housing that houses electrical components related to biomedia extrusion. Additionally, the mount to hold mechanical parts responsible for making the barrel design is a printed component. The primary positives to these parts being printed are increased familiarity of the devices utilized, a lower overall cost, and mechanical adaptability to potential errors. Regarding the former two, by printing these parts, the team can minimize budget expense whilst adjusting components on the fly when noncritical errors occur. This allows for a larger ability to put increasing loads on this printer when testing the safety and reliability of the prototypes throughout the design process. This is due to the unique adaptability of printed parts replicability and adjustment limited only to the time required for their creation. The same biomedical students responsible for the bioprinting processes also headline this subdomain due to their familiarity with SolidWorks software and experience within 3D printers. This combination for quick failure identification and editing skills from previously designed components that emphasizes the positive nature of printed part adaptability.

Chemical: This domain, whilst not having subdomains, is perhaps the most crucial for the creation of biomedia that is viable and validatable for tissue engineering applications. This is headlined by the research done in previous literature review and the cell proliferation expertise of Dr. Diggs and the biomedical students. The target of these components is a combination of chemical processes and purity of acquired materials necessitated to create viable biomedia. This functional area required the most validation time to ensure quality prior to live testing and encompasses all required chemical processes involved in creating an environment for cellular proliferation.

Electrical: This functional area has the most sub functional areas which is to be anticipated in the novel creation of a medical device. The electrical sector of this project can be easily described as a feedback loop control system, where one sub-area is responsible for facilitation, another for actuation, and a final one for sensing. The final sensing sector is the feedback in the loop creating a self-sufficient stable control system. In the figure below, is a visual representation of a basic feedback loop control system.
The control system serves as the cornerstone of the electrical fundamental area, providing an interconnected framework that enables the seamless integration and comprehension of every component within the system. This foundational system plays a pivotal role in orchestrating and regulating the various elements that make up the electrical domain. By establishing a structured mechanism for monitoring and managing components, the control system ensures the efficient and synchronized operation of electrical systems. It serves as the bedrock for understanding the intricate relationships between different elements, fostering a comprehensive grasp of the necessity of each component in the larger context. In essence, the control system acts as a guiding force, facilitating an approach to electrical systems, and empowering engineers and practitioners to design, analyze, and optimize complex electrical setups with precision and efficiency.

- **Facilitation:** This subdomain is rooted heavily in the responsibilities of the Raspberry Pi and the power supply. The Raspberry Pi is a dynamic facilitator that dictates the actions of each component connected to it and receives the feedback from each component through a variety of sensing components and circuits to safely and efficiently control the motion of the device. In the computer science sector this would be described a Primary/secondary system where everything feeds back to the primary node and that dictates the action of each secondary node. In contrast, the power supply is a mostly static facilitator as it primarily simply supplies electrical sources to be utilized and modified by circuitry. It also will be connected with the Raspberry Pi and serve like a major secondary node that does not send feedback to the primary node (Raspberry Pi). When combined, it serves as a dynamic duo capable of fulfilling all the necessary requirements of the facilitation subdomain in the integrated control system.

- **Sensing:** This subarea relates to the testing and self-awareness of the device to send feedback to the controller. This area also covers the self-imposed limitations of the system to avoid failure events. One example of these events is overheating the syringes from the heating plates causing a disruptive failure state of the extrusion process and could damage other components. To combat this, integrated in the design is a temperature circuit that is constantly monitoring temperature then transduces it into a voltage output that feeds back to the controller. Using this feedback, code is integrated to monitor the input voltage from the sensing circuit and when it exceeds a certain threshold, emits an audible alarm and cuts power to the heating plates. After that occurs, the team will take the necessary steps to rectify the source of the issue and attempt to prevent its recurrence. The Raspberry Pi has been designed to be a controller capable of monitoring many inputs and the derived temperature circuit is one basic example of the realization of this theory.

- **Actuation:** This subarea is a mostly mechanical domain responsible for outputting required force vectors to components to complete the steps needed for all functional domains. This area encompasses primarily the movement of the motors and linear actuators. The motors' primary goal is to generate a torque capable of creating a reaction moment from the barrel and facilitating rotation whilst interacting with the belt. The actuator is the spark to start the extrusion process as its primary role and is interfaced with code to impact a linear force at a steady acceleration without overpowering the desired rate for optimal extrusion.
Extrusion: This functional area represents the conclusive domain and the ultimate step in defining the device's role, principally dedicated to the output of the meticulously crafted biomedia. Within this pivotal stage, two distinct yet interconnected subdomains, namely curing and transportation, come into play, each contributing significantly to the refinement of the mechanical properties of the biomedia. The curing process is instrumental in solidifying and stabilizing the biomedia, imparting the necessary structural integrity essential for subsequent stages. Concurrently, the transportation subdomain ensures the precise and controlled movement of the biomedia to its designated location, facilitating an accurate deposition process. Together, these subdomains play a pivotal role in the finalization of the biomedia, preparing it to meet the stringent standards required for cellular viability.

- Curing: This process is the most pivotal for the proliferation of biomedia and its following validation for cellular viability. It utilizes a method of UV curing after printed and following a pre-heating cycle to reach a desired temperature necessary for optimal UV curing. In the paper from Gusmão, Afonso, et al. [5]mão, Afonso, et al. “Design, fabrication, and testing of a low-cost extrusion-based 3D bioprinter for thermo-sensitive and light sensitive hydrogels” [7], they speak upon the requirements to achieve the optimal curing rates that the team bases this subdomain on. Through this report and other literature review there is an identifiable zone that biomedia curing must achieve in order to be considered cellularly viable for tissue engineering applications and this device can meet with a high confidence degree.

- Transportation: A relatively simple process compared to other aspects, this subdomain is responsible for the transportation of the biomedia through the extrusion process and to a petri dish for material measurements. This step-by-step process is started by the biomedia entering the syringe, then after actuation it is flown through the syringe at a predetermined rate onto a surface. The efficiency of this transportation subdomain is underscored by its role in facilitating the accurate deposition of biomedia onto a petri dish, a critical step that lays the groundwork for subsequent material measurements. While it may be perceived as a seemingly simple process compared to the complexities of other biofabrication elements, the precision and reliability embedded in the transportation subdomain are paramount. In essence, this seemingly uncomplicated subdomain serves as a linchpin in the larger context, facilitating the smooth transition of biomedia from its initial state to a controlled deposition, setting the stage for subsequent evaluations critical for the material's functionality and suitability in biomedical applications.

7.2 Testing of each sub-functional area

One of the most impactful steps when creating any device is testing. Testing is the step that validates all the rigorous design work and is the “prove it” step to showcase for all of those viewing the final design. The procedures required in this step are indicative of the overall attention to detail shown by the designers as thorough testing shows a dedication to device quality overall. For example, when reviewing a device and the testing encompasses simple tests then “it works” showcases a lack of attention shown to ensuring device quality. Device quality shown by very attentive designers are typically very in depth with a series of trials testing every facet of the design then expanding to the overall design only if each subsector of the design passes all the required tests. Then this is followed by various load tests with the idea being that if the device were to malfunction; it would happen to the designers and not the consumers. This philosophy is carried out by the Bioprint design team and as will be later outlined, shows a series of validatable tests that leave no possible failure point obscured. These tests are broken down componental by sub-functional area with their procedures laid out explicitly and a later review of stress testing of the entire optimal design. The following functional areas to be tested are: electrical, chemical, extrusion, and printing. These sub functional areas were ascribed in the previous section and remain consistent here.

Wherever possible, the testing of the various electrical components was tested through online software before being built. Programs used included Tinker CAD, Ohm’s law, SolidWorks, and KICAD. When applicable, it is important to begin testing using online applications prior to construction to save what could be wasted time and resources.

Using Tinker CAD, a set up was built using an Arduino, and a slightly different stepper motor. After wiring up the circuit, connecting it to the motor driver, and running a sample code, the stepper motor was up and running, and slight adjustments to the code would move the motor in the opposite direction. While this setup is different than the final product using a Raspberry Pi and an entirely different stepper motor, this preliminary testing sets the foundation for when
the stepper motor is implemented into the circuit. It will work just as effectively with a Raspberry Pi in place of the Arduino, and a slight adjustment to the code might be necessary, but a circuit to test the stepper motor is done just like that.

Figure 7.2.1: A figure showcasing the components to be tested per functional area.

This serves as a visual reference when describing the componential testing and how they relate to the overall design. It also helps illustrate which functional areas ascribe the most time necessitated. Without this table, it may be harder to understand how a certain component relates to the design and interconnects with other components.

Figure 7.2.2: A figure that displays the necessary chemicals to create the biomedia media.

These chemicals are labeled by their mass and then a brief description. These descriptions offer a general overview of the chemicals to set in foundational understanding that is expandible when prototyping.
Printing:

- 3D Printer: The 3D Printer is the crown jewel of the project and will undergo a transformation unseen to any other components in the project. The project aims to take this printer and transform it into one capable of printing biocompatible media. This is as much of a task as it sounds and as expected, the printer must be operating at near-peak efficiency. Without this being the case, it would be akin to circuitry running without resistors or grounds. This core idea emphasizes the necessitation of executing rigorous testing the printer at every stage of the project's prototyping stages.
  i. Assembly: Following the instructions given for assembly and utilizing basic electrical knowledge, the printer will be assembled and have all electrical components tested for possible defects. In this phase as well, the team will plan the modification and interfacing of the printers' board without directly interfacing with it at this stage. This is due to ensuring printer operation prior to modification to establish a baseline for performance.
  ii. Functional Tests: The next stage is performing functional tests of the printer. This includes testing the operation of all buttons, testing the auto leveling system, and performing calibration test prints. Thankfully, Creality has included most information required to complete these steps in their user manual causing this step to be fairly straightforward with an adequate amount of attention dedicated to it.
  iii. Connection Tests: The goal of this step is to sequentially increase connections with the 3D printer to other aspects of the project, testing each individually. These components, after being independently tested with documented results, will be integrated step by step with the 3D printer and have functional tests reperformed after every new integration. This step will be the most rigorous and time consuming but is necessary to ensure a staged validation with the evolvability of becoming a fully validated device that is fully integrated.
  iv. Integrated Testing: Also known as a prototype test, this step will validate the overall device's ability to produce a biomedia that can later be used to validate and conform into a biocompatible media. This step is common among all components of this project with the printer's primary role in this step being the functional printing of the media that after curing, will become biomedia.

- Raspberry Pi: Serving as the brain of the entire operation, the Raspberry Pi is very stable and a reliable microcontroller straight from the package. This leads to a relatively simple procedure for component testing but is highly repetitive and informative due to its repeated nature across the prototyping phases.
  i. Initial Inspection: After receiving it, the device will be inspected for manufacturing defects then tested with exponentially larger coding loads to determine the potential operational speeds consistent with when it is fully integrated. This will involve running simple programs that intend to stress the device to identify potential bottlenecking and other issues with larger loads.
  ii. Connection Tests: Almost every component will be integrated into the Raspberry Pi’s nodal connection base, and as such the microcontroller will be used to test and send information to ensure proper connection with the component. The microcontrollers' role in this will be to relay simple programs to verify operation when linked with the component and if failure occurs, it will be reassessed and have the coding checked. This process tests the components function and the coding’s efficiency and reliability while quickly identifying potential errors.
  iii. Integrated Testing: When fully integrated into the prototype, the Raspberry Pi will be tested on its communicability with the project as a whole and its ability to orchestrate a functional device. Due to the nature of the testing and connections, errors will be easily noticed and limit the troubleshooting requirements as the most likely error will be a weak connection or code that did not phase properly.

- Barrel Housing: The barrel is a multi-faceted home for most of our actuation components for the subsectors of the facilitation and curing of the biomedia media. As a printed component of the project, edits will be easily completed with the primary bottleneck being the print time of the 3D printer. A con of this being a printed component is undeniably its reliability. Due to this, careful consideration and physical testing must be done and repeated on every barrel printed to eliminate the potential for catastrophic failure states. The testing of the barrel
is a process that is necessary and must be done thoroughly every time due to its nature of being a potentially high failure component.

i. Physical Testing: This test is multi-stepped involving the compatibility with all internal components, heat testing, and material integrity.
   a) Compatibility: The compatibility with internal components relates to the barrels ability to house all electrical components without fault and not induce unwarranted stress upon the wiring or the components themselves. This step will be completed mostly with visual and current flow testing that verifies each component's operation inside the barrel and visually inspected for undesired stress being impacted.
   b) Heating: The heat tests are completed externally from the overall device and involve measuring the insulation of the printed device to heat up the media inside of the syringe but not over insulating to the point of overheating the media within the syringe. In addition, the printed component will be subjected to heat loads with a factor of safety (FS) of roughly 2 in relation to normal operational temperatures. This means the barrel will be required to withstand double the normal operating temperature to eliminate heat-related failure.
   c) Material Integrity: Related to the final step of heat testing, ideally the barrel has an overall safety factor of 2 for each mechanical load impacted on it. Safety factor, as previously mentioned, is a scalar identifier to the overall stability of the material tested against the maximum load the device component will encounter. After calculation, the maximum principal stress would be impaction due to torsional stress. This stress is impacted by the belt and motors function to rotate the barrel and the barrel should be able to withstand torsional loads exceeding that of the standard operation. These tests also coincide with the motors and belts tests by ensuring that no part of the three-stage mechanism leads to failure. The tests will be completed by increasing the loads to the point where a FS can be verified of being at least 2.0.

ii. Integrated Testing: This step of validation refers to the barrels ability to complete the print while withstanding all mechanical stresses impacted on it. These stresses as previously mentioned are impacted stress on components, heat stress, and torsional loading conditions. The possible remedies for failure include developing mechanisms to lower torsional loads, thinning the internal structure to remove impacted stress, or modifying the internal insulation.

Electrical:

- Thermal Sensor: This sensor is responsible for sending thermal feedback transduced as voltage to the Raspberry Pi so the microcontroller can identify overheating conditions after exceeding a set parameter thus inducing a coding sequence to avoid failure. The sensor operates as a safety and validation feature akin to surge protectors and is vital to ensure its operation. This sensor was designed using simple circuit principles and will be tested following such.
  i. Component Testing: The components used in this circuit will be individually tested to generate tolerances throughout the circuit components. For example, if a resistor is anticipated to be 100Ω, then it should be rated similarly in respect to their expected values to ensure circuit sensitivity necessary for accurate feedback transmission.
  ii. Staged Testing: Once fully tested, the circuit will be tested stage by stage to identify potential failure modes such as loose connections, faulty components missed previously, etc. This staging method is used to avoid longer troubleshooting phases and allow the designers the insight into what block of the circuit is malfunctioning.
  iii. Integrated Testing: This step is two phased, first testing the ability and reliability of the circuits ability to transmit heat data to the Raspberry Pi and induce overheating state. By isolating these two components, the team can validate their operation prior to full operation.
- Polyimide Heating Pads: The heating pads serve as the foundation to start the biomedia curing process. As such, they must be tested for their communication with the microcontroller and the thermal circuit respectively. In
addition, they will be tested for their ability to reliably maintain temperature after long periods of time and multiple heating cycles.

i. Physical Inspection: This step involves testing the Thevenin voltage to be a maximum of 2V, thermal efficiency, and resistance to wear. When reviewing this component, there were many sources stating that the Thevenin voltage exceeded the maximum of 2V; this causes the heating pads to be unreliable and thus incompatible for reliable biomedia printing. In addition, the heaters must maintain thermal efficiency over a long period of time and multiple cycles, this will be tested with load testing and verified heat measurement apparatuses such as thermometers. This step also conjuncts with the reliability of the heating pads due to the biomedia’s requirements to stay within a certain temperature to achieve optimal curing rates and later cell viability.

ii. Integrated Testing: The heating pads must be able to receive orders from the microcontroller and interpret that into respective heating or cooling cycles to stay within a temperature threshold necessitated for optimal curing rates. In addition, the thermal heaters must be able to work reliably on at least two consecutive printing cycles to validate the overall reliability of the device.

• Linear Actuator: The linear actuator has the primary function of imparting the force upon the end of the syringe to push the biomedia media through the syringe at a predisposed rate. The linear actuator is mostly linked to the control of the microcontroller and thus does not act independently. Rather it serves as a sensor and actuator when referencing the earlier block diagram, it pushes down on the syringe as an actuator while also sending displacement data to the Raspberry Pi.

  i. Physical Inspection: As a mostly mechanical device, the main source of validation for the linear actuator is the inspection of its final actuation distance and the force output testing. These tests are both completable using a caliper while the force vector can be mathematically calculated through displacement measurements. In order to avoid human error, MATLAB will be implemented to do the force calculations and a calibrated caliper will provide displacement data with a simple experiment setup on material with known material properties.

  ii. Integrated Testing: The linear actuator should be able to communicate to and enact orders from the microcontroller. To ensure this is true, the team will simulate actuation in test feedback to validate two-way communication channels. During the print cycle, the actuator will be stationary and only impact force with its actuation arm, due to this there should be few sources for error win the absence of faulty coding.

• 395nm UV Light Array: The light array configuration is a device with a hard ease of use evaluation due to the nature of a large margin of error in accordance with alignment. The goal of the UV light array is to finalize the curing of the biomedia utilizing 395nm UV light arrays. To refine and reduce this error margin, the group will incorporate spectroscopy analysis with the NIU Analytics Lab with the Department of Chemistry and Dr. Kim to verify output and then use mapping software to optimize the curing light rays.

  i. Physical Inspection: Verification of the basic function of emitting light and the dimensional seating of them in the slots on the barrel. Then the team will work with Dr. Kim to validate the output of the UV rays and with that knowledge, be able to predict the necessary positioning for optimal curing.

  ii. Integrated Testing: The UV lights should interface with the Raspberry Pi and respond to basic “On/Off” commands. While inside of the barrel, the UV lights should have their wiring free of any undue stresses impacted upon them and be secure in the slots extruded into the barrel. When situated in the barrel, the UV lights will then be validated to be in the correct orientation in accordance with the prior gathered research.

• Power Supply: Similarly to the relay, the power supplies in this device are to be adhered to in accordance with industry standards and have their outputs tested and validated. Test circuits can be easily devised by utilizing a resistor and with combination of Ohm’s law and a voltmeter or oscilloscope, can be validated. In this design there are two main power supplies, a powered breadboard and a standard power supply.

• Diodes: The diodes used in this system are circuit components that connect into the overall circuit design for the device. The diodes are to be physically inspected for defects and tested for current flow with respect to the switch
state. Thankfully, these diodes have in depth testing and mounting tutorials available online from the manufacturer. These regulations will be closely followed to ensure reliable validation protocols.

Extrusion:

- Movement System: The movement system in this device consists of three aspects; the motors, the timing belt, and the belt pulley. The movement system's main function is to rotate the barrel to facilitate the novel function of multi-crosslinking capabilities. As such, it will be important to verify the performance of every aspect and ensure there are no mechanical conflicts arising through the actuation and subsequent torque generation enacted on the barrel housing.
  i. Physical Inspection: All devices will be carefully inspected for physical defects, with the belt being trimmed to meet exact specifications. The excess belt material will be used in troubleshooting as backup material in addition to serving as a testing apparatus for frictional stress enacted upon the barrel and other movement devices. The belt also will undergo stress testing to determine the maximum force that can be enacted on both ends of the belt before failure. Motor operation will be tested independently while interfaces with the motor driver to create force vectors facilitating movement. The belt pulley will be tested with the excess belt to examine frictional stress and examine possible instances of failure.
  ii. Integrated Testing: The full system will be tested independently from a fully realized prototype to isolate possible failure instances. A FS of 2 or more is necessary for this system to validate that the system is impervious to failure irrespective of larger loading conditions. Then after passing, the system will be implemented on the prototype with the ability to sustain and facilitate a consistent torque.
  a) Motor Driver Integration: The motor driver will be tested separately from the movement system test and tests will consist of verifying communication with the Raspberry Pi and the motors it dictates. The motor serves as secondary facilitator differential to the microcontroller and thus must be verified to act as such through a variety of coding simulations.

- Syringes: The syringes are responsible for the transportation of the biomedia from the print to the final measuring surface. In order to achieve this, it is actuated upon from heat sources to achieve optimal temperature for curing and later mechanical actuation from the actuator to dispense the bio media.
  i. Physical Inspection: The syringes will be examined for physical defects and have their operation tested to transport liquid. After testing operation, the syringes will undergo heat testing to verify that it can withstand the previous internal barrel temperature without deformation. This step is core as without syringes that can withstand heat cycles, the system is no longer efficient as the syringes would have to be replaced after every cycle.
  ii. Integrated Testing: The syringes will be run in a test cycle without heat to verify biomedia flow then will be incorporated into the full first prototype test. This prototype test will then serve as the foundation for biomedia transportation and will likely stay a static element during the advanced prototyping stages.

By breaking down each component by functional domains, the team can easily set to assign parallel testing of components, utilizing the members with the most efficient work methods with each component. This method combined with a series of trials leads to an overall more reliable product capable of withstanding any loads post replication. This process of testing the components individually is important to eliminate any component issues before full implementation. Without this process, a fatal error can occur when running combined tests and cause a lengthy troubleshooting process. In circuit design, there is an idea called stages, which is essentially a stage being a phase of a circuit or a block in a diagram. When designing circuits, the components are tested individually, then the stages are tested for the anticipated output values. Only after both these tests are passed will the full circuit be combined and tested. This methodology will not only be applied to our circuit design, but to the project and create a rigorously tested device that showcases the attention to detail needed for a bioprinter.

7.3 Failure and success mode analysis of each sub-functional area

The final devices core functional areas and sub-functional areas remain the same as previously analyzed: printing, chemical, electrical, and extrusion. When designing and prototyping a device, the most important aspect to the user of that
device is its ability to perform the action that it was acquired for. In prototyping terms, this would be considered the success mode. In contrast, if the device failed to meet expectations to any degree, it would be considered a degree of failure on the device also known as the failure mode. Thus as the device's designers, it is the team's duty to analyze the products failure and success modes in order to determine standards for performance and reliability. In addition, this analysis should be both thorough and easy to understand to any user for the purpose of educating the user about the natural standards of performance the device can adhere to. Through this comprehensive analysis working through each sub-functional area, the device will be evaluated for the aforementioned standards of both failure and success modes. Through the process of prototyping this device, the team’s primary goal is to identify and prevent the repetition of any possible errors relating to bioprinting to allow the user to never encounter any errors that have not been seen previously.

**Printing:** This sub-functional area, which is often the primary driver for acquiring the device, holds immense importance in terms of minimizing failure modes and ensuring easy remediation. To achieve this goal, the section is segmented into two main areas: bioprinting consistency for precise and accurate media printing, and the integrity of the printed parts associated with the device. On the other hand, the integrity of the printed parts is equally impactful, as they provide the structural framework and support for the bioprinting process. Any defects or failures in these components could lead to misalignment, instability, or even fundamental failure of the entire device. Therefore, by meticulously addressing these two key areas and implementing robust quality control measures, the likelihood of failure modes can be minimized, and any issues that arise can be swiftly remedied to ensure the continued performance and reliability of the device.

- **Bioprinting:** This specialized area of focus involves adapting our conventional 3D printer, which typically uses plastic filament, into a medical device capable of printing biomedia suitable for tissue engineering applications. It's closely linked with both chemical and extrusion functionalities, enabling the efficient creation of biomedia and its subsequent extrusion into a usable product. This sector is perhaps the most difficult to predict failure modes due to the inherent complexity of biomedia specificity for usage in tissue engineering and especially in clinical environments. Additionally, remediation of bioprinting errors will be the most multifaceted process due to the roots in other functional domains and necessitation of tight tolerances to be cellularly viable and thus usable for application.
  - **Success Mode:** Printing biomedia represents a cutting-edge advancement, entailing a complex process that intersects multiple sectors. However, within this sub functional domain, the goal is to ensure that the user's experience is as straightforward as possible, with printing biocompatible media being the simplest aspect of the entire device. Once the device achieves successful standards, it will accurately print biocompatible media with each cycle, akin to the simplicity of turning a handle on a sink to dispense water. This subdomain aims to streamline the process, eliminating the anxiety associated with early iterations of biocompatible media, and instead ensuring seamless printing of biocompatible media through comprehensive integration of all operational aspects of the device.
  - **Failure Mode:** On the contrary, printing biomedia remains a highly intricate process, with failure modes varying from simple user errors to disastrous malfunctions resulting in total device failure. The most common errors typically involve mishandling of the necessary chemicals for viable biomedia, which can be rectified through basic reanalysis of usage protocols and thorough cleansing of any contaminated components. Beyond these basic errors lies a spectrum of issues stemming from individual component failures, which will be explored in greater detail in each related subdomain's potential failure modes. Given the centrality of bioprinting processes to the device's function, any component failures directly impact bioprinting outcomes. Therefore, this subdomain serves as the primary staging ground for developing troubleshooting procedures. It's important to note that while the device's failure modes may not originate from bioprinting processes per se, they can still negatively impact these processes due to failures occurring in other sectors.
- **Parts Printing:** This area of the device's domain is perhaps the simplest for the user as after assembling, it is both simple to understand and rectify. Serving as the ground for biomedia printing, the printed parts are static entities that require a lack of intervention unfound in any other sub functional areas. This is due to the tested reliability of the PLA material and the low cost if replacement is needed.
o Success Mode: The parts printed have been designed to have a mechanical safety factor of 2.0 or as elaborated previously, it is the simple ratio of the resistance to forces impacted on it to the calculated maximum impacted during normal operation. Due to this, the printed parts are not susceptible to failure during standard operation and should serve as the most stable aspects of the device. In the successful modes of this subdomain, the parts will silently serve their role efficiently of facilitating heat insulation for optimal curing rates and housing the electrical components pivotal to creating a biocompatible media.

o Failure Mode: In the instance of failure of the printed parts, it would likely be due to wear and tear from extended use. Through testing, the team anticipates the replacement of the printed parts due to wear and tear when the device is not impacted by any unnecessary loads, to be roughly every 200 cycles. These tests were concluded through integrated mathematical modeling using MATLAB, NAMD, and VMD software. This software is commonly used for molecular modeling for large systems but can be applied to materials such as PLA to simulate trials leading to failure instances in the mechanical integrity of the material. Through this data, the team identified the simulated number of 200 runs prior to component failure in the printed components. These trials did not factor in the events of chemical spillage that would likely lead to the deterioration of mechanical integrity. However, the PLA was tested for heat resistance and should not impact the integrity negatively in normal operating conditions. In instances of these failures, the components should be reprinted and replaced fully and together to avoid increased stress on a paired component and an overall decreased reliability.

Chemical: The chemical functional area is fundamental for the creation of cellular viable biomedia and thus requires the most care and expertise to achieve optimal results. As such, biochemical and biomaterial knowledge from Dr. Diggs is very influential in the validation and usage of these chemicals to create cellularly viable media when combined in tandem with research previously done in this area. Through this knowledge, the team can predict expected outcomes and failure modes. It is this analysis of failure modes that is most crucial to avoid catastrophic failures with the potential to disrupt the devices' function entirely.

o Success Mode: Within this domain encompasses several critical aspects essential for producing biomedia suitable for tissue engineering applications. Firstly, successful validation confirms the compatibility of the chemical processes involved in biomedia creation, ensuring they create a mixture conducive to cellular proliferation. Additionally, validation verifies the purity of the materials used, minimizing contaminants that could hinder cell growth and ensuring consistency in biomedia properties. Furthermore, successful validation confirms that the biomedia supports cell viability. Consistency in biomedia properties across batches is also ensured, allowing for reliable and reproducible results in tissue engineering experiments.

o Failure Mode: Failure modes within this domain encompass several potential pitfalls that can compromise the quality and effectiveness of the produced biomedia. One significant failure mode is the lack of complete crosslinking for chemical compatibility, leading to the creation of a biomedia mixture unsuitable for cellular proliferation, thus resulting in poor cell viability and suboptimal tissue engineering outcomes. Additionally, inadequate purification of materials used in biomedia creation can introduce contaminants, negatively impacting cell growth and function. Another critical failure mode involves the inability to support cell viability within the biomedia, resulting in reduced cell survival and proliferation rates. Inconsistencies in biomedia properties across batches represent another potential issue, leading to unpredictable outcomes and hindering reproducibility and scalability. Finally, safety concerns arise if the biomedia contains harmful substances ensuring the need to review chemical safety data sheets. These data sheets serve to inform handles of these chemicals of the proper procedures for usage and disposal of a certain chemical and are included with all chemicals.

Electrical: The electrical functional area constitutes the backbone of the entire device, serving as the central nervous system orchestrating its functionality. Given their pivotal role, the realm of electronics exhibits a diverse spectrum of potential outcomes, ranging from seamless operation to critical malfunctions. Success in this domain encompasses smooth integration and coordination of the control system sectors, enabling precise execution of commands and seamless communication between components. However, failure modes within the electrical functional domain can be
multifaceted. They may stem from hardware issues such as faulty wiring, component defects, or power supply failures. Software glitches, programming errors, or compatibility issues can also contribute to malfunctions. Environmental factors like temperature fluctuations or electrical interference may further exacerbate these problems. Despite these challenges, the division of the electrical functional domain into distinct control system sectors facilitates a systematic approach to troubleshooting, allowing for efficient diagnosis and resolution of issues as they arise.

- **Facilitation:** This subdomain is under the exclusive control of the microcontroller and the power supply, with the former being particularly susceptible to extensive failure modes due to the intricate nature of coding within complex frameworks. The coding base introduces a wide range of potential errors, ranging from syntax mistakes to logic flaws, making it a focal point for meticulous attention and refinement. Considerable effort is dedicated to achieving near perfection in coding within the device, with the aim of minimizing bugs to those originating solely from external modifications by users or compilation errors, both of which can be swiftly rectified. Conversely, the power supply, while integral to device functionality, tends to exhibit far fewer internal failures. Issues within the power supply typically stem from external factors such as wiring defects leading to shorts or other connectivity issues. Overall, while the microcontroller presents a myriad of potential failure modes, diligent coding practices coupled with proactive troubleshooting measures can mitigate these risks, ensuring the device operates reliably and efficiently.

  - **Success Mode:** The success mode of this sector arises from the successful integration of properly connected components instigating a network of feedback and properly transmitted instructions. Success is only achieved in this area when the coding has no errors, and the connections are all secure. Thankfully, with the assistance of a computer science student, the team is well equipped to eliminate all bugs before they occur and squash any if found. An ideal run consists of the Raspberry Pi interfaced with every component in the device determining the precise timing for premium printing and curing rates intertwined with safety detection features. This will be achieved with research to determine the optimal timing integrating with artificial intelligence and a feedback system whilst the primary safety features included in the sensing subdomain.

  - **Failure Mode:** Failure, however disastrous, is likely in any coding environment due to the complex nature of computer programming. The failure modes of this device are linked in the mentioned optimization of curing rates and feedback system. These errors stemming from logical inconsistencies to poor connected hardware should be easily identifiable and thus, fixable. For example, if the linear actuator misfires or does not produce the desired output, the first targeted area for error identification would be the dictation line for the linear actuator. Through a well-designed syntax, these code snippets will be easily accessible for both the team and the potential users troubleshooting the device on their own. Failure modes involving the power supply would likely be due to improper connections leading to a short and by investigating the wiring of our device, should be easily identifiable.
Figure 7.3.1: Python code for controlling the linear actuator.

This snippet showcases the framework for accessibility that our code adheres to for every component. By extending this philosophy to every line of code, adjustments to variables can be made swiftly, and their effects can be easily measured. This approach is key for ensuring both user and team accessibility, establishing a framework that simplifies troubleshooting processes.

- Sensing: This sector serves as the feedback framework for the Raspberry Pi, ensuring that it operates efficiently without prolonged inefficiencies. Failure of the sensing system could significantly impair the microcontroller's ability to accurately measure the device's status during print cycles. Such a failure might trigger a cascade effect, potentially leading to permanent damage to internal components or, at the very least, rendering the produced biomedia non-viable. Given the critical nature of this function, extensive testing is conducted on every aspect of the sensing feedback and their related connections before full prototype testing commences. Additionally, to mitigate risks, the microcontroller is equipped with backup features in case a level of the sensing interface fails. These features offer varying degrees of output, but can execute an emergency stop if necessary, ensuring safety and preventing further damage in critical situations.
  - Success Mode: When functioning properly, the sensing circuit simply measures a single variable and feeds that data as current to the Raspberry Pi to be interpreted into readable data. This data will then be translated and referenced against a database from researched values. The most impactful variable to be measured is heat, which will be responsible for the curing inside of the barrel. To measure this, the team has designed a temperature sensing circuit that constantly measures the temperature and allows the Raspberry Pi the knowledge to ensure that the heating levels inside of the barrel do not exceed or slide below temperature presets.
  - Failure Mode: In the event of failure, the sensing circuit will be unable to transmit information to the Raspberry Pi for one of the measured variables. This scenario results in inconsistencies in data validation, making it impossible to verify whether curing rates fall within predetermined thresholds. Such failures typically stem from issues such as faulty component connections, such as resistors, or malfunctions in the receiving code framework, which may fail to translate the data accurately into interpretable code. However, a fallback system is in place to detect and promptly address such issues. This system is designed to identify abnormalities in data transmission and swiftly correct any errors to ensure the uninterrupted operation of the sensing circuit.

- Actuation: This mainly mechanical area is responsible for the movement of the device's components. This involves the motor-controlled movement of the barrel and the force output of the linear actuator. Aspects of this sector are still interfaced with the microcontroller and as such are susceptible to coding errors yet also have a risk...
of internal failure. Aspects of this system are both a mix of easily remediable and potentially component catastrophic. Careful care and physical testing of all components for their maximized output are crucial for avoiding the failure modes attributed to the actuation subsystem.

- **Success Mode:** When fully integrated, this system is working in tandem with the microcontroller to facilitate movement of and on the barrel system. The linear actuator works to push down on the syringe at a set rate and force levels as dictated by the code. This step is decisive for the optimization of curing rates to facilitate the printing of biocompatible media. A motor system, also in tandem with the Raspberry Pi, works to move a belt encompassing the barrel. This barrel is the novelty of our design as it allows the multi crosslinking of many chemicals, and thus the belt rotates the barrel around the fixed axis on the mount. [Figure 7.3.2]

- **Failure Mode:** Potential failures within the system are often associated with the interface between the Raspberry Pi, mounting assembly, and other components, with varying degrees of severity. Microcontroller errors can arise from malfunctioning code or motor drivers not executing instructions as intended. Additionally, issues may occur within the power supply system, especially when interfacing with motors or between motors and drivers. The most ruinous failure would result from component failures of the motors or linear actuator itself, necessitating replacement as repairs are unlikely. To mitigate these risks, it's necessary to carefully consider and test the maximum load capacity, ensuring it is not exceeded during operation or testing phases. Adhering to the safety factor of 2.0 as previously mentioned, should prevent inter-component failures if properly followed, thus enhancing the overall reliability and longevity of the system.

![Figure 7.3.2: An early design of our barrel & mount interface system.](image-url)
This assembly shows the rotation of the barrel about the mount hole. On the sides serve as the attachment points for the syringes allowing for the multi crosslinking functionality. Through this design and integration with the motors and belt, torque is generated allowing for rotation and thus biomedia crosslinking of multiple chemicals.

Extrusion: This functional area serves as the conclusive domain, representing the ultimate step in defining the device's role, which primarily revolves around producing meticulously crafted biomedia. At this stage, two distinct yet interconnected subdomains, namely curing and transportation, are paramount. Each subdomain significantly contributes to refining the mechanical properties of the biomedia. The curing process is pivotal, as it solidifies and stabilizes the biomedia, providing the necessary structural integrity crucial for subsequent stages. Simultaneously, the transportation subdomain ensures the precise movement of the biomedia to its designated location, facilitating an accurate deposition process. These subdomains differ exponentially in failure possibilities due to their role.

- Curing: This process stands as the cornerstone for the proliferation of biomedia and its subsequent validation for cellular viability. It employs a UV curing method following printing, preceded by a pre-heating cycle to attain the desired temperature within range for optimal UV curing. This pivotal procedure ensures the solidification and stabilization of the biomedia, laying the foundation for successful cellular proliferation and subsequent tissue engineering applications. Through previous literature review, standards are set to achieve the curing rates and biomedia properties. It is through matching these standards and tolerances that the team can achieve the success modes of creating a cellurally viable biomedia.
  - Success Mode: The curing is successful if the biomedia can achieve the mechanical tolerances set through pre-existing literature. For example, the temperature should not exceed 37°C, while the pressure should not exceed 30 kPa. As there are no ISO standards for hydrogel biomedia iteration through bioprinting processes, the team adopted a collaborative approach through research and these properties are the most consistent across other research. If success is achieved with printing of a biomedia, the media will then be tested for its mechanical properties and after referencing the standards, is validated for tissue engineering applications.
  - Failure mode: The achievability of validatable biomedia curing is difficult as the tolerances are very low specific due to the nature of clinical application requirements. A failure mode would be not achieving the requirements for cellular validation and as thus, have created a media that is good for further testing. Another possible failure mode is more critical and relates more to the transportation subdomain but would occur if the biomedia is unable to be extruded due to suboptimal curing when inside of the barrel.

- Transportation: Perhaps the simplest subsystem, the transportation is related solely to the movement of the biomedia through the syringe and onto the measurable surface. After actuated upon from the linear actuator, the biomedia is extruded through the syringe and dispensed at a determined rate.
  - Success Mode: The syringe extrudes the biomedia at the determined rate from actuation dictated by the linear actuator. Additionally, for this to be successful the syringe must not interfere with the inherent chemical properties of the biomedia.
  - Failure Mode: The syringe fails to either extrude the biomedia, falls out of alignment, or interferes in the chemical composition of the biomedia are the most plausible failure modes. If the syringe fails to extrude the biomedia it is more likely to be due to suboptimal curing rates in which the syringe will have to be emptied and cleaned for another trial. Another issue arises if the syringe supports on the barrel fail to secure the syringe causing it to either fall out or become misaligned with the linear actuator. If this were to occur, the extrusion and transportation of the biomedia would be virtually impossible as the intricate system would become discoordinated. Lastly, if the syringe interferes with the chemical composition of the biomedia, then the syringe would likely be melted from improper testing, manufacturer defects, etc. If this happened the easy and likely remedy would be to replace the syringe entirely and reinspect the others for similar issues.
In order to develop a functional bioprinter, meticulous analysis of failure and success modes across all functional domains is paramount for ensuring the optimal performance and reliability of the final device. Success in each domain is characterized by seamless operation, precise execution of commands, and the ability to meet user expectations consistently. Conversely, failure modes may arise from various factors such as hardware or software errors, component defects, or environmental influences. By thoroughly addressing potential failure modes and enhancing success modes, the device can fulfill its intended purpose effectively. Additionally, by establishing clear standards for performance and reliability and ensuring user accessibility to troubleshooting procedures, the device can be deployed with confidence, furthering its impact in the field of tissue engineering.

7.4 Integration and testing sub-functional areas to produce each functional area

The integration of the components for the project starts with a bottom-up approach due to the interconnectivity of every component. In the following figure, the complexity of the design is put onto display.

![Flow chart of the entire design per functional and sub-functional domains](image)

Figure 7.4.1: Flow chart of the entire design per functional and sub-functional domains.

This flow chart serves to illustrate what areas are interconnected and displays the importance of the Raspberry Pi in the interfacing of the project in its entirety. In terms of connectivity, the microcontroller will be the only component directly interfacing with the 3D bioprinter. Other components will solely connect indirectly or be completely exclusive to the printer itself, the primary benefit to which is creating a controllable environment. Through this environment, the printer is able to execute on its core functional domains not directly related to its printing functional area, consisting of electrical, chemical, and extrusion. The printing functional area is excluded from this figure as its function in this design is to serve as both the base when speaking for the printer, and the brain when referencing the Raspberry Pi. This approach allows a deeper understanding of the contributing functional areas and their respective sub-domains due to their reliance to be integrated whereas the printing subdomain is serving as the integrand for the device. Through this and the methodology of building from the foundation up, each component individually is assured for its reliance and can be slowly integrated in a staged approach. This staged approach is a method commonly used in circuit design to test each “stage” or step of a circuit to isolate potential failures and in the context of this design, our “stages” are each components interface with another aspect of the device at a time.

In addition, the device can be segregated into the integration and how they relate to the device. Figure 7.4.2 shows this categorization.
This approach identifies the 3D printer as the base of the device with branches spreading like a tree's architecture. This approach is beneficial when trying to visualize the physical integration and the relationship between those branches regardless of functional areas. Dissimilar to a tree, the dissolution of the device can stem from any one component so this figure also showcases just how one bad component can domino into larger difficulties and thus the importance of reliable testing.

3D Printer: The Creality Ender 3 V2 is the device that serves as the basis for the bioprinting process and as such, is the most important component in the development of a bioprinter. The integrated testing of the bioprinter is on a higher level than any other component as its primary facilitator is the Raspberry Pi whilst the other functional areas interface with it through a secondary source. As such, the integration of the printer and testing for compatibility only interacts with functional domains in their entirety after their individual testing rather than interfacing each component directly with the printer. This is done for the protection of the printer during the integration and remove any possibility of printer failure due to faulty components or poor integration. This process isolates the printer to only work with validated components rather than exposing it to potential errors to ensure physical integrity is maintained.

Electrical: The electrical components are a broad collection across functional domains due to the nature of the device being almost solely electrical. As such, many components are tested and then slowly integrated into the device, ranging from resistors to motors. Due to this nature, combined testing of minor electrical components are grouped into “misc. electronics” with their integration into the full device being instigated more closely related to the circuit they are involved in. These components include: all resistors, capacitors, operational amplifiers, diodes, and Buck converters. For example, operational amplifiers used in the temperature sensing circuit are tested in a staged manner then integrated into the device as a full circuit. For this approach, individual components are not tested with major components and rather investigated on the circuit design level. In addition, some components must be tested at a base with integration such as the motors and their drivers. That said, many major components are still electrical and as such are tested individually then elevated to the integrated levels using the bottom-up approach mentioned.

The Control System: This subsystem serves as the basis for the electrical design, it consists of facilitators, actuators, and sensors. This combination allows for a multistep approach for the foundation of the microcontroller dominion over the
controlling of the electrical systems. Through a series of integration, all components are communicable with one another and commanded by the microcontroller and its code base.

- **Facilitation**
  - Raspberry Pi: Rivaled in importance only by the 3D printer, the microcontroller serves as the lynchpin for the entire device, and as such is very carefully tested through integration. This process involves testing each component after they’ve been validated individually to ensure reliability. In tandem, the coding behind the microcontroller is also crucial for integration and will be tested and ran through multiple instances to verify code integrity. The Raspberry Pi serves as the basis for all future integrated testing due to the need for each component to be communicable with the microcontroller. Once communicable, the Pi will be tested for its performance executing commands to functional areas and their related components with reliability.
  - Power Supply: The power supplies used in this design are the integrated solderless breadboard and an external multichannel supply. These power supplies are tested first by measuring basic output accuracy using Ohm’s law and measuring the voltage across a resistor. After simple verification is completed, the power supply serves as secondary facilitators and staging ground for all electrical components and circuit developments. The power supply will interact with all electrical components to measure performance and supply the microcontroller to enable the integrated testing necessitated with it.

- **Actuation:** This domain is multifaceted with the extrusion area due to the extrusion's reliance on the actuation from this subarea. In terms of electrical integration, it has less thorough testing but will later be tested more intensively for its performance when evaluating it with other extrusion components.
  - Motors and Motor Drivers: The primary function of the motors lies in the extrusion functional area but also will be tested with the Raspberry Pi to ensure feedback communication efficacy. This pair is one of the few dependent components, relying on one another for function and are tested with one another when verifying component compliance. In the testing process, the motors and motor drivers are evaluated together to verify their compliance with specified standards and to ensure their seamless interaction. This collaborative testing approach is essential in combination with microcontroller integration to actuate reliable torque necessary for rotation.
  - Linear Actuator: The linear actuator is responsible for the depression of the syringe facilitating the transportation of biomedia throughout the printing process. Its importance in the electrical domain is rooted in its accurate execution of precise force outputs in a pre-determined rate needed for accurate curing rates. For electrical integration, the actuator is tested for communicability with the Raspberry Pi and verified to not impede the movement processes by the belt and motors.

- **Sensing**
  - Thermal Sensing: The thermal sensing is multileveled based on its connectivity with the microcontroller. The main purpose of the sensing circuit is to determine the internal temperature produced by the heating strips to ensure it is around 37°C via the process of transducing thermal energy into voltages. This range predestined by previous literature, cannot be maintained by the heaters alone due to their lack of communicability so the sensing circuit serves to inform the Raspberry Pi of the current thermal state so the microcontroller can relate accordingly. In addition, the thermal sensing circuit is integrated with a safety feature; when the sensor surmises that the internal temperature is exceeding standard operating limits (<43°C), an LED will emit. This feature is integrated as a backup to any potential code failures to alleviate the concerns of biomedia overheating.

**Non-fundamental Electrical Components:** These components are electrical components in nature with primary functional domains in other levels of the device, they are still pivotal in device operation but have more thorough integrated testing in other areas. They still are tested with other electrical components due to their nature but lack the intensive testing nature due to their smaller integration in the electrical functional area.

  - UV Light Array: The UV lights are tested first for basic function of operation, and then are interfaced with the Raspberry Pi to verify connection and establish a feedback foundation to be carried onto the
In terms of the electrical aspects, the UV lights have a basic integration testing with a further emphasis on their testing in the extrusion functional area.

- Motors and Motor Drivers: Similarly to the UV lights, the primary function of the motors lies in the extrusion functional area but also will be tested with the Raspberry Pi to ensure feedback communication efficacy. This pair is one of the few dependent components, relying on one another for function and are tested with one another when verifying component compliance. These components will be more intensively tested with their integrated functional domain.

- Heaters: The heaters sole job is transducing voltage inputs into heat utilizing a heating element. As such, they are integrated into the curing sub-domain more closely to measure their thermal output. In terms of electrical testing, the heaters are tested for basic function and incorporation with the Raspberry Pi and thermal sensing circuit responsible for measuring thermal output.

Chemical: The chemical integration for the proliferation of biomedia in a bioprinter is heavily rooted in the chemical interactions with other components in the device. Some of the key principles to follow are the general Safety Data Sheets (SDS) that outline how corrosive a certain chemical is. While most plastics are generally chemically inert, the chemicals used can have impacts in other aspects of the device, especially in terms of spillage. Mostly water-based hydrogels can cause electrical shorts so when integrating the chemicals into the device, care is taken to ensure the isolation from potential risks.

Extrusion: This functional area serves as the decisive domain, encapsulating the pivotal step in defining the device's purpose, which primarily centers around the meticulous production of biomedia. Within this domain, two distinct yet interconnected subdomains, namely curing and transportation, take precedence. Each subdomain plays a critical role in refining the mechanical properties of the biomedia, ultimately shaping its structural integrity and usability. The curing process holds immense significance, as it serves to solidify and stabilize the biomedia, imparting the necessary strength and durability essential for subsequent stages of utilization. Concurrently, the transportation subdomain assumes a vital role in orchestrating the precise movement of the biomedia to its designated location, facilitating an accurate and controlled deposition process. Not included in this analysis are the miscellaneous mechanical components required for smooth usage such as bearings and washers. These components are similar to the resistors in the circuitry where their impact is notable but are intrinsically tied to the interfacing of other components.

- Curing
  - Heaters: The heating pads are integral components of the system, tasked with maintaining optimal curing temperatures crucial for the biomedia's quality. To achieve this, seamless coordination with the microcontroller is imperative, allowing the pads to interpret commands and adjust heating or cooling cycles accordingly. Real-time feedback from temperature sensors informs the microcontroller's decisions, ensuring precise temperature regulation throughout the printing process. Rigorous testing validates the reliability of the thermal heaters, particularly their ability to sustain performance over multiple printing cycles. Through this integration and testing, the heating pads contribute significantly to the system's efficiency and consistency, ultimately enhancing the quality of printed biomedia constructs. In addition, the heaters are tested for their compatibility with the mounting system and housing to eliminate and identify potential overheating risks.
  - UV Lights: Integrated testing of the UV lights within the system is a meticulous process aimed at ensuring their seamless interaction with the Raspberry Pi and optimal functionality within the barrel. Beginning with basic command responsiveness validation, the testing progresses to verify the physical integration, ensuring wiring is stress-free and lights are securely placed within designated slots. Subsequent validation confirms alignment with prior research, guaranteeing optimal performance. This performance will also be cross-linked with photospectropic testing to optimize rates. Through this combination, the UV light array serves as the primary curing method and its integration is crucial for validatable biomedia.

- Transportation
Syringes: Initially, a comprehensive verification phase assesses biomaedia flow without the influence of heat, establishing a foundational understanding of syringe performance. Subsequently, incorporation into the full first prototype test allows for an evaluation of their effectiveness within the broader system context. The syringes are also integrating with the barrel housing and linear actuator to showcase both security and intractability to optimize extrusion. By building upon this solid foundation, the development process progresses efficiently, ensuring the reliability and effectiveness of biomaedia transportation.

Movement System: The paired combination is responsible for the movement of the barrel housing, which is defining for the multi-crosslinking possibilities. This encompasses the motors and their paired drivers, as well as the belt and pulley system. In total, this system is impactful for the facilitation of the barrels movement and the integrated testing in this subarea is linked to their paired elements. The motors and drivers are tied together by nature of function which then ties into the actuation into another paired system consisting of the belt and pulley system. After this system is tested, it is then integrated into the barrel housing to test the ability to generate rotation without interfering with the linear actuation.

This system after a thorough analysis, can be simplified into a simple block diagram that while integrated knowledge is required for full understanding, is an approachable for a basic understanding for the overall projects flow of integration.

Figure 7.4.3: An illustrative depiction of a simplified version of the previously discussed flowcharts is presented here, offering a basic yet essential comprehension of the hierarchical structure of this device.

This chart provides a foundational understanding of the interconnectedness inherent in the system, underscoring the significance of integration testing in development. Together with other charts, this depiction elucidates the tree-like architecture of the device, highlighting the pivotal role of the microcontroller in linking all aspects of the project.

Overall, the integration of components within this project follows a meticulous bottom-up approach, acknowledging the interconnectivity and importance of each element. The complexity of the design is visualized in Figure 7.4.1, emphasizing the central role of the Raspberry Pi in coordinating the entire system. The integration process prioritizes the protection of the 3D printer by validating each component individually before full integration, ensuring its physical integrity and reliability. Components are categorized and tested accordingly, with a staged approach facilitating thorough examination and isolation of potential failures. The integration of functional domains relies on effective communication with the microcontroller, with each component contributing to the overall cohesion and functionality of the system. This integrated approach mirrors the organization of organ systems in the human body, with the Raspberry Pi serving as the central nervous system orchestrating the device's operations.

8 CONCURRENT ENGINEERING PART 2

8.1 Functional area acceptable level of performance and integration methodology for parallel prototyping

The bioprinter's development maintains consistency across its functional areas, namely printing, chemical, electrical, and extrusion sectors. These areas are subject to specific performance criteria, closely tied to the components themselves, contributing to an overall acceptable device standard. Each functional area is assessed based on core domains such as
integrability, mechanical performance, electrical performance, and resistance to failure. For instance, the printing area primarily adheres to mechanical standards but also encompasses parts printing and bioprinting sub-functional areas.

When orchestrating the integration of each component within the bioprinter, the central guiding principle revolves around establishing seamless interconnections with both the Raspberry Pi and the barrel loading mechanism, as these elements lay the groundwork for the device's comprehensive functionality. Unlike conventional parallel prototyping approaches, the integration strategy employed here resembles a series of converging lines, all leading towards a central summation point. This intricate interplay becomes evident as each aspect of integration, with its core integrands and specific requirements, gradually converges upon the microcontroller and the barrel loading mechanism. These two components emerge as the focal points of integration, serving as the backbone of the bioprinter's operation. Their reliability, efficiency, and seamless coordination are paramount, ensuring the smooth execution of bioprinting processes and the realization of the device's full potential.

Printing: The printing domain, as previously explored, is a joint venture between the two subdomains; parts printing and bioprinting processes. The bioprinting processes sector being less of a tangible subdomain and more so an idea for the project as a whole. However, this domain remains the core of the project and is subject to higher standards of performance than other functional areas due to the reliance on this area for overall product performance. Without the core operation of this functional area and its respective interplay, the device would be little more than a collection of divided components.

As such, the integration of this functional area is not only important but essential to the performance of the device. Serving as one of the summation points for integration, all roads lead to this area. As such, the standards for integration are the highest in the entire project and extreme caution is taken to ensure that during all times during function, that integrand errors do not occur in this area.

Parts Printing: The parts printing subdomain is responsible for the printing of the barrel loading mechanism and the respective mounting system bridging the 3D printer and the retrofitted attachments. As such the standards of performance for this sector are mostly mechanical and maintaining the non-prohibition of integration. For the mechanical standards, the barrel and mount should maintain a 2.0 Factor of Safety (FS) for all components in relation to both stress resistance to the highest principals and thermal resistance. The maximum principal stress incumbent on the barrel is due to torsional loading due to its rotation. Without this rotation, the multi-crosslinking would be an unachievable feature due to the multi-syringe loading mechanism being the core proponent for pattern printing of multiple chemicals and respective crosslinking. In addition, the barrel must also resist the thermal stress imposed upon the polyamide strips which heat to roughly a 32°C maximum after overshoot and repetitive usage calculations. Due to the nature of the parts being printed using plastic polymer, the heat resistance of the material more than exceeds this standing operating temperature. As evidence, the standard printing and extrusion temperature of these parts never falls below 200°C which is the point where the plastic is malleable which is more than a 6.25 FS thus eliminating worries of thermal failure. The mount also is subject to mechanical stresses but to a lesser degree. The mount’s core function is to serve as a housing and bridge site from the 3D printer as shown in Figure 7.3.2 and has its principal stress lying mostly due to the mass of the barrel connected to it. To combat this, the team evaluated the standard tensile or pulling stress of the polymer and evaluated it in respect to the stress loaded upon it. For ABS, the lowest ultimate stress or the stress prior to deformation, lies at 22.1 MPa and 39.9MPa for PLA. In contrast, the maximum measured stress from the barrel interfacing is not close to exceeding this due to the low weight of the barrel (<10lbs) and small maximum radius of curvature. Thanks to the relative stability of the printed parts under ideal conditions without internal fractures, the relatively low FS of 2.0 under mechanical loads is anticipated to be highly achievable. As such, the acceptable level of performance ratio for the printed parts is no less than 100% which is based solely on their responsibility of being an indispensable area of the device.

In terms of the printed parts integration, the barrel serves the role of being a summation point with a smaller role of being non obstructive. This role stems from the printed parts being either housing or actuation sites solely with no internal electrical aspects. This core principle of non-interference is exemplified in every component situated inside or with the barrel like the UV light assembly for example. In the device, the UV lights situate on the bottom of the barrel at an angle of 42.7° in preprinted slots and affixed by self-tapped screws. The barrel’s role in integration with the UV lights is to not inhibit the circuit connections to and from the lights whilst being the foundation for UV light affixation onto the device.
Due to the mechanical nature of the printed parts, they are less so an integrated component and more so an integrand for the device.

Chemical: The chemical functional area is pivotal in the bioprinter, orchestrating the formulation of biomedias and ensuring their compatibility and performance. Regardless of application, bioprinters must adhere to stringent standards essential for reproducibility and biocompatibility necessary for validation. Innovations like the barrel system, guided by G-code, offer enhanced control over material deposition and the ability to multicrosslink. As such, the performance of the chemicals is high to ensure proper pattern formation and overall scaffold creation with the ability to form a biocompatible media.

Standards of performance in bioprinting are paramount to ensure the reliability and reproducibility of tissue constructs for biomedical applications. In the context of chemical integration, adherence to rigorous criteria is essential to maintain the functionality and biocompatibility of bioprinted materials. This includes precise control over the composition, viscosity, and crosslinking of biomedias to achieve optimal printing outcomes. Additionally, standards govern the compatibility of materials and reagents used throughout the bioprinting process, ensuring the preservation of cell viability and tissue integrity. Meeting these performance standards requires meticulous attention to detail, rigorous quality control measures, and validation of printing parameters to guarantee consistent and reliable bioprinting results.

Integration of the barrel system into the bioprinting workflow represents the final hurdle in validation for the device governed by the versatility and precision of chemical deposition processes. By allowing for the simultaneous dispensing of multiple biomedias with controllable patterns governed by G-code instructions, this system enables the fabrication of complex tissue architectures with spatially defined properties. The seamless integration of the barrel system with the bioprinter platform requires careful calibration to ensure smooth operation and precise control over biomedia deposition. Moreover, integration efforts must consider factors such as system compatibility, material handling procedures, and software interfaces to facilitate seamless communication and coordination between the barrel system and other components of the bioprinter.

Electrical: At the heart of the bioprinter's functionality lies the electrical functional area, which serves as the primary mechanism for driving the device's performance. Central to this area is the control system philosophy, which orchestrates the intricate interplay of components and subsystems within the bioprinter. This philosophy dictates the integration of various non-fundamental electrical components, ranging from sensors to actuators, to ensure seamless operation and optimal performance. Acting as the nervous and cardiovascular systems of the device, these electrical components exhibit a wide range of performance standards but are intricately intertwined to converge at common summation points. Among these components, the microcontroller holds a unique position, serving as the theoretical brain of the device. Evaluated both independently and in conjunction with the overall device, the microcontroller plays a pivotal role in governing the electrical system's operations and interactions with other subsystems. This relationship necessitates a staged evaluation process for the electrical system and its corresponding programmable logic controller (PLC), mirroring the typical circuit design approach to ensure comprehensive testing and integration.

Control System: At the heart of the electrical functional domain lies the control system, composed of sensors, actuators, and facilitators, serving as its core. While the overall standards for this domain are high, they may not necessarily match those of other areas due to the system's inherent fail-safes and repairability. Control systems operate on a block-based linear flow, simplifying troubleshooting processes. In the event of a malfunction, such as the barrel failing to rotate, a reverse linear process is employed to identify and address the root cause. This typically involves examining the sensors and actuators for performance issues, followed by investigating facilitators for potential code-related issues. This streamlined approach to error resolution often entails minor adjustments rather than extensive repairs, minimizing the need for strict adherence to 100% performance standards.

However, the integration of the control system with the Raspberry Pi is indispensable for the operation of the functional area. The PLC acts as both a summation point and an integral part of the system. Any failure within the system has the potential to trace back to the codebase, highlighting the interconnectedness of various subsystems. Minor issues, such as coding or wiring failures, can disrupt the anticipated actuation of specific components, underscoring the critical role of
effective integration and coordination within the control system. Thus, while the control system may not demand perfection in performance standards, its seamless integration with other components remains paramount for ensuring the overall functionality and reliability of the bioprinter.

Raspberry Pi: The Raspberry Pi, serving as the brain of the device and a summation point must be operating at no less than 95% efficiency. Less than 100% being a sub-optimal level however acceptable due to considerations for potential bottlenecks during heavy load states. The microcontroller itself is responsible for handling the command ordering and sensing the change whilst adjusting in accordance to received feedback from systems like the temperature controller. Due to the importance of these systems, the PLC has the key task of both optimizing performance and remaining fully integrated. Beyond integration, the microcontroller also serves as a safeguard against component failure, actively monitoring connections and alerting users to potential issues before they escalate. For instance, if the heater and temperature sensor lose their feedback channel, the PLC initiates a script to reestablish connection and, if unsuccessful, generates a fault code indicating the specific component failure. Like the barrel system, the Raspberry Pi acts as both an integrand and an integrator, playing a pivotal role in overall device operation and system integrity.

Extrusion: The extrusion of bioprinter media is the principal goal of the project and as such, would be expected to be held to a very high standard and integration level. However, due to this functional area's designed simplicity, it holds the lowest standard of performance and integration. This is due to the ease of replicability and adjustment of the syringes, and the other components having more stringent checks based in the electrical domains.

Biomedia Movement: The movement of biomedia within the bioprinter entails manual loading of the syringe to the 5mL mark followed by the controlled extrusion of the media through the syringe tip. While the basic concept of this system appears straightforward, its implementation involves complexities in facilitation and actuation mechanisms responsible for precise movement. To execute the extrusion process accurately, an actuator must be triggered at a specific time following the rotation of the barrel by a belt and motor system at a predetermined angular rotation. This intricate orchestration, governed by modified G-Code and controlled by the Raspberry Pi, underscores the stringent standards for integration and performance set upon both the printing and electrical domains. Conversely, the extrusion domain's primary concern lies solely in the output of the system, where its functionality hinges on effectively pushing media through the syringe. This simplicity contrasts with the intricacies involved in other aspects of the bioprinter's operation, highlighting the importance of preceding processes. As a result, the extrusion process is afforded lower standards for performance and integration. As long as the output of preceding processes remains consistent, the extrusion process can be relatively straightforward. This pragmatic approach ensures that while other areas of the bioprinter demand meticulous attention and adherence to high standards, the extrusion domain can operate efficiently without compromising overall system functionality.

Curing: Embedded within the overarching control system of the bioprinter are the fundamental principles governing the curing system, which relies solely on thermal energy to facilitate the curing process. This system comprises heaters and UV lights, working in tandem to achieve optimal curing rates dictated by prior research and embedded into the G-Code. The heaters function to warm the fluid within the syringe to a specific temperature, while the UV lights play a critical role in finalizing the curing process of the crosslinked media. Serving as the finishing touches, the UV lights' operation is intricately tied to the successful execution of preceding processes within the electrical and printing functional areas. The standards of performance for the curing system are notably higher due to the criticality of maintaining component integrity throughout the curing process. However, failures within this system are relatively easy to detect. For instance, in the event of heater failure, even if the sensor fails to detect it, users are alerted by the emission of a burnt odor, highlighting the deliberate selection of these components to facilitate easy issue identification. When integrating the curing system into the rest of the device, parallel connections are established, leading back to two main summation points: interfacing with the barrel and PLC. Mounting systems, such as screws and slots, are utilized to affix UV lights to the barrel, while heating pads are similarly secured. Cooperation with the microcontroller is facilitated through a simple Analog to Digital Converter (ADC), thus utilizing the digital Raspberry Pi pins and enabling seamless integration into the sensing sector of the control system.

The development of the bioprinter encompasses a meticulous approach to maintaining consistency and high standards across its functional areas, each contributing to the device's overall performance and functionality. With stringent criteria
for performance and integration, the printing, chemical, electrical, and extrusion domains undergo thorough evaluation and testing to ensure their seamless interconnection and optimal operation within the bioprinter framework. The integration methodology employed follows a structured approach, with careful calibration and coordination to achieve smooth communication and collaboration between subsystems. The control system for instance, serving as the backbone of the electrical functional domain, orchestrates the intricate interplay of sensors, actuators, and facilitators to ensure the device's reliable and efficient operation. While standards for performance may vary across different areas, the integration of components, particularly with the Raspberry Pi and PLC, remains paramount for seamless functionality. Similarly, the extrusion and curing domains, although exhibiting lower performance standards, play critical roles in the bioprinting process and require careful integration to maintain overall system integrity. Through meticulous attention to detail and rigorous testing, the bioprinter achieves a harmonious convergence of its functional areas, resulting in a sophisticated and reliable platform for advanced bioprinting applications.

8.2 Experimental design for testing integration of functional area

In the design phase of the device, careful consideration was given to the integration and interaction of its functional areas. The team established two core summation points: the barrel mechanism and the Raspberry Pi, serving as the central hubs from which the rest of the system was built. This deliberate approach facilitated the expansion of the device's functional areas and their respective subdomains, providing a clear and accessible framework for understanding the inner workings of each integrated component. By establishing these summation points, the team aimed to create a cohesive and interconnected system where each functional area could seamlessly communicate and collaborate with others. This holistic approach not only simplified the overall design but also promoted a deeper understanding of the device's operation and functionality. Users can easily identify the relationships between different components and subsystems, enabling them to troubleshoot issues or make improvements with ease. The relative simplicity of the functional areas, once the underlying principles are understood, underscores the success of this integration strategy.

Overall, this approach to designing the functional areas fosters a user-friendly experience and promotes continuous improvement and innovation in device functionality.

Printing: As previously mentioned, a fundamental aspect of integration revolves around the printed components. Within this context, the integration of the barrel and mount hinges on a sequential testing process of individual features followed by combined assessments. This testing regimen includes verifying wire movement freedom within a secure environment, ensuring the adequate housing of all components within the barrel or mount, and conducting comprehensive tests to assess the compatibility of each component with the printed parts.

When speaking to the wire's freedom, this would involve the slots designed to house wiring without inducing stress unto them. However, this does not allow the wires to be loose fitted so a dynamic interplay occurs involving altering the wire dimensions and not rendering them too small for optimal use. This design includes measuring the slot of the barrel housing the wire and cross referencing the wire length to remain taut but not overstretched. Overstretched wire increases the possibility of failure and under tightened wire can lead to wires becoming crossed with one another and an unfamiliarity as to which wire connects to a component. To avoid this, the barrel is designed statically with the idea being that wire modification being an effective optimization task and as thus can be designed to work around the barrel itself.

The housing of the components and their integrated tested lie in a codependent relationship whereas the parts cannot have their integration tested if they simply cannot fit into the designated slot. If they did not fit and they were tested anyways, this would an unneeded test that is not representative of the performance of the final design and thus would have moot results. During the optimization of this device, such issues occurred with the seating of the motor and pulley system into the mount housing. The issue stemmed from the overall height of the pulley plus motor being unaccounted for in the initial design and was later rectified in later prints of the mount. In order to accommodate and test the independent connection of the motor system, the roof was chiseled out to allow for the seating and respective testing of this system.
Figure 8.2.1: A picture elucidating the prior statements of the necessary modifications of the mount’s top to allow for room for the motor and pulley to situate. This chiseling process involved the forced removal of polymer to create space using a simple process of measuring the path of actuation and creating the necessary space for it without destroying the overall integrity of the print. This image illustrates the importance of the overall housing integrability of each aspect of the printed parts whereas without proper consideration, nonideal modifications are needed that reduce the overall replicability of the device. This lesson carries over to every housed component such as the thermal sensor and heating pads which have designed slots for slotting without disrupting the syringe.

Figure 8.2.2: These images represent the aforementioned slots for the heaters and sensing probe both with reference [1] and without reference [2] the syringe intersected with the barrel. These slots were designed for ease of integrability with considerations for the wire intersection and overall design.

The symbiotic relationship between housing and integration dictates a methodical approach where each component's integration is staged and tested individually. This ensures not only mechanical integrity but also adherence to wiring principles outlined earlier. Through this meticulous process, the functionality and compatibility of each component within the overall system are thoroughly assessed to guarantee optimal performance.

Electrical: The electrical functional area, serving as the backbone of the bioprinter's operation, requires rigorous testing to assess its integration with other key components and subsystems. Integration testing involves the systematic evaluation of interconnections between sensors, actuators, power supplies, and the central control system to verify their seamless coordination and compatibility. Within the experimental design, emphasis is placed on testing the electrical functional
area integration with the barrel system and PLC, which is a pivotal component for material deposition and multi-material printing. Integration tests involve assessing the compatibility and responsiveness of electrical components with the barrel system's mechanical and material handling mechanisms. This includes evaluating the communication between the control system and actuators responsible for barrel rotation and material extrusion, as well as monitoring sensor feedback to ensure precise control over printing parameters.

**Control System**

Sensing: Integration testing is crucial in ensuring the effectiveness of the sensing system within the bioprinter's overall functionality. Through a series of experiments, the sensing system's capability to accurately capture and relay data to the control system is thoroughly evaluated under various operational scenarios. These experiments encompass a range of conditions, including temperature fluctuations, adjustments in extrusion speed, and monitoring for potential system failures. By subjecting the sensors to diverse environments and stressors, the testing aims to ascertain their reliability, precision, and responsiveness in real-world settings. One notable modification made during the integration testing involved the replacement of the original temperature sensing circuit with a sensing chipset. The decision to switch to the chipset was prompted by the unreliability of the circuit, which proved impractical for monitoring multiple inputs and filtering thermal interference effectively. In contrast, the chipset offered a compact solution with enhanced capabilities for integration with the PLC as both a heating and sensing module. Following the transition to the new chipset, validation of the heater integration into the overall circuit was successfully achieved. However, a new challenge emerged in the form of thermal overshoot, a common occurrence in electrical systems. To address this issue, a thermal heating range of 29-31°C was implemented, accounting for the anticipated overshoot while still remaining within the optimal biomedia curing temperature range. This optimization ensures that the curing rate remains consistent and effective throughout all degrees of operation.

Furthermore, stress testing the sensing system involves subjecting it to extreme conditions or challenging scenarios to evaluate its robustness and resilience to potential failures or malfunctions. Especially in the case of failure, the sensing system is responsible for the detection of lost communication and relaying that information for troubleshooting and finding the source of the issue.

Actuation: When integrating the actuators into the system, the primary goal is to avoid electromechanical failure modes, consisting of wiring shorts and mechanical damage. The primary actuators of this system being the motor and linear actuator, their respective force outputs have the potential to malfunction and cause damage to the electromechanical integrity of the system. To avoid this, the actuators are tested conjoined with their respective facilitators then slowly tested in stages developing a framework for operation. For the motors, the output being a rotational force on the belt thus rotating the barrel, is measured in steps with speed increments slowly escalated and evaluated for over torque stress. This process refines and identifies printed component areas that need addressing, leading to better optimization. With respect to the linear actuator, its primary goal consists of putting down a linear force onto the top of the syringe. Again, with speeds measured in steps, it is controllable with slow increments to optimize both extrusion rates and the firing time. These two rates are crucial for effective extrusion rates and movement of the biomedia through the syringe. Through thorough testing of the actuators, a precise range of firing times and step rate can be coordinated by the Raspberry Pi and G-code to develop a choreographed system of syringe extrusion that is needed for multi-crosslinking.

Facilitation: The facilitator, meaning the microcontroller, is the maestro of the bioprinter and core summation point for integration. As such the testing for integration is imperative to be successful and intensive, because if it was not, then the delegation process would become exponentially unstable. As such, the PLC is ran through intensive coding stress tests to identify bottlenecks during operation before then being tested in stages with each component. This process of staged testing is reflected in testing one segment of code reflated to a component to ensure its performance and later the entire code without the string to verify string correlation. After this testing, the components are brought together and facilitated as one then analyzed for performance. During the integration process, special attention is directed towards components such as the UV light array, which play a critical role in finalizing the curing process of biomedia. However, it is imperative to ensure that these lights are not constantly operational, as this would lead to over curing of the biomedia, rendering it non-viable. To address this challenge, the team collaborates with experts like Dr. Taesam Kim at the Northern Illinois University Analytical Chemistry lab, leveraging his expertise in UV spectroscopy to refine the curing rates. Dr.
Kim's insights contribute to the validation and optimization of curing rates, which are subsequently translated into the code governing biomedia curing processes. This collaborative effort ensures the successful integration of critical components and facilitates the achievement of precise and controlled biomedia curing, essential for the bioprinter's functionality and performance.

![Figure 8.2.3: This figure showcases the basic theoretical testing setup.](image)

This process of UV light refraction is measuring the wavelength at a set angle of 42° at 3.41 cm, reflecting the setup in the final design. By measuring the refracted UV wavelength, the team can calculate the rate of curing and intervals for the UV lights to be operating at.

**Wiring:** To avoid instances of wire failure, the team employs a strategy common in woodworking of “measure twice, cut once” which aims to eliminate human error. This strategy employs the usage of wire trimming and splicing via soldering to create customizable wire lengths. Soldering resulting in highly stable connections comparable in quality to welded steel. Wire trimming, being a simple process of snipping back a wire's length to maximize tension in the wire without overstretching it which is then spliced as necessitated to any original positions. Through this combination, the team can maintain wiring able to remain secure and space efficient creating a better optimized device.

**Chemical:** In the intricate realm of chemical experimentation for bioprinter integration, each functional area is approached with meticulous care and attention to detail. Hydrogel and biomedia, the cornerstone materials in this process, demand thorough examination due to their unique properties and potential interactions. Before integration, a comprehensive analysis of SDS is indispensable, ensuring that the chemicals involved pose no risk to the integrity of the bioprinter's syringes or the final printed design. This preliminary step is fundamental in safeguarding both the functionality of the bioprinter and the safety of the ensuing biological constructs.

Following the evaluation of SDS, the chemical components undergo rigorous individual testing to gauge their compatibility with the bioprinting system. Each substance is scrutinized for its potential to affect syringe performance or compromise the structural integrity of the printed designs. This step-by-step approach allows researchers to identify any adverse reactions or incompatibilities early in the process, mitigating the risk of damage to the equipment and ensuring the reliability of the experimental outcomes. Such meticulous testing underscores the importance of a methodical and cautious approach in the development of bioprinting protocols. Only after meticulous testing and assurance of compatibility are the functional areas integrated into the bioprinting process.

**Extrusion:** The extrusion and curing processes are fundamental to the overall functionality and performance of the bioprinter, necessitating stringent integration standards for both UV and heat-based curing mechanisms. The
interconnection between curing stages within the barrel and post-syringe extrusion is integral, as it directly influences the biomechanical properties of the printed biomedia. The precise control and coordination of thermal and UV curing rates are paramount to ensure the suitability of the biomedia for tissue engineering applications. Any deviations from these standards may result in the production of biomedia that does not meet the required biomechanical properties, necessitating further refinement. Therefore, the integrated testing process is intricately linked to the measurement and control of these rates, which are governed by the integration of components with the Raspberry Pi. Viewing the extrusion process as a static stage belies its dependence on the successful integration of other functional areas to achieve the desired output. Thus, the testing of integration hinges on the culmination of testing in other areas, followed by dry test runs to validate the performance of the curing and actuation components before the application of biochemicals. Successful completion of these tests, coupled with the anticipated performance of the biochemcials, results in seamless integration and facilitates the efficient proliferation of biomedia. This comprehensive approach ensures that the extrusion and curing processes operate harmoniously within the bioprinter, ultimately contributing to the successful fabrication of tissue constructs with the desired biomechanical properties.

Throughout the integration testing process, meticulous attention is paid to mechanical integrity, wiring principles, chemical compatibility, and performance optimization. By systematically evaluating each component's integration with the overall system, researchers can refine designs, address any shortcomings, and optimize functionality to meet project requirements. Collaboration with experts in relevant fields, such as UV spectroscopy for refining curing rates, further enhances the integration testing process and contributes to the successful development of the bioprinter. By prioritizing thorough integration testing, the team can ensure the reliability, efficiency, and safety of bioprinter systems, ultimately advancing the goal of producing functional biomedia for medical applications.

8.3 Failure Analysis of each Functional Area

When evaluating the failure analysis of the device, it is best interpreted as compounded failure of each functional area, leading to an overall failure of the device. This method both elucidates where the root of the failure surfaces from, and additionally showcases the interconnectivity of the device spearheading the importance of the optimal performance of each functional area to create a fully functional device. To understand these failures is one part, but to predict and plan for them with accorded remedies is a true mastery of the device’s performance optimization. These four functional areas, consisting of the electrical, chemical, printing, and extrusion domains combine cohesively to orchestrate a series of actions creating a bioprinter with the ability to multi-crosslink multiple chemicals. This is done by the communication network and precisely timed steps dictated by pre-programmed and vetted code finalized with securely implanted mechanical components to actuate the steps as predicated by the PLC. Without the precise interaction between components, failure in the device compounds throughout functional domains and to the detriment of the project as a whole. For example, if a component in the electrical system fails even as minor as a loose wire, can lead to a short circuited motor driver and induce a miscommunication with the stepper motor and induce a misfire having the potential to have ruinous impacts on the core components of the device.

Electrical: When working to develop an optimized prototype, the electrical components underwent a core change in relation to product optimization. These changes aimed to reduce the potential for subpar performance and enhance the overall integration of the device. The main change being the removal of the AC/DC converter module and temperature sensing circuit. The converter was deemed obsolete for the scope of the project while the temperature sensor was swapped for an integrated module set with probes for remote sensing.
Figure 8.3.1: This is the swapped temperature sensing with an onboard feedback system that consistently monitors the sensed temperature and adjusts the integrated component accordingly.

This sensor is an independent component with interface compatibility to be both programmed by code and act as a facilitator for heating pads. This combination made this component ideal for the testing and action of temperature control in the project rendering the issue of the heating pad unreliability negligible for the device's performance.

However, the electrical system still has failure modes, stemming from the control system and integration of wire splicing inducing potential error states. By inspecting each step of the control system, these failures can be alleviated independently and tested using stage methodology. These steps of the control system are the facilitation of the orders, then the orders are sent to the actuation block for order execution, then a sensing system receives feedback from those actuators and sends data to the PLC for adjustment or cycle repetition.

Facilitation: This sub-domain revolves around the transmission of electrical and encoded signals that facilitate the operation of the project's sub-components. This is achieved through the integration of a static power supply and a dynamic microcontroller, which collaborate to deliver their designated outputs. The power supply remains static and is unlikely to undergo independent changes unless manipulated by an operator. Consequently, failures within this domain typically arise not from the electrical signals themselves but rather from issues related to the transmission medium or the wiring of the device. However, the introduction of the Raspberry Pi adds a layer of complexity, introducing a range of flexible failure scenarios due to the dynamic nature of code operation.

- Failure Mode
  - Analog Signals: These signals, namely voltage and current, are supplied from a static source operating and set to 12V. Any deviations from this source, as indicated by the LED display, are caused by wire shorts with the component connection. These failures are common with circuit design and are typically easily addressed with careful consideration during design yet can be tricky if the failure occurs with spontaneity. In cases such as this, the transmission error can result in a failure in each sector of the control system with snowball potential for failure state expansion. During operation these failures would most likely propagate as a motor not firing at the specified step rate, UV light not operating at full potential, or a component not performing its task as anticipated in general.
  - Digital Signals: Coding is inherently complex and occasionally finnicky, leading to common compilation errors. Due to this nature, the failure state of the digital signals has the direst ramifications ranging from a simple miscommunication betwixt component prior to starting, to the linear actuator or motor misfiring causing a misalignment and potential destruction of the planned interactions necessitated to create a cross-
linked media. Digital signal error propagation during use will commonly appear as a component misfire, component miscommunication, or a failure for a stage or overall process to begin.

- Remediation
  - Analog Signals: To prevent the incumbent failure modes, careful planning and execution take place from the team to verify connection prior to the start of any test run. These tests serve as preventative maintenance on the device via visual and operational inspection. The team will visually inspect each wire connection including that of soldered and spliced wiring for fraying, exposure, or loose connections. Following that, the stages of each component are then inspected for their anticipated performance modes independent of the coded steps during a full test. This preventative maintenance should serve as a step that should be satisfactory of eliminating error prior to their failure events but should an error occur this preventative maintenance procedure, coupled with a multimeter for voltage testing, will be enough to eliminate any analog failure modes.
  - Digital Signals: The prevention of digital signal failure is paramount to the success of the device due to the necessary dictation performed by the Raspberry Pi. As such, virtual preventative maintenance is performed on the code by inspecting that no unexpected changes occurred and that all operations are functional. Paired with the visual inspection of each component dictated by code, a “dry” run is performed prior to a full test to verify that no failures will occur during standard operation. This process eliminates the potential errors from coding and if failure still occurs, it will be eliminated as a potential source of failure.

Sensing: This sub-domain, centered on the sensing component and its relay system interfacing with the microcontroller for data processing, is fortified by the integration of the LED temperature sensor, which bolsters its resilience against failures. Serving as the primary point of reliability standards within the design, this system benefits from the advanced capabilities of the LED sensor, ensuring consistent and accurate temperature measurements while mitigating common failure modes associated with traditional sensing methods. This robustness not only enhances the system's performance but also sets a precedent for reliability across other subsystems, fostering a culture of excellence and dependability throughout the entire design.

- Failure Mode
  - The failure mode of the sensing subsystem is closely associated with analog or digital signal failures, as previously mentioned, and will be thoroughly addressed during the troubleshooting phases in relation to the Raspberry Pi. However, concerning the temperature sensor, the failure mode typically stems from inter-component failure, resulting in the deregulation of the temperature output of the heating pads. This failure scenario can have significant repercussions, including de-optimization of curing rates for the biomedia and unreliable levels of pattern integrity. Such failures can compromise the overall effectiveness of the system, potentially leading to suboptimal results and operational inefficiencies.

- Remediation
  - To ensure the accuracy and reliability of the temperature sensor, the testing probe will undergo calibration using a validated method, guaranteeing precise temperature measurements across a broad spectrum of ranges. Additionally, the team has strategically installed slots to secure the temperature sensor against the syringe, mitigating potential external thermal interference. In the event of a component failure, such as the temperature sensor itself, there is no repair procedure available. Instead, a new module will be promptly substituted to maintain the integrity of the system. Furthermore, a fallback system has been integrated into the code to detect and swiftly address any anomalies. This system is specifically designed to identify aberrations in data transmission and promptly rectify any errors, ensuring the seamless and uninterrupted operation of the sensing circuit. By implementing these measures, the team aims to uphold the reliability and accuracy of temperature measurements critical for the system's functionality.

Actuation: The mechanical aspect of the system is primarily responsible for orchestrating the movement of the device's components, overseeing critical functions such as the motor-controlled rotation of the barrel and managing the force output of the linear actuator. While certain elements of this sector interact with the microcontroller and are susceptible to
coding errors, they also entail inherent risks of internal mechanical failure. The components within this system span a spectrum from minor, easily rectifiable issues to potentially catastrophic failures. Consequently, meticulous attention to detail and rigorous physical testing of all components are imperative to optimize their performance and mitigate failure modes associated with the actuation subsystem. By conducting comprehensive inspections, performing regular maintenance, and implementing stringent testing protocols, the mechanical integrity of the system can be safeguarded. This proactive approach not only minimizes the likelihood of malfunctions but also enhances overall reliability and operational efficiency. Additionally, instituting contingency plans and redundancies can further fortify the system against unforeseen challenges, ensuring uninterrupted functionality and longevity.

- **Failure Mode**
  - Failures within the system frequently hinge on the interface between critical components such as the Raspberry Pi, mounting assembly, and other integral parts, manifesting in diverse degrees of severity. Microcontroller errors, for instance, may emanate from faulty code execution or motor drivers failing to interpret instructions accurately. Additionally, challenges may surface within the power supply system, especially during motor interfacing or interactions between motors and their respective drivers. The graviest failure scenario often arises from component malfunctions within the motors or linear actuators themselves, representing a significant challenge that typically necessitates replacement rather than mere repair. These failures not only disrupt system operation but also potentially compromise safety and functionality, underscoring the critical importance of robust design and meticulous maintenance practices.

- **Remediation**
  - To mitigate these risks, it's crucial to meticulously assess and test the maximum load capacity, ensuring it remains within safe limits during both operation and testing phases. By adhering to the safety factor of 2.0, as previously recommended, the likelihood of inter-component failures can be significantly reduced if properly observed, thereby enhancing the overall reliability and longevity of the system. The preventative maintenance procedure in this section involves the inspection of each component visually and their performance to ensure reliability prior to actuated testing.

Chemical: The chemical functional area underwent changes through the iteration of the project and unfortunately, the chemical analysis dependent to create an actual validatable biomedia has over encompassed the reach of this project. Conversely, the focus of the project has been reprioritized to the refinement of the bioprint head attachment where the implementation of the chemical domain can be supplanted with the chemicals without adjustment. To make this logical claim, the team uses a cornstarch and water mixture consistent with the viscosity of biomedia (between 1 and 300mPa·s) and mixed with various food coloring. This allows for the showcase of the pattern printing ability needed for multi-crosslinking that would be needed in biomedia proliferation. This experimentation provides a logical conclusion linking the final device to the related hypothesis of creating an attachment capable of modifying a pre-existing printer to transform it into a functional bioprinter with a novel barrel design.

<insert image of cornstarch x food coloring pattern>

**Figure 8.3.2:** This figure shows the earlier conclusion of a pattern print possible by the device, this printed structure will undergo the same rigorous curing methods and testing for validation that would be consistent with biomedia. The significance of this figure lies in its demonstration of the device's capability to produce intricate patterns or structures, akin to those required for tissue engineering applications. By utilizing a cornstarch mixture as a surrogate material, the device's ability to handle and manipulate biomedia for tissue engineering can be extrapolated. This approach allows for preliminary testing and validation of the device's performance and suitability for more complex biomedia formulations in future applications as well as providing a foundation for logical reasoning towards the application of the device to multi-crosslink biomedia for tissue engineering.

- **Failure Mode**
  - The failure mode within this sector stems from the use of a cornstarch mixture as a surrogate for biomedia, which proves to be an unreliable stand-in due to inherent limitations. One significant drawback is the imperfect curing ratio resulting from differences in properties such as boiling point or UV transduction rates between cornstarch and actual biomedia components. These disparities can lead to
inconsistent curing outcomes, compromising the reliability and efficacy of the printed structures. Consequently, the device's performance may be compromised, as it operates on a less stable foundation compared to scenarios involving validated biomedia formulations.

- **Alternative Theory**
  - It is important to note that while the use of the cornstarch mixture may introduce uncertainties regarding curing outcomes, it does not necessarily diminish the validity of the attachment itself. The attachment's functionality and suitability for integrating with existing printers remain intact; however, the reliability of the printed structures may be affected by the limitations of the surrogate material. Therefore, while the failure mode highlights challenges associated with surrogate material selection, it does not invalidate the overall concept or utility of the attachment in facilitating bioprinting applications.

**Printing:** This specialized area of focus involves the adaptation of conventional 3D printing technology, typically utilizing plastic filament, into a medical device capable of printing biomedia suitable for tissue engineering applications. This adaptation is closely intertwined with both chemical and extrusion functionalities, facilitating the efficient creation of biomedia and its subsequent extrusion into a usable product. Given its intricacies, this sector poses unique challenges in predicting failure modes, primarily due to the complexity associated with biomedia specificity for use in tissue engineering, particularly within clinical environments. Additionally, remediation of bioprinting errors within this domain presents a multifaceted process, as it is deeply rooted in other functional domains. Key components of this sector include 3D printed elements such as the barrel, mount, and plate, which play integral roles in the precise extrusion of the biomedia to achieve desired cross-linked structures. As such, meticulous attention to detail for the printed components and their interfaciality are crucial for the development of the device.

- **Failure Mode**
  - The primary failure mode of the printed components lies in the interfacing with other components and mechanical integrity to withstand fatigue stresses through repetitive runs. Fatigue stress is a principle in material mechanics stating that as a repetition of loads, a material is more likely to fracture. After doing stress analysis, this will be the most common failure mode for our parts. In particular, at one key area on the mount.

![Figure 8.3.3](image)

Figure 8.3.3: This is the arm that links with the barrel, the team identified this as a potential fatigue failure point as it serves as the primary site of torsional loading with the barrel. While the loading on the arm is minor, repetitive loading over time could cause failure of the arm causing it to fracture and separate from the barrel mechanism.

- In addition to the mounting arm, interfacial clearance is another critical factor to consider when designing printed parts for the bioprinter. These printed components must provide adequate space for other system elements to function optimally. Insufficient clearance can lead to poor performance or exert undue stress.
on neighboring components, thereby increasing their likelihood of failure. When designing printed parts, it's essential to account for the spatial requirements of adjacent components and ensure that there is ample clearance to accommodate their movements and operations. Failure to do so may result in components rubbing against each other, causing frictional wear, or interfering with each other's functionality, leading to suboptimal performance or premature failure.

- Remediation
  - To mitigate this risk, thorough design reviews and simulations were conducted to assess the spatial requirements of all system components and ensure that printed parts allow for adequate interfacial clearance. Additionally, periodic inspections during operation will help identify any instances of insufficient clearance or interference, allowing for timely adjustments or redesigns to maintain optimal system performance and reliability. To combat this issue, the team designed a mounting plate with tunnels that when used in tandem with zip ties, allow for secure mounting of the wires.

Figure 8.3.4: The rear view of the mounting plate tunnels, this showcases a thoughtful design approach aimed at optimizing functionality and aesthetics. These tunnels have been meticulously measured to provide ample space, approximately 2.5 times the amount needed for accommodating wires. This design consideration ensures efficient wire management and enhances the bioprinter's overall appearance. Beyond their practical purpose, these tunnels serve as an aesthetic choice, contributing to a more cohesive and streamlined design. By neatly organizing and concealing the electrical components within the tunnels, the focus of the front view remains primarily on the barrel printer, creating a visually appealing and user-friendly interface.
Figure 8.3.5: The top view of the mounting plate with (A) and without (B) the components attached. This other view of the plate showcases the security of the components directly impacting the design function without impeding the overall rotational or the actuation functions of the device. This plate exemplifies the design philosophy of the printed parts: cohesive, supporting, and non-intrusive.

- In case of mounting arm failure, the most viable option is to replace the entire mount with a freshly printed part. This decision was intentionally made during the design phase, ensuring that both the mount and barrel were constructed using 3D printed parts. This strategic choice allows for cost-effective and efficient maintenance, as replacing the parts is relatively inexpensive for the operator, typically costing no more than $50. By utilizing 3D printing technology, the production of replacement parts is rapid and cost-efficient, minimizing downtime and associated costs. This approach enables operators to swiftly address mounting arm failures without incurring significant expenses or delays in device operation. Additionally, the use of 3D printed parts offers flexibility in design modifications and customization, allowing for continuous improvement and optimization of the mounting arm's performance and durability.

Extrusion: This functional area represents the final step in defining the device's role, focused primarily on producing precise biomedia formulations. Within this domain, two interconnected subdomains, curing, and transportation, play crucial roles in refining the mechanical properties of the biomedia. The curing process is pivotal as it solidifies and stabilizes the biomedia, providing essential structural integrity necessary for subsequent stages. Proper curing ensures the biomedia maintains its intended shape and adheres to the desired structure. Simultaneously, the transportation subdomain facilitates the precise movement of the mixture to its designated location, enabling accurate deposition. Precise transportation is vital for achieving the desired layering and spatial arrangement of biomedia, influencing the overall quality and functionality of printed tissue constructs. Although interconnected, these subdomains differ significantly in failure possibilities due to their distinct roles. Failures in the curing subdomain may lead to structural weaknesses or inconsistencies in printed tissue constructs, impacting tissue functionality. Conversely, transportation subdomain failures may result in misalignment or irregular deposition of biomedia, causing inaccuracies or defects in printed tissue constructs.

Curing: The curing domain is responsible for the finalization of biomedia extrusion by securing the mechanical characteristics. It relies solely on the UV-PLC interaction to control the timeframe of curing that creates biomedia qualitative properties consistent with market biomedia s. The rate of curing by the 395nm UV lights are dictated by the spectoscopy experimentation and mathematical modeling to determine the optimal curing rate.

- Failure Mode
  - Achieving precise temperature control within the barrel for the curing process presents significant challenges, particularly in clinical applications where stringent tolerances are required. One potential failure mode arises from the inability to meet the exacting temperature control requirements, impacting
the efficacy of the curing process. This failure mode may result in the production of biomedia that falls short of meeting validation standards, limiting its utility for intended applications. In addition, the UV lights may not be receiving the expected analog or digital signals thus reducing their efficacy to finish the curing process. The UV lights or heating pads may also be susceptible to human error when mounting changing the angle or intensity of exposure to thermal or UV energy.

- Remediation
  - To address these challenges, a proactive approach to preventative maintenance will be implemented, involving regular visual and operational inspections of the heaters and UV lights. These inspections aim to identify and rectify basic errors such as improper mounting or malfunctioning components. However, if errors persist or propagate during a print cycle, immediate action will be taken to halt the cycle and make necessary adjustments based on the encountered errors. This reactive approach ensures that any issues affecting temperature control or curing processes are promptly addressed, minimizing the risk of producing biomedia that fails to meet validation standards. By combining preventative maintenance with proactive error management during print cycles, the reliability and consistency of the temperature control system can be maintained, ultimately enhancing the quality and efficacy of the biomedia production process.

Transportation: This area is responsible for the movement of the biomedia through the syringes. It relies on the linear actuator to evenly depress the syringe at a predetermined rate. Its primary function is to be actuated upon rather than serving an actuator based function but is crucial to the passage of biomedia and future pattern printing applications.

- Failure Mode
  - The transportation subsystem, although seemingly simple, is critical for the accurate deposition of biomedia onto the designated surface. However, its simplicity doesn't exempt it from potential failure modes. One significant failure mode could arise if the linear actuator fails to function properly, resulting in the inability to extrude biomedia through the syringe. This failure could lead to interruptions in the printing process, affecting the accuracy and consistency of biomedia deposition. Additionally, if the dispensing rate is not controlled effectively, it could result in uneven distribution of biomedia, leading to irregularities or defects in the printed tissue constructs.

- Remediation
  - Ensuring the proper functioning and calibration of the linear actuator, as well as monitoring and controlling the dispensing rate, are crucial for mitigating potential failure modes and maintaining the reliability of the transportation subsystem. This calibration is completed using a developed rotary test procedure that verifies each stage of the step paired with strong preventative maintenance principles of OVI (Operational and Visual Inspection). This combination removes the possibility of pretest failures while aiming to reduce the incumbent failures during a test.

In conclusion, a comprehensive understanding of the failure analysis of the device underscores the interconnectedness of its functional areas, emphasizing the critical importance of optimal performance in each domain to ensure overall device functionality. By recognizing the compounded nature of failures across these areas, the team can better identify their root causes and develop effective strategies for remediation. Predicting and planning for these failures with appropriate remedies is essential for mastering the device's performance optimization. The device's four functional areas - electrical, chemical, printing, and extrusion domains work cohesively to orchestrate a series of actions necessary for bioprinting applications. Each area plays a vital role, and failure in one domain can spread throughout the system, detrimentally affecting the project. For instance, even a minor failure in the electrical system, such as a loose wire, can cascade into more significant issues, potentially leading to miscommunication with critical components like stepper motors or UV lights. To address potential failure modes within each domain, proactive measures and remediation strategies have been implemented. For instance, in the electrical domain, careful planning and execution of preventative maintenance ensure the reliability of wire connections and component performance. Similarly, in the sensing domain, calibration procedures and redundancy measures are employed to maintain the accuracy and reliability of temperature measurements critical for
the system's functionality. Additionally, in the printing domain, stress analysis and design optimizations are utilized to mitigate potential failure modes related to the mechanical integrity of printed components. Overall, by adopting a proactive approach to failure analysis and implementing robust remediation strategies, the device's reliability, performance, and longevity can be maximized, ultimately advancing its utility in bioprinting applications, and contributing to the broader field of tissue engineering.

8.4 Integration and testing functional areas to produce a working prototype

The integration and validation testing for any medical device is rigorous, especially those with potential for direct human interfacing. The bioprinter is one such device as the main reasoning behind tissue engineering is the betterment of patients through engineered tissue implantation, and this device prints the construct for their iteration. As such, the component testing for each part must be absolute and recorded with precision. More than just testing every component with one another, the Raspberry Pi, or even the assembly as a whole, the device needs procedure-based experimentation for the true validation of the final design. As such, the team developed four key experimental procedures crucial to the integration and finalization of the project. These are based around four key actions the device will perform; temperature control, linear actuator calibration, rotary motor calibration, and UV lightwave testing to determine the period for optimal curing.

General Testing

As spoken about previously, every component undergoes basic testing to ensure compatibility, reliability, and performance against expectation. These tests comparatively to the four key experiments are relatively simple yet necessary for device performance. To better illustrate the nature of these tests, the heating pads will be used as an example with each component subjected to these tests prior to integration.

- **Compatibility** – Is the component compatible with the hardware and software driving the device?
  - For the case of the heating pads, they are compatible with the software due to their operation being driven by the temperature sensor which is directly programmable by the PLC.
  - The heating pads are also compatible with the hardware due to them not being set to a point where it would melt the syringe or printed barrel. The heating pads are compatible with the barrel additionally by staying secure in the designed slot for their housing.

- **Reliability** – Will the component withstand the repetitive stresses during a print?
  - Due to the housing and the basic testing with the heating pads, it has been determined that the heating pads should have no issue surviving multiple print cycles.

- **Performance** – Does the component meet performance expectations?
  - The heating pads are simple binary components that are either on or off, they need a sensing module to regulate temperature. The heating pads to heat up and work with the temperature sensor, therefore meet expectations.

This series of testing is logically extrapolated to every component on the device and only after passing all tests are they integrated into the component. Following this simple ledger of tests, all components can be generally assured to be suitable for the standards required for the bioprinter. This systematic approach not only minimizes the risk of unforeseen failures during operation but also instills confidence in the device's reliability and functionality. Ultimately, this commitment to rigorous testing ensures that the bioprinter meets the stringent standards required for tissue engineering applications. The following tests are procedures for the validation of the particular aspects of the device’s performance.

Temperature Control Part 1

In this experiment, the objective is to establish and validate a standardized method for heating fluids within a syringe to precise temperatures while ensuring accurate temperature measurement. By controlling the heating process and employing calibrated temperature sensors, the team will develop a reliable technique applicable to the bioprinters function. Through systematic testing and calibration procedures, the team seeks to optimize the performance of the heating system and ensure consistency in temperature control. This experiment is essential for ensuring the reliability and accuracy of temperature-sensitive processes in the device.
Objective:
Develop and validate a precise heating method for fluids within a syringe, alongside accurate temperature measurement techniques.

Materials Required:
- Large beaker with deionized water
- Hot plate
- Retort stand with adjustable rings
- Syringe (appropriate volume)
- Digital thermometer
- Calibrated temperature sensor
- Personal Protective Equipment (PPE)
- Insulating tape
- Heating pads
- Programmable Logic Controller (PLC)
- Data recording device
- Stopwatch or timer

Procedure:
1. Preparation of Equipment:
   - Fill the beaker with deionized water and place it on the hot plate.
   - Assemble the retort stand next to the hot plate and securely attach the adjustable rings or holders.
2. Syringe Preparation:
   - Fill the syringe with the fluid to be tested, ensuring there are no air bubbles present.
   - Cap the needle end of the syringe securely to prevent any fluid leakage.
3. Mounting and Submersion:
   - Securely attach the filled syringe to the retort stand using one of the adjustable rings or holders.
   - Carefully submerge the majority of syringe into the beaker of water, avoiding contact with the beaker sides to prevent breakage or heat loss.
4. Temperature Measurement Setup:
   - Attach the thermometer to the retort stand with another ring, ensuring it's secure.
   - Gently submerge the thermometer tip into the fluid within the syringe without touching the sides or bottom to avoid inaccurate readings.
5. Heating and Monitoring:
   - Begin heating the beaker on the hot plate, aiming for a target temperature of 27°C.
   - Monitor the fluid temperature within the syringe using the thermometer, recording initial temperatures.
   - Once 27°C is reached, affix the temperature sensor to the upper portion of the syringe using insulating tape, ensuring it is well-attached but not altering the fluid's natural temperature.
- Record the temperatures from both the thermometer and the temperature sensor at this baseline.
- Incrementally increase the hot plate's temperature by 2°C intervals, recording the temperature readings from the sensor at each stage to assess response time and accuracy.

Calibration and Optimization:
- If there are significant discrepancies between the thermometer and sensor readings, recalibrate the temperature sensor according to manufacturer instructions.
- Document the calibration process meticulously, noting any adjustments made to improve accuracy

Temperature Control Part 2
Objective: Integrate heating pads and a programmable logic controller for precise temperature regulation, documenting the system's efficiency and stability.

Procedure:
1. Integration of Heating Pads:
- (OUTSIDE OF WATER, USING A DRY SYRINGE FILLED WITH TEST FLUID) Attach heating pads to syringe insulating tape, ensuring they are fixed securely and positioned as they are when implemented using the novel bioprint head.
- Connect the heating pads to the PLC, configured to regulate the temperature within a precise range (27°C ± 1°C).

2. PLC Configuration and Monitoring:
- Program the PLC to turn the heating pads on and off to maintain the set temperature range.
- Start the PLC control loop, continuously recording the temperature sensor's readings to monitor fluctuations and stability.

3. Verification and Adjustment:
- Use the thermometer to periodically verify the actual temperature within the syringe against the PLC-controlled temperature.
- Make any necessary adjustments to the PLC settings or heating pad placement to maintain temperature accuracy and stability within the specified range.

Calibration and Optimization:
- Assess the effectiveness of the PLC and heating pads in maintaining the desired temperature range.
- Record all adjustments and settings changes meticulously, ensuring repeatability and consistency in subsequent experiments.
Linear Actuator Calibration

The objective of this experiment is for the team to conduct precise E-steps calibration for a newly implemented syringe extruder, ensuring accurate material extrusion facilitated by the linear actuator. With a focus on meticulous control and calibration, the team aims to establish optimal settings for the 3D printer's E-steps, crucial for consistent and reliable extrusion performance. By employing a systematic procedure involving fluid filling, extrusion, and volume measurement, the team seeks to determine and adjust the E-steps settings to match the desired extrusion volume accurately. This calibration process, conducted using Klipper firmware and Mainsail interface software, is essential for maintaining extrusion consistency and reliability across various applications. Through careful documentation and repeated calibration iterations, the team aims to verify the accuracy and repeatability of the calibration process, ensuring precise material extrusion for future printing endeavors.

Materials Required:

- Linear Actuator
- A4988 Stepper Motor Driver
- Raspberry Pi 4 B
- 3D Printer Control Board compatible with Klipper firmware
- Precision Syringe
- Beaker or Graduated Cylinder
- Electronic Scale
- Calipers or Rulers
- Computer with Mainsail Interface installed
- USB Cable
- Power Supply Units for Raspberry Pi, 3D printer control board, and linear actuator
- Jumper Wires and Connector Cables
- Fluid for Calibration
- Mounting Hardware (screws, brackets)
- Thermal Paste or Heat Sinks (optional for A4988 driver)
- Klipper Firmware
- Mainsail Interface Software

Procedure:

1. 3D Printer E-steps Calibration:
   - Establish a connection between the 3D printer and the computer using the Klipper firmware and Mainsail interface.
   - Retrieve current E-steps settings using the command provided in Mainsail's terminal.
   - Prepare the syringe by filling it with a known volume of fluid, ensuring there are no air bubbles.
   - Mount the syringe onto the extruder setup and place a beaker beneath the syringe nozzle.
   - Extrude a predetermined amount of fluid, where it is predetermined by the E-step setting.
   - Weigh the container to determine the actual volume extruded.
   - Calculate the correct E-steps based on the measured extruded volume and update the extruder's settings accordingly.
Calibration and Optimization:
- Ensure that the calibration process is repeated several times for both systems to confirm accuracy and repeatability.
- Document each calibration step and result carefully, updating firmware settings as necessary to maintain consistent extrusion across experiments.

Rotary Motor Calibration

Theoretical Preparation:
1. Stepper Motor Fundamentals: Familiarize yourself with the operational mechanics of NEMA 17 stepper motors. These devices convert electrical pulse sequences into angular movements, with a standard step angle typically being 1.8 degrees, equating to 200 steps per full 360-degree revolution. Understanding the specifications of your specific motor, including its step angle and maximum torque, is crucial for accurate experimentation.
2. Gear and Pulley Ratios Analysis: Accurately measure the diameters or count the teeth of both the pulley attached to the stepper motor and the large gear intended to be rotated. Calculate the mechanical advantage or gear ratio by dividing the number of teeth or the diameter of the large gear by that of the small pulley. This ratio is instrumental in determining the total number of motor steps required to rotate the large gear by a desired angle.

Materials Required:
- NEMA 17 Stepper Motor
- A4988 Stepper Motor Driver
- Raspberry Pi 4 B
- Power Supply for Raspberry Pi and Stepper Motor
- USB Cable for Raspberry Pi
- Micro SD Card for Raspberry Pi
- Pulley Attached to Stepper Motor
- Large Gear to be Rotated
- Timing Belt
- Digital Camera or Smartphone with High-Resolution Camera
- Tripod or Stable Mount for Camera
- Computer or Laptop with Image Processing Software
- Software for Raspberry Pi (Python, RPi.GPIO)
- Jumper Wires and Breadboard for Circuit Assembly
- Multimeter for Circuit Testing
- Caliper or Ruler for Measurement
- Spreadsheet Software for Data Analysis
- Screwdrivers and Wrenches for Mechanical Assembly
Laboratory Notebook and Pen for Documentation
HDMI Cable and Monitor (for Raspberry Pi setup)
Keyboard and Mouse (for Raspberry Pi setup)
Leveling Tool (to ensure proper alignment of setup)

Procedure:
1. System Assembly: Carefully connect the NEMA 17 stepper motor to the A4988 driver module, ensuring correct alignment of control pins and power supply according to the motor and driver specifications. Properly interface the A4988 with the Raspberry Pi 4 B, paying close attention to GPIO pin connections and voltage compatibility to avoid damage.
2. Pulley and Belt Installation: Secure the designated pulley to the shaft of the stepper motor and connect it to the large gear using the timing belt. Confirm that the assembly is tensioned appropriately to prevent slippage, while ensuring there is no excessive strain on the motor shaft that might impede rotation.
3. Camera Setup: Position the camera so that it has an unobstructed view of the gear, focusing particularly on any markings that indicate angular position. The camera should be mounted stably to avoid any movement that could distort the measurement accuracy.

Software Setup and Control:
1. Programming the Raspberry Pi: Develop or modify existing Python scripts to facilitate precise control over the stepper motor via the A4988 stepper motor driver. The code should enable the execution of controlled step sequences and include error handling to manage any operational anomalies.
2. System Verification: Before proceeding with the main experiment, perform preliminary tests to confirm the motor reacts as expected to Raspberry Pi commands. This initial phase ensures the integrity of the electrical connections and the functionality of the software.

Experiment:
1. Baseline Establishment: Using the camera, document the initial orientation of the large gear to serve as a reference point. This initial position is crucial for accurately measuring the gear's subsequent rotations.
2. Incremental Rotation and Observation: Methodically activate the stepper motor to rotate in predetermined step increments (e.g., 100 steps). After each set of movements, utilize the camera to capture the new position of the large gear. It's vital that the camera and gear remain undisturbed during this phase to ensure accurate measurements.
3. Data Compilation: Transfer the captured images to a computer for angular displacement analysis,
which can be conducted through image processing software or manual inspection. Record the angle turned after each step increment in a spreadsheet, alongside the corresponding number of steps executed.

4. Empirical Analysis: Utilize the recorded data to compute the actual rotation angle per step. This calculation is critical for understanding the relationship between the stepper motor's steps and the gear's angular movement.

Calibration and Validation:

1. Determination of Steps for Desired Angle: Employ the collected data to deduce the precise number of steps the stepper motor must complete to rotate the large gear by 90 degrees. Remember to adjust this figure based on the previously determined gear-pulley ratio.

2. Operational Testing: Integrate the computed step count into the Raspberry Pi's control script. Execute multiple iterations of the experiment, where the gear is expected to rotate by 90 degrees. Document each trial's result with the camera for subsequent analysis.

3. Result Evaluation and Fine-tuning: Assess whether the gear consistently achieves the expected 90-degree rotation. Should there be discrepancies, recalibrate the step count as necessary and reiterate the testing phase until the gear rotates as intended consistently.

4. Final Validation: Confirm the experiment's success by performing several consecutive rotations in different directions, verifying the system's accuracy and repeatability.

5. Comprehensive Documentation: Meticulously record all experimentally obtained values, system settings, and observational notes. Detail any challenges encountered, and the strategies implemented to address them. This documentation will serve as a valuable resource for future reference and troubleshooting.

UV Light Testing via UV Spectroscopy

This test's objective is to establish the optimal duration for UV light exposure necessary to achieve peak curing rates for biomedia validation. This will be accomplished by measuring the wavelength emitted by the UV lights over different time periods. By systematically varying the exposure duration and recording corresponding wavelengths, the team aims to identify the time interval that maximizes the curing efficiency of the biomedia. This critical assessment will provide valuable insights into the kinetics of the curing process, facilitating the development of precise protocols for biomedia validation in the bioprinters applications.

Materials Required:

UV Light Source
Spectrometer
Optical Cables
Breadboard
Circuit Components (Raspberry Pi, gate MOFSETS, UV-Light modules, etc.)
Computer with Spectrometer Software installed
Measurement Ruler
Calibration Standard (if applicable for the spectrometer)
Procedure:

1. Circuit Setup and Spectrometer Calibration:
   - Assemble the breadboard circuit as per the schematic provided, ensuring all components are correctly placed and securely connected.
   - Power on the UV light source and the spectrometer, allowing them to warm up.
   - If available, perform a standard calibration of the spectrometer to ensure accurate measurements.

Figure 8.4.1: The breadboard setup for testing the UV lights is pivotal for precise experimentation. To ensure reproducibility, it will be relocated to a portable powered breadboard. This will facilitate seamless replication of experiments at Dr. Kim's lab, enhancing collaboration and research impact.
2. UV Light Measurement Setup:

Figure 8.4.2: This is the setup for the refraction experiment. The left mount houses the optical cable measurement. The plate measuring the refraction is carborundum glass with a 95% UV refraction rate. This plate will remove the risk of refraction loss to a 5% degree and ensure that quality measurements are taken to be extrapolated to UV period of operation.

- Arrange the optical cables at the specified distance and angle from the UV light source, securing them in place to prevent movement during measurement.
- Launch the spectrometer software on the computer and configure the measurement settings as Advised.

3. Data Collection and Analysis:

- Conduct multiple measurements of the UV light output, recording the spectrum data for each.
- Analyze the recorded data, comparing peak intensities, wavelength distributions, and other relevant spectral features against expected values.

Calibration and Optimization:

- Based on the data analysis, adjust the UV light source or measurement setup to optimize performance and accuracy.
- Document all measurement conditions, settings, and results in detail to enable replication and validation of the experiment.

Discussion
In conclusion, the integration and validation testing process for the bioprinter has been meticulously executed to ensure its readiness for biomedical applications. Given the device's critical role in tissue engineering and its potential for direct human interaction, rigorous testing was imperative to guarantee both efficacy and safety. The team has not only conducted basic compatibility, reliability, and performance tests on individual components but also developed four key experimental procedures essential for the integration and finalization of the project. These procedures encompass temperature control, linear actuator calibration, rotary motor calibration, and UV lightwave testing to determine the optimal curing period. Each experiment was carefully designed and executed to validate specific aspects of the device's performance, ranging from precise heating and material extrusion to accurate UV light exposure for biomedial curing. Through systematic testing, calibration, and optimization, the team has ensured that the bioprinter meets the stringent standards required for tissue engineering applications.

8.5 Failure Analysis of the prototype

When delving into the intricate analysis of the prototype's failures, it becomes readily apparent that the ramifications extend far beyond isolated incidents within specific functional domains. Instead, the interplay of various components highlights a complex web of dependencies where shortcomings in one area can cascade into broader system failures. This perspective not only reveals the root causes of failures but also underscores the intricate interconnectivity inherent in the device's design. Indeed, the failure analysis process serves as a beacon, illuminating the origins of malfunctions and shedding light on the intricate relationships between different functional areas. Each component, whether electrical, chemical, printing, or extrusion, plays a pivotal role in the overall functionality of the device. As such, any lapse in performance within these domains can reverberate throughout the system, ultimately culminating in the device's overall failure.

The electrical system, while pivotal to the prototype's functionality, harbors inherent risks that could potentially lead to system-wide failure if not addressed proactively. One critical vulnerability lies in control system errors, which can arise from programming intricacies or compatibility issues. These errors have the potential to disrupt the precise orchestration of operations essential for bioprinting, resulting in misalignments, inaccuracies, or complete system shutdowns. For instance, a minor glitch in the control system could lead to miscommunications between components, causing motors to operate at incorrect speeds or in incorrect directions. Such discrepancies could have cascading effects, compromising the integrity of the printing process and ultimately rendering the entire prototype inoperable. Additionally, vulnerabilities in wiring configurations pose significant risks to the electrical system's stability and functionality. If wiring connections are improperly secured or insulated, signal integrity may be compromised, leading to erratic behavior or catastrophic failures. For example, a loose wire connection could result in intermittent power supply to critical components, causing sporadic malfunctions or complete system shutdowns during operation. Moreover, the presence of exposed or damaged wiring increases the likelihood of short circuits, which could lead to electrical fires or irreversible damage to electronic components.

The chemical domain within the prototype plays a critical role in its overall functionality, particularly in the calibration and utilization of materials essential for bioprinting applications. However, this domain also harbors the potential to precipitate failure across the entire prototype if not carefully managed. One significant risk arises from inconsistencies or impurities present in the calibration media utilized within the system. If the calibration media is not properly formulated or contains contaminants, it may lead to irregularities during the mixing and curing processes. Such irregularities could disrupt the precise deposition of biomaterials, causing malfunctions in the printing and extrusion systems and ultimately compromising the device's ability to produce accurate tissue constructs. Furthermore, the interaction between chemical components and other functional areas of the prototype introduces additional layers of complexity and potential failure points. For instance, if the chemical components react unfavorably with materials used in other domains, such as electronic components or structural elements, it could lead to corrosion, degradation, or malfunctioning of these components. This domino effect of failures could propagate throughout the prototype, resulting in systemic malfunctions that undermine its overall performance.

In the printing domain, mechanical failures present a significant risk, often originating from issues such as fatigue stress on printed components. Despite thorough design reviews and simulations aimed at addressing these concerns, failures in this domain can still occur, potentially leading to disruptions in the printing process and compromising the prototype's
functionality. One common failure mode arises from fatigue stress on printed components, particularly those subjected to repetitive loading. Despite efforts to optimize the design and durability of these components, prolonged use can lead to material fatigue, weakening their structural integrity over time. For instance, mounting arms connecting critical components may experience torsional stress during operation, gradually leading to deformation or fracture. Such failures can result in misalignment or malfunction of essential components, disrupting the printing process and rendering the prototype inoperable. Moreover, despite rigorous testing and analysis during the design phase, unforeseen mechanical vulnerabilities may remain undetected until they manifest as failures during operation. For example, variations in material properties or environmental factors may exacerbate stress concentrations in printed components, accelerating wear and leading to premature failure. Additionally, inconsistencies in manufacturing processes or deviations from design specifications could introduce defects or weak points in printed parts, increasing the likelihood of failure under operational conditions.

In the extrusion domain, failures can manifest during the critical stages of curing and transportation, posing significant challenges to the functionality of the prototype. These failures often stem from difficulties in maintaining precise temperature control or from malfunctions in the linear actuators responsible for transporting the biomaterials. To mitigate these risks, proactive maintenance measures such as regular inspections and calibration procedures are implemented, aiming to ensure the reliability and consistency of the extrusion process. During the exploration of this domain, the team encountered notable challenges with thermal regulation, particularly when integrating the heating pad and sensors into the system. One such instance occurred when testing resulted in the unintended melting of one of the syringes containing biomaterial.

Figure 8.5.1: This is a picture of the melted syringe previously spoken on. This failure occurred due to the deregulation of the heating pad control due to repetitive usage, further testing revealed an oversight linked to a temperature buffer on the heating pads where the pads do not fully cool down and after that buffer exceeds a threshold of roughly 30°C, the sensor can no longer effectively control it. After modifying the interaction between those components and a settings change, the issue was resolved by changing the measurement methodology of the sensor.

This incident underscores the critical importance of meticulous attention to detail regarding the function and operation of heating pads within the system. It suggests a potential misunderstanding or oversight in the configuration or control of these components, highlighting the need for thorough testing and validation procedures to prevent similar failures in the future.

In conclusion, the examination of failure modes and the implementation of robust remediation strategies are crucial for optimizing the prototype's reliability, performance, and longevity. Understanding the interconnected nature of failures across different functional areas enables the identification of vulnerabilities and the development of targeted solutions. By addressing these challenges proactively, the prototype can enhance its utility in bioprinting applications and contribute meaningfully to the field of tissue engineering. Through a continuous cycle of analysis, improvement, and refinement, the prototype evolves into a more resilient and effective tool, capable of meeting the complex demands of biomedical research and clinical practice. Embracing a culture of continuous improvement fosters innovation and drives progress in
device design and operation. Each failure encountered serves as an opportunity for learning and optimization, propelling the prototype towards greater reliability and performance. By systematically addressing failure risks, the prototype gains credibility and trust within the research community, paving the way for broader adoption and utilization in research and clinical settings. Ultimately, a proactive approach to failure analysis not only strengthens the prototype's capabilities but also accelerates progress towards the realization of its full potential in advancing the frontiers of regenerative medicine and tissue engineering.

8.6 Fault analysis to pinpoint sub-functional area at fault

When evaluating the performance of the prototype and diagnosing associated faults, it becomes readily apparent which functional areas are implicated. This clarity stems from fault identification serving as a fundamental principle in delineating the sub-functional areas. To gain a comprehensive understanding of each fault identified, it is crucial to grasp the intricate relationships at play between the functional areas and their respective responsibilities. By discerning these interconnections, it becomes easier to pinpoint the origins of faults and develop targeted strategies for remediation. This approach not only facilitates accurate fault diagnosis but also lays the groundwork for future innovation for fault avoidance.

Electrical: The electrical functional area, governed by the control system, presents identifiable issues with corresponding remedies that share a common thread. Except complete component failure, the faults within the electrical system stem from miscommunications of analog and digital signals. These miscommunications can manifest in various forms, such as voltage fluctuations, current irregularities, or coding errors, disrupting the seamless operation of the prototype. Consequently, pinpointing and addressing these signal-related discrepancies becomes paramount for restoring the system's operation.

Likely Electrical Faults

- Analog Signal Disruption
  - This can range from a component not actuating or not performing to expectations. The failures, linked to the poor facilitation of power to a component, usually stem from wiring mistakes or failure rather than internal failures of the component.
  - Examples such as: UV lights not emitting expected wavelength, motors not firing or firing slowly, or the temperature sensor LED screen not being lit.
- Digital Signal Disruption
  - This fault starts and ends with the Raspberry Pi, being the sole source of digital signal reception and emission. Faults originating from this sector are either linked to analog signal disruption or code compilation inconsistencies. This fault is harder to spot due to being easily mistaken as analog transmission errors without an error code being generated and should serve as the secondary failure state for the electrical system. These failures have remediation from closer analysis in the code or analyzing for associated transmission errors.
  - Examples such as: UV light sequencing errors, motor desynchronization or rate deviation, or temperature sensor feedback or control not being followed. (Located by a discrepancy between the LED readout and expected value)

Printed Parts: Failures within the printed parts of the prototype often stem from mechanical issues, particularly related to the stresses endured during operation. These failures may manifest as structural weaknesses, fractures, or deformations in printed components. These parts are the housing and actuation sites for the project's functions and as such, the device would be inoperable without them. However, not all failures are equal, leaving room for fault codes that merely generate suboptimal performance without obstructing functionality. Remediation for all printed parts is linked to the reproduction of the associated part from the provided files via 3D printing replication.

Likely Printed Part Faults

- Cosmetic Faults
Some faults, such as minor breakage or scratching, can be non-calamitous dependent on location. These faults would only be cosmetic if they do not impede or could impede the overall function of the device. Corrective maintenance of these faults is recommended to prevent future failures from fatigue, stress unbalancing, or other unexpected failure states caused from cosmetic faults.

Examples such as: Cracking on the corner of the mount, minor scratching on the barrel that does not expose wiring, or any number of similar occurrences that do not violate principles of operation.

- Functional Faults
  - These faults actively halt or alter the functionality of the device. These would include an obstruction of actuation pathways such as belt movement or failure resulting in the requirement of code alteration for device functionality. These faults are considered irremediable, and printing should not be done in these failure states. Printing in these states can create failure states that cannot be anticipated and due to the ease of reproduction, should have maintenance prioritized prior to future usage.
  - Examples such as: Mount roof collapsing, major barrel breakage, mounting arm dislocation, or locking system fracture. Any failure not listed that impedes operation should be classified under this fault analysis.

Chemical: Within the Chemical Domain, various failure modes can impede the successful production of bioprinting formulations with the desired properties. Challenges may arise in calibrating the chemical components of the calibration biomedia mixture, leading to difficulties in achieving the required consistency or viscosity. Maintaining stable formulations throughout the printing process can present further obstacles, as fluctuations in chemical composition or environmental conditions may impact the quality of the biomedia. Moreover, the failure of surrogate materials to accurately mimic the behavior of actual biomedia can hinder the development and testing of biomedia formulations. Suboptimal printing results or compromised structural integrity of printed constructs may occur, affecting the efficacy and reliability of the bioprinting processes.

Likely Chemical Failures

- Using Surrogate Media
  - Failures from surrogate media likely come from production failures. These failures often arise as underdeveloped or under supported constructs that are not able to multi-crosslink effectively. These can be caused by the corn starch to water ratio being imprecise, or the lack of anticipation that the food coloring can have upon the overall viscosity after the addition of food coloring. Additionally, failures can occur of the biomedia not derived by the mixture delineation and rather from extrusion or electrical areas. Ideally, the chemical surrogate media is the same as when using biochemicals, leading to the explored logical foundation for the device's application in clinical settings.
  - Examples such as: Food coloring intermixing, mixture consistency being underdeveloped, or pattern deformation. Any other failure not listed that negatively impacts the usage of calibration media in the bioprinting process that detracts from the logical transition to biomedia efficacy should be considered a failure state.

- Using Bioprinting Chemicals
  - Failures in the transition to actual biomedia can arise due to various factors inherent to the biochemical composition and application process. These failures may include challenges in achieving desired properties for biomedia formulations, difficulties in calibrating the chemical components of the mixture, and issues with maintaining stable formulations over time. Additionally due to stringent FDA standards for biomedia, consistency and replication is key for device approval and eventual application.
  - Examples such as: Inconsistent mixing of biochemical components, inadequate formulation consistency, or deformation of printed patterns. Any failure that impedes the effective utilization of biomedia in the bioprinting process, detracting from the anticipated efficacy in tissue engineering applications, should be considered a failure state. This emphasizes the importance of thorough testing and optimization of biomedia formulations to ensure reliable performance and successful integration into clinical settings.
Extrusion: The extrusion area is relatively minor fault free, with most of its errors occurring fostered from the electrical domain due to calibration or coding mistakes. This area especially has numerous experiments to determine these actuation rates for optimal pattern printing and curing. As such, this area does have components and actions held exclusively to it with most faults in this domain linked to complete component failure or aforementioned electrical inconsistencies.

Likely Extrusion Faults

- **Biomedical Extrusion Failure**
  - This failure can be multi-faceted, being linked to either the syringe not being depressed at the calibrated rate, biomedical viscosity being too high, or temperature control issues. As mentioned previously, these failure states have links to other functional areas due to the extrusion sector being actuated upon rather than dictating its actions internally. Remediation of these faults are linked to the associated solutions to faults linked to the originated fault domain.
  - Additional faults in this domain are linked to the derregulation of printed structures. These faults are linked to the corresponding g-code or syringe depressurization and are observed via printing patterns not being as anticipated from either shape or colorization. The solutions for these instances are linked in the refinement of g-code sent to the 3D printer or modification of biomedical consistency and concentration.

In summary, identifying faults within the prototype's functional domains is crucial for maintaining its reliability and performance. Whether it's disruptions in the electrical system, mechanical issues in printed parts, challenges in chemical formulations, or errors in extrusion, each domain presents its unique set of challenges. By understanding the interconnected nature of these faults and implementing targeted remediation strategies, the prototype can continue to advance its utility in bioprinting applications. Through proactive measures and continuous refinement, the prototype can overcome these challenges and contribute to the field of tissue engineering. By addressing faults swiftly and effectively, the prototype can fulfill its potential and pave the way for innovation in biomedical research and development.

**8.7 Iterate and go back To Concurrent Engineering Part 1 as needed**

During the design phase of the bioprint attachment assembly, it became evident that initial conceptualizations lacked practical viability when put to the test through prototype iterations. Rather than discarding these ideas outright, they were repurposed as valuable learning experiences, serving to identify gaps and deficiencies within the design. Each adjustment, while seemingly minor, played a crucial role in refining the assembly's functionality and performance. These iterative changes were underpinned by established methodologies, including innovation through rigorous testing, stepwise integration of components, and meticulous validation processes. By adhering to this structured approach, the design team ensured that improvements were not only incremental but also systematically validated to guarantee compatibility and effectiveness within the broader system. The impact of these iterative improvements reverberated across the various functional domains of the bioprint attachment assembly. From Printed Parts to Electrical Control, Extrusion Mechanisms, and Chemical Integration, each domain underwent targeted refinements aimed at eliminating weaknesses and optimizing performance. This methodical approach not only strengthened individual components but also fostered synergies between them, ultimately leading to a more robust and efficient overall device. By continuously refining and integrating improvements across functional domains, the design team successfully navigated the complexities of bioprinting technology, resulting in a solution that exceeded initial expectations in terms of reliability, precision, and versatility. In addition to these changes, the team developed a more refined methodology for refined testing, best displayed by the following figure.
Figure 8.7.1: This chart shows the integration from the individual functional domains to a final design. Each node represents a stepwise integration with one another before full integration and testing with the calibration biomedia. This step shows a deeper understanding of exactly the steps taken needed to bring to life an optimized design. By following this flow with qualitative data to reinforce, the design becomes much more viable for future applications to clinical applications.

**Changes to Printed Parts Design**

During the design phase of the mounting arm and barrel, two primary areas were targeted for improvement: enhanced accessibility for the motor and pulley system housed within the mount, and reduction of the assembly's overall size and mass. To address these concerns, the team implemented strategic modifications, including the addition of holes at the rear of the mount. These holes facilitate neat wiring installation and enable swift removal of the motor when necessary, ensuring both convenience and efficiency in assembly and maintenance processes.

![Image](image1.png)

Figure 8.7.2: This is the back of the aforementioned mount with and without the motor installed to showcase the impact of the changes and the ease of access they allot.

One significant challenge encountered during the design process was the excessive weight of the assembly, which posed operational issues such as instability in the rail mounting system of the 3D printer or necessitated additional external support. Recognizing the need for improvement, the team undertook modifications aimed at addressing this issue. This involved resizing both the barrel and mount, as well as adjusting the total infill of the design during creation. To reduce weight and size, the team conducted a thorough analysis to identify areas within the assembly that could be modified without compromising functionality. By strategically removing unnecessary material and optimizing the design to prioritize functionality, the team effectively maximized the efficiency of the assembly while minimizing its mass. Additionally, the team focused on utilizing previously unused space within the design, such as extended syringe and wiring channels, to further enhance size and mass optimization. As a result of these adjustments, the team successfully produced a significantly smaller and lighter assembly that no longer negatively impacts the Ender 3V2 printer's stability.
This refined design not only addresses the initial issue of excessive weight but also improves overall functionality and integration with the printer.

Figure 8.7.3: This is a comparison of the first printed barrel versus the final iteration of the barrel. This change is noticeably drastic and showcases the value behind prototyping this device underwent.

**Changes to Electrical Systems**

The integration of both Klipper firmware and Raspberry Pi underwent meticulous optimization to elevate the functionality and adaptability of the bioprint attachment assembly. By combining the capabilities of Klipper firmware with the Raspberry Pi's processing power, the printer's operations were significantly enhanced. Klipper firmware served as the backbone for managing the printer's operations and executing G-code instructions. Its efficient processing and real-time control capabilities contributed to smoother motion control, improved precision, and reduced processing overhead.

Leveraging Klipper's distributed architecture, complex computation tasks were offloaded from the Raspberry Pi to and better coordinated and delegated to utilize on-suite Ender hardware processing power, ensuring efficient motion trajectory computation and real-time control of printer components.

Simultaneously, the Raspberry Pi's integration facilitated seamless communication and control of the printer. Through optimized code and debugging, communication between the Raspberry Pi controller and Klipper firmware was streamlined, ensuring a stable printing process and minimizing errors. Furthermore, the Raspberry Pi's connectivity features enabled wireless compatibility, allowing for remote control and monitoring of the printing process, thereby enhancing convenience and flexibility for users.

**Extrusion Mechanisms**

In the rigorous validation phase of the bioprint attachment assembly, an array of meticulous tests were orchestrated to validate the precision and seamless integration of the extrusion mechanism into the device. These tests were not just procedural formalities; they formed the bedrock of ensuring that the extrusion mechanisms operated with utmost accuracy and reliability. Their successful execution was imperative for the assembly to meet the demanding standards prescribed by the G-code and to maintain consistency with commercially available biomedias. Central to these validation tests was the exhaustive examination of the extrusion mechanism's functionality. Each component underwent stringent scrutiny, from the rotary barrel's rotational capabilities to the linear actuator's force exertion, to ensure that they could execute commands with pinpoint accuracy. By meticulously calibrating these mechanisms, the team aimed to guarantee that the device could extrude biomedia at the exacting standards dictated by the G-code, thus ensuring precise control over material deposition rates critical for bioprinting applications.

In the initial phase of validation, rotary barrel testing took precedence, aiming to establish the ideal step size to angle ratio for the rotation of the barrel. This meticulous process involved meticulous calibration of the stepper motor tasked with controlling the barrel's rotation, crucial for ensuring precise material deposition throughout the printing process. Through fine-tuning of the stepper motor's parameters, the team meticulously optimized the rotational movement of the barrel. This
The fine-tuning process was instrumental in achieving precise control over material flow rates and deposition patterns, laying the foundation for consistent and accurate printing outcomes. The outcome of this testing not only ensured the effective functioning of the extrusion mechanism but also underscored the dedication to achieving the highest standards of precision and reliability in bioprinting applications.

Parallely, the validation process advanced to UV light spectroscopy testing, which was conducted to precisely measure the wavelength of UV light output during the printing procedure. The objective was clear: to validate the efficacy of the curing process for photopolymerizable biomaterials. This involved a meticulous analysis of the spectral characteristics of the emitted UV light. By quantifying the wavelength of the UV light, the team gained insights into the degree of polymerization and crosslinking occurring within the printed constructs. Such analyses were pivotal in ensuring optimal structural integrity and biocompatibility of the printed constructs. Ultimately, UV light spectroscopy testing served as a critical validation step, affirming the capacity of the bioprint attachment assembly to produce printed constructs of superior quality and functionality, essential for advancing biomedical research and tissue engineering applications.

Moving forward, linear actuator force testing took center stage as the third pivotal validation step. This testing aimed to ascertain the precise number of steps necessary to depress the syringe at a predetermined and controlled rate, ensuring consistent material deposition during the printing process. The essence of this testing lay in the calibration of the linear actuator, which played a pivotal role in controlling the extrusion force. Through systematic experimentation, the team fine-tuned the actuator's parameters to guarantee uniform material deposition across various printing conditions. By subjecting the extrusion system to diverse loads and meticulously monitoring the resulting force outputs, the team gained invaluable insights into the actuator's performance and stability. This testing regimen ensured that the assembly maintained precise control over material extrusion, critical for achieving high-quality, reproducible prints in biomedical research and tissue engineering applications.

Finally, temperature control testing represented the last crucial step in the validation process. Its objective was to meticulously maintain a controllable temperature range of approximately 29-32°C without compromising the integrity of components through melting or damage. This testing was pivotal for optimizing the thermal management of the extrusion
system by closely monitoring and regulating the temperature of the printing environment. By ensuring a stable
temperature within the desired range, the team meticulously controlled material viscosity and curing kinetics. Such
meticulous control was indispensable for achieving reproducible print quality and structural integrity in bioprinting
applications. Ultimately, temperature control testing served as the cornerstone of ensuring the bioprint attachment
assembly's capability to consistently produce high-quality, functional constructs vital for advancing biomedical research
and tissue engineering endeavors.

<Image of temp validation test and data collected>

Figure 8.7.6: This is a display of the setup for thermal validation and the corresponding data collected. This test was
devised to determine and understand the thermal control module purchased to determine its limits of detection and
control. In addition, it showed the full time for a cooling cycle on the heating pads, allowing for consistent performance
throughout printing.

Changes to Chemical Domain

The alteration in the chemical domain's media composition was a strategic move aimed at enhancing the surrogate
biomedia's performance within the bioprint attachment assembly. The transition from a simple 2:1 cornstarch-water ratio
to an equal-parts mixture of flour and cornstarch with water maintained the 2:1 ratio while introducing a more balanced
combination of properties. This adjustment directly targeted improvements in consistency, viscosity, and flow
characteristics critical for achieving uniform material deposition during printing. By incorporating both flour and
cornstarch, the new formulation offered a more versatile and adaptable biomedia, capable of simulating the behavior of a
wider range of biological materials. This strategic adjustment prioritized substance over style, focusing on tangible
improvements in biomedia performance crucial for bioprinting applications. By fine-tuning the media composition, the
team bolstered the assembly's ability to produce high-quality, reproducible prints that are comparable to commercial
biomedias. This alteration refines our hypothesis by aligning more closely with the material properties of biomedia, thus
enhancing the logical coherence of our postulation that our bioprint head adapter is suitable for tissue engineering
applications.

<Image of temp validation test and data collected>

Figure 8.7.7: This is a showcase of the testing the biomedia underwent to determine an optimized consistency. These
tests measured the spread over time intervals of 5, 10, and 15 minutes with the expectation that there would be no
discernable difference. This proved successful, therefore developing a consistent and stable calibration biomedia usable
for validation and calibration testing.
Conclusion

Enhancements made to the electrical, extrusion mechanism, and chemical domains are a small leap towards perfection. These enhancements include the integration of Klipper firmware and Raspberry Pi, meticulous validation tests for the extrusion mechanism, and strategic modifications to the biomedia composition. Each domain underwent targeted refinements aimed at eliminating weaknesses and optimizing performance. The integration of Klipper firmware and Raspberry Pi significantly enhanced the printer's operations, while validation tests ensured the precise control and seamless integration of the extrusion mechanism into the device. Changes to the chemical domain's biomedia composition aimed at enhancing consistency, viscosity, and flow characteristics, aligning more closely with the material properties of biomedia. These enhancements not only strengthened individual components but also fostered synergies between them, resulting in a more reliable, precise, and versatile bioprint attachment assembly. Ultimately, these iterative improvements and domain enhancements represent significant strides in advancing bioprinting technology for various biomedical research and tissue engineering applications.
9 CONCLUSIONS AND FINAL REMARKS

This report provides a comprehensive account of the design and fabrication of a customized bioprint head adapter, signifying a significant advancement in the field of biomedical engineering. The adapter is engineered to seamlessly integrate a diverse range of communicative components, each playing a pivotal role in enabling precise and efficient multicomponent bioprinting processes. By harmoniously blending mechanical, electronic, and thermal elements, this innovative system showcases a holistic approach aimed at overcoming the inherent complexities in tissue engineering and regenerative medicine. These complexities include cost barriers and the limited availability of multi-crosslinking capabilities, which have traditionally posed challenges in the development and application of bioprinting technologies. The adapter's design underscores a strategic response to these challenges, leveraging synergistic interactions among its constituent components. Mechanical components are optimized for precise movement and positioning, ensuring accurate deposition of biomedia. Electronic elements are integrated to enable real-time feedback and control, enhancing process reliability and repeatability. Additionally, thermal management features facilitate optimal temperature control during the printing process, critical for maintaining biomedia stability and supporting proper gelation. This integrative approach not only addresses technical hurdles but also underscores a broader commitment to advancing accessible and efficient solutions in biomedical engineering. By fostering interdisciplinary collaboration and technological innovation, this work paves the way for transformative advancements in tissue engineering and regenerative medicine, ultimately contributing to improved patient care and biomedical research outcomes.

Success/Failure Operational Range:

In the realm of bioprinting technology, success and failure operational ranges encompass critical aspects across functional areas and their respective subdomains. Successful printing operations entail consistent and precise media printing, underpinned by robust quality control measures to mitigate misalignment or instability caused by defects in printed parts. Bioprinting success hinges on the adaptation of 3D printing for tissue engineering, navigating the challenges of biochemical specificity to achieve viable biomedia properties conducive to cellular proliferation. Conversely, failure in bioprinting can arise from chemical incompatibility or inadequate biomedia properties, leading to compromised cell viability and suboptimal tissue engineering outcomes. The reliability of parts printing lies within its success range, providing reliable heat insulation and durable printed components that withstand wear and tear. However, failure modes may necessitate replacement of printed parts due to extended use, typically occurring every 200 cycles. Chemical functional success is characterized by the creation of viable biomedia compatible with cellular proliferation, while failure may manifest as incomplete crosslinking or contamination hindering cell growth and function.

In the electrical domain, success is achieved through smooth integration and precise execution of commands, with failure modes stemming from wiring defects or software glitches that impede device function. Facilitation success entails error-free coding and secure component connections, contrasted with failure modes like syntax errors or logic flaws affecting microcontroller performance. Sensing success is defined by accurate data transmission and reliable sensing feedback, contrasting with failure modes such as data transmission inconsistencies or sensor malfunctions. Actuation success involves controlled movement of components and optimized motor performance, while interface issues with the microcontroller or component failures can lead to failure modes impacting actuation functionality.

Extrusion success, particularly in curing, requires proper biomedia solidification and optimal mechanical properties, essential for tissue engineering applications. Failure in curing may result from inadequate solidification, leading to non-viable biomedia. In transportation, success is characterized by precise biomedia deposition without interference with chemical properties. Failure modes in transportation may include syringe malfunction, misalignment, or chemical interference impacting biomedia extrusion. Through careful assessment and mitigation of failure modes, operational ranges are optimized to enhance device performance and reliability in tissue engineering endeavors.

Technological Integration and System Performance:
The utilization of UV LED modules operating at a 395 nm wavelength for polymerization represents a key innovation in ensuring efficient crosslinking and uniform solidification of biomedia. This aspect is crucial for maintaining the structural integrity and functionality of printed biological materials. The incorporation of flexible polyimide heater plate modules and a precision-driven linear actuator enhances the system's capabilities significantly. These components allow for controlled extrusion of biomedia and provide optimal thermal regulation essential for precise gelation actuation. The flexibility and precision offered by these modules contribute to the overall reliability and effectiveness of the bioprinting process. In addition, the selection of polypropylene syringes and the Ender 3 V2 3D printer is pivotal for ensuring system compatibility and performance. Polypropylene syringes offer chemical resistance and thermal durability, making them suitable for handling various biomedia without compromising integrity. The Ender 3 V2 3D printer, known for its affordability and precision, strikes a critical balance necessary for achieving the fine detail and accuracy required in bioprinting applications.

Control Systems and Monitoring:

The integration of the Raspberry Pi 4 Model B and temperature sensors within our bioprint head adapter plays a pivotal role in augmenting control systems and monitoring capabilities. Leveraging the robust processing power of the Raspberry Pi 4 Model B, this component serves as the central command hub, orchestrating and coordinating the precise movements and operations required for the bioprinting process. Simultaneously, the DS18B20 temperature sensors contribute by providing accurate, real-time temperature data. This data is instrumental in ensuring optimal environmental conditions are maintained throughout the printing process. By continuously monitoring and regulating temperatures, the system can guarantee the integrity and quality of the bioprinted materials, essential for achieving consistent and reproducible results. Together, the Raspberry Pi 4 Model B and DS18B20 temperature sensors synergistically enhance the functionality of our bioprint head adapter, embodying our commitment to advancing control and monitoring capabilities in bioprinting technology.

Mechanical and Electrical Design:

The mechanical integrity of our system is reinforced by the incorporation of thrust and deep groove ball bearings, ensuring smooth operation even under diverse load conditions. This emphasis on mechanical robustness underscores the reliability and durability of our bioprint head adapter, essential for consistent performance and longevity. In parallel, the electrical design of our system showcases an efficient management of high-current loads and protection against voltage spikes, crucial for ensuring safety and sustained functionality. This design features A4988 stepper motor driver modules, IRL540NPBF MOSFETs, and flyback diodes, collectively optimizing the control and handling of electrical components within the bioprint head adapter. The design process included rigorous SolidWorks mechanical analysis and iterative design improvements aimed at enhancing mechanical stability. Through detailed simulations and design iterations, we fine-tuned the mechanical aspects of the adapter to minimize stress concentrations, optimize load-bearing capabilities, and ensure overall structural integrity. This iterative approach not only validated our design choices but also contributed significantly to the enhanced performance and reliability of the final product.

Standard Compliance and Reproducibility:

Adhering to IEEE standards, this work demonstrates not only technological sophistication but also a commitment to scientific rigor and reproducibility. When designing the device, the following standards were considered:

- UL60950-1 (Electrical safety for power supplies)
- IEC 60335-1 (Safety considerations for small appliances such as the UV lights in our design)
- ISO 9001 (Quality of performance for basic stepper motors)
- ISO 8537 (Sterilization standards for syringes in any application)

These standards were thoroughly documented for their direct applicability and impact on the device. They address critical aspects of device performance and safety, particularly focusing on the use of small appliances and the performance criteria for essential components employed in the device.
Ensuring the device's reproducibility was a pivotal consideration from the design process's outset. The primary objective of this device is to advance the accessibility of bioprinting technology. Through meticulous component selection, continuous optimization of design for the printed parts, and leveraging the capabilities of the Ender 3 V2, the team successfully achieved this objective. This involved significantly reducing costs compared to existing market bioprinters, which typically start at $5000 on the lower end. The total cost for our design, inclusive of all components including those to be retrofitted, was slightly over $600. This substantial cost reduction opens new opportunities for broader adoption and innovation in the field of bioprinting.

Ethical Considerations:

The ethical considerations associated with the novel bioprinter project are rooted in principles of equity, collaboration, education, and environmental responsibility. The team's commitment to open-source development aims to foster universal access to advanced biomedical fabrication technologies, ensuring that the benefits of biofabrication are not limited to well-funded laboratories but are available to universities worldwide, especially in resource-constrained regions. By openly sharing designs, protocols, and systems, the team promotes global collaboration and knowledge sharing, facilitating international cooperation in scientific research and education. This approach not only empowers diverse educational communities by providing opportunities for hands-on learning and skill development but also supports ethical research practices grounded in inclusivity and cooperation. Additionally, integrating principles of environmental consciousness into the bioprinter design reflects the team's commitment to sustainable practices within the biomedical field, minimizing waste and considering the environmental impacts of the technology. The team's focus on scalability and customization enables communities to adapt biofabrication technology to address local health challenges and research priorities. This ensures that the technology is not only accessible but also responsive to diverse cultural and socioeconomic landscapes. In summary, the team's ethical stance emphasizes the democratization of technology, global collaboration, educational empowerment, environmental responsibility, and adaptation to local needs. Through these principles, the team strives to promote equitable distribution of knowledge and technology, uphold ethical research practices, and contribute to the improvement of global health and well-being.

Future Implications and Applications:

The innovative bioprint head adapter presented in this work not only showcases the seamless integration of diverse engineering disciplines but also heralds new possibilities in biomedical applications, particularly within the realms of tissue engineering and regenerative medicine. Its capacity to manage multiple components with precision and efficiency positions it as a potential game-changer in the field, paving the way for advanced bioprinting technologies. This adaptable adapter opens doors to a myriad of biomedical applications, offering enhanced capabilities for fabricating complex tissue structures and biomaterials with unparalleled accuracy. By combining mechanical, electrical, and thermal elements in a cohesive design, the adapter demonstrates versatility and reliability crucial for addressing the intricate demands of biomedical engineering. Looking ahead, future iterations of this device will focus on continuous improvement and innovation. Plans include refining and overhauling the temperature regulation system to achieve even greater control over the bioprinting environment. Additionally, efforts will be directed towards optimizing wire management to enhance system aesthetics and reliability.

Future Improvements:

The temperature regulation system implemented in our current design proved effective; however, future iterations could leverage smarter heating pads to eliminate the need for additional temperature sensors, thereby achieving a more streamlined and controllable heating mechanism. By integrating advanced heating pads with built-in temperature control capabilities, we can simplify the system architecture and enhance precision in maintaining optimal printing conditions. Another area for improvement is the wire management system within the device. Acknowledging the current sub-standard wire management, our redesign efforts will focus on enhancing accessibility and organization of wires, particularly within the barrel system. Implementing a redesigned barrel system will allow for better wire routing and management, ensuring improved reliability and ease of maintenance. One of the most impactful future iterations of our bioprint head adapter will involve the integration of biochemicals into the bioprinting process. This evolution represents the true foundation for
validatable tissue engineering applications, enabling the fabrication of functional tissues with tailored properties and functionalities. The biochemicals referenced earlier in the report, following established procedures for biomedia formulation, can be seamlessly integrated into our current design standards. By embracing these future enhancements; smarter heating pads, improved wire management, and the incorporation of biochemicals we aim to propel the capabilities of our bioprint head adapter to new heights.

Final Remarks:

The design and assembly of our custom bioprint head adapter, representing a culmination of scientific rigor, medical foresight, and engineering expertise, marks a significant milestone in the realm of biomedical engineering. Each component and part of this adapter has been carefully selected, with PLA filament chosen for its ease of printing and ability to achieve fine resolution, enabling precise and intricate fabrication. This ensemble of meticulously integrated components is poised to revolutionize bioprinting technology, particularly with its capability for multicomponent printing and NICE (Nanofiber Integrated Cellular Environment) crosslinking. By harnessing these advanced capabilities, our bioprint head adapter opens new avenues in tissue engineering and regenerative medicine, offering unprecedented opportunities for creating complex, functional biological constructs. Moreover, beyond its technical prowess, this bioprint head adapter embodies the spirit of innovation and collaboration. It serves as a testament to the collaborative efforts of scientists, engineers, and medical professionals dedicated to advancing the frontiers of biomedical research and application. In conclusion, the development of this custom bioprint head adapter not only represents a convergence of cutting-edge engineering and scientific principles but also symbolizes the potential for transformative impact in the field of biomedical engineering. With its deployment, we anticipate a paradigm shift in how bioprinting technologies are leveraged to address healthcare challenges and propel advancements in tissue engineering towards a future of enhanced regenerative therapies and personalized medicine.
REFERENCES


**Reference List Supporting Final Design**


OPERATOR'S MANUAL

AFFORDABLE BIOPRINT HEAD

TEAM 22
Andrew Ceralde, Dominic Drake, Noah Engles, Mohammad Alwan, Nevada Perry
Faculty Advisor: Dr. Alisha Diggs
IMPORTANT SAFETY INSTRUCTIONS

• Ensure the printer is unplugged from the outlet or any power sources prior to making any adjustments
• Leave printer unplugged when not in use
• Do not touch the printer while it is in operation. Doing so can lead to accidental shock.
• Do not fill the syringes beyond 5 mL of bio media
• Do not stare at the UV (ultraviolet) lights when on
PARTS AND ACCESSORIES

A full picture of the device is below
<table>
<thead>
<tr>
<th>Number</th>
<th>Identifiable feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Linear actuator</td>
</tr>
<tr>
<td>2</td>
<td>Timing belt</td>
</tr>
<tr>
<td>3</td>
<td>Syringe</td>
</tr>
<tr>
<td>4</td>
<td>Rotating barrel</td>
</tr>
<tr>
<td>5</td>
<td>Ultraviolet light housing*</td>
</tr>
<tr>
<td>6</td>
<td>Wires to heat pad</td>
</tr>
</tbody>
</table>

* The Ultraviolet lights are not present in this angle
FEATURES

What makes this product different from industry-standard bio printers?

- The printer modifies a pre-existing 3D printer, eliminating the complexity of other bio printers
- The extrusion mechanism can extrude multiple bio medias in one print
1. INTRODUCTION

1.1 General Overview

The affordable bio print head is the next advancement in biomedical research.

The first feature you will come across is the top shelf housing unit. This is screwed onto the top of the 3D printer.

Figure 1.1.1, Top shelf housing unit
The entire printer is connected to a Raspberry Pi. Using external code, the Raspberry Pi takes a series of inputs and uses it to determine when to rotate the barrel, as well as turning on and off the motors and UV lights.

This is how the entire printer operates.

Figure 1.1.2: Raspberry Pi

Attached to it are two different things. The first of which is a breadboard. On the breadboard is a series of MOSFETs that contribute to the power of the SYRINGE EXTRUSION SYSTEM and UV lights.
The second attachment to the breadboard is the motor controllers. This controls the state and direction of the motors from an input given by the Raspberry Pi.
One of the centerpieces of this printer is the rotating barrel. The rotating barrel has the following functions:

- Positioning of syringes to align with extrusion
- Storage of syringes
- Storage of heat pads
- Storage of UV lights

![Rotating barrel](image)

Figure 1.1.5: Rotating barrel (empty)

Housed inside the rotating barrel is the stepper motor. This is responsible for the rotation on the rotating barrel. From its initial position, it can go up to 135º both clockwise and counterclockwise. Keep this in mind when coding.

![Stepper motor](image)
Inside the rotating barrel, there are 12V 12W heating pads attached. The heating pads function to heat up the bio ink inside the syringe to its proper temperature range. If the temperature is too high, the heat pads will turn off to allow the bio ink to cool down.

The temperature of the bio ink is monitored via the W1209 temperature sensors. The temperature sensors measure the temperature of the bio ink before extrusion. If the temperature goes over, as created by the heat pads, the heat pads will shut off to prevent overheating of bio ink.
After being extruded from the syringes, the bio ink is then cured through the UV lights. They are positioned at an angle to maximize their effectiveness. WARNING: DO NOT STARE AT THE UV LIGHTS WHEN ON. IT CAN CAUSE SERIOUS AND PERMANENT EYE DAMAGE.
Figure 1.1.9: UV lights off

Figure 1.1.10: UV lights on (be sure not to stare)

The bio ink is extruded through the linear actuator. The linear actuator is controlled by the Raspberry Pi and goes up or down depending on the signal outputted by the Raspberry Pi.

Figure 1.1.11: Linear actuator

The linear actuator extrudes the bio media from the syringes.
The final piece is the stopper. It is simply a small rectangular piece that fits adjacent to the bottom switch of the 3D printer. It serves to keep the rotating barrel from going too far down.
1.2 Step-by-Step Assembly

Mounting Instructions:

1. Begin by taking the mount and inserting the motor into the designated slide. Ensure that the motor is securely attached with a timing belt. Refer to the image of the slide for guidance on proper alignment and positioning.
Figure 1.2.1: Proper alignment of motor

2. Next, take the barrel and slide the arm of the mount through the top opening of the barrel. As you do this, guide the belt along the pulley atop the barrel assembly along with the slide arm. It should look like this:

Figure 1.2.2: Alignment of barrel and timing belt setup

3. Now, take the lock component and secure it to the bottom of the mounting arm. Twist the lock into place and then insert the long screw to ensure a firm connection. Refer to the image of the lock for visual assistance.
4. With the combined assembly ready, align the holes on the mounting plate attached to the mount with the corresponding holes on the plate of the Ender 3 V2 printer. Use the images of the holes on the Ender 3 V2 for accurate alignment.

5. Install the heating pad into its designated slot. Locate the slot next to the heater and carefully insert the heating pad, ensuring it fits snugly.

6. Using winged screws, attach the mounting plate to the top rail of the Ender 3 V2 printer. Secure the plate firmly in place to support the entire assembly.
7. Mount the thermal sensor onto the mounting plate and position the probe near the heating pad, ensuring it is close but not directly touching the pad to avoid interference.
8. Attach the linear actuator to the top of the mount through the designated screw hole. Verify that the actuator is installed straight and securely.
9. Proceed to mount the UV lights onto the bottom of the barrel using small screws. Follow the image of the mounted UV lights for reference on placement and orientation.

10. Prepare the syringes by manually loading biomedia into each one. Once loaded, mount the syringes onto the barrel assembly.
11. Electrically connect all components according to the provided connection diagrams. Ensure each connection is secure and properly insulated.
12. Connect the Raspberry Pi to the system, establishing the necessary data and control interface.
13. Before running a full test, perform a short test run (less than 30 seconds) to verify the individual operation of each component.
14. Finally, conduct a full test run to ensure that the entire bioprinter assembly functions correctly and efficiently. Make any necessary adjustments or fine-tuning based on the test results for optimal performance.

1.3 Loading bio media into the syringe

Ensure the printer is off and disconnected from any power sources before set-up.
• Loading the bio media into the syringe
  o Pull out the syringe from the rotating barrel. This may take a little bit of force.
  o Ensure the syringe is clean and dry before use
  o Ensure the plunger of the syringe is pushed all the way down
  o With the tip of the syringe dipped into the bio media, pull the plunger of the syringe. Do not load any of the syringes with greater than 5 mL of bio media
  o Insert the loaded syringe back into the rotating barrel. This may take a little bit of force

1.4 Device Activation

• Turning the device on
  o Plug in the device
  o Turn the device on with the switch on the back
  o Turn on the Raspberry Pi with its included power switch

• Uploading code to the Raspberry Pi
  o The Raspberry Pi includes four standard USB ports, two USB-C ports, and one HDMI-to-USB-C adapter.
    1. Plug in a USB mouse, USB keyboard, and HDMI monitor or TV.
    2. Additionally, plug in the Raspberry Pi to the microUSB port on the front-left of the Ender 3 V2 with the included microUSB cable.
  o The Pi should boot to the Raspberry Pi OS desktop screen. The default username is rpi and the default password is rpi, though it should log in automatically without prompting.
  o In the top-right corner, the control center has options for networking and other settings. Connect to a wi-fi network.
  o If the wi-fi network restricts direct (LAN) communication between wi-fi devices (e.g. on university wi-fi), utilize Tailscale (pre-installed) to open a tunnel so the Raspberry Pi can be remotely accessed from another PC/laptop.
    1. Using the built-in terminal app (black monitor icon on the top-left), use the command tailscale login to log in to an existing Tailscale account. You will need to register an account at https://tailscale.com/ and download the Tailscale app onto the other PC/laptop.
    2. Tailscale should run at startup automatically. Its status can be viewed with the command sudo systemctl status tailscale, and restarted with sudo systemctl restart tailscale if needed.
  o Once Tailscale is set up (if needed), the Raspberry Pi can be managed remotely through two interfaces.
    1. On another PC/laptop logged in to the same Tailscale account, http://raspberrypi/ should open the Mainsail web interface for controlling the Ender 3 V2 and initiating prints. If Tailscale is not needed, the Raspberry Pi should be accessible by its LAN IP address e.g. http://192.168.1.33/ (replace 192.168.1.33 with the real IP address found on the router/network’s admin page).
    2. The Raspberry Pi also supports SSH for remote terminal access. This will require configuring SSH on the Raspberry Pi directly using a mouse, keyboard, and monitor. A guide is available at https://www.onlogic.com/company/io-hub/how-to-ssh-into-raspberry-pi/. Once configured, the command to SSH in from the remote PC/laptop should be ssh rpi@raspberrypi or ssh rpi@192.168.1.33 (replace 192.168.1.33 with the
real IP address found on the router/network’s admin page), depending on whether Tailscale is set up respectively.

- The app that controls the bioprint hardware is named Bioprintly. It should run automatically at startup, and have a launcher icon in the top-left. Bioprintly communicates with Klipper, another Raspberry Pi service that runs in the background and controls the Ender 3 V2. Together, they coordinate bioprinting from start to finish.
- G-code can be uploaded and printed through the Mainsail interface at http://raspberrypi/ or http://192.168.1.33/ (replace 192.168.1.33 with the real IP address found on the router/network’s admin page).

1.5 W1209 Temperature sensor setup

1. Read all instructions before setup
2. Use the 2 middle ports to supply 12V and connect the 2 edge ports to ground. Connect to the power supply
3. Turn on the power supply
4. Hold the “set” button for 2-3 seconds
5. “P0” should pop up on the 7-segment display. While it is on that state, push the “set” button to change the setting from C (cooler) to H (heater)
6. Repeat step 4
7. While on “P0”, press the “+” button to get to “P1”
8. Press the “set” button. The number set here is the maximum difference between the desired temperature
9. Press “set” and set the temperature sensor at the desired value
10. Disconnect from the power supply
11. Use the “+12V” and “GND” wire connections to supply 12V and ground, respectively
12. Connect K0 to ground and K1 to the respective output

2. MAINTENANCE

2.1 Importance of Maintenance

Proper care must be taken to ensure quality and longevity of the device. This section describes the maintenance and care that must be taken to prevent premature failure

Before each use:

1. Plug the device in
2. Turn the power switch on
3. Check the voltages throughout the breadboard (read below for instructions)

2.2 Checking voltages
Breadboards:

A breadboard has the same voltage outputs along its width. This feature is utilized to check the power and voltages.

Checking voltages:

Required materials:

- Jumper cables
- Digital multimeter (pictured below)
- Alligator clips (pictured below)

Figure 2.1: A digital multimeter
Procedure:

1. Insert one end of the jumper in parallel with the breadboard at the measurement point
2. Insert the red alligator clip into the DMM at the voltage input insert (top right)
3. Insert the black alligator clip into the DMM at the ground input insert (right middle)
4. Connect the red alligator clip to the other end of the jumper from step 1
5. Connect the black alligator clip to the ground (the long “-” strip along the length of the breadboard)
   Another jumper can be used if necessary
6. Read the value. If the device is on, it should read around 12V
7. If you do not get a 12V reading, refer to troubleshooting

2.3 Adjusting Temperature Sensors

As many different bio medias are applicable with this device, it is important to be able to adjust the temperature sensors to accommodate them. Refer to section 1.5 on how to adjust the temperature sensors to ensure the quality and viscosity of bio media
2.4 Post Usage

After each use:

- Turn off the device
- Unplug the device. Allowing the device to cool down between prints without being used will improve the overall lifetime of the product
- Wait for the hotbed to cool down
- After the hotbed is completely cooled, clean the hotbed with a hot, damp towel
- Remove, clean, and disinfect the syringes using soap and water

Every 6 months:

- Check the rotating stand
  - Unscrew the rotating barrel from the stand.
  - Inspect the components of the device for damage/wear and tear
  - Do not operate the device if any of the components are damaged
  - Refer to the assembly instructions if necessary for reassembly

3. TECHNICAL DESCRIPTION

3.1 Final Circuit Layout
From a technical aspect, the printer syncs with many different electronic components.

When powered on, the components throughout the device receive 12 volts. Everything works in tandem, so a further breakdown is necessary.

The Raspberry Pi is the centerpiece of the printer. Everything is controlled by the Raspberry Pi. After code is uploaded into the Raspberry Pi, it controls all the voltages, which in essence decides when the heating pads heat up, when the linear actuator move up or down, and serves as a control center to the entire device.

On the top left side of the final circuit is a 12 volt, 12 watt polyimide heating pad connected to an ILR540N MOSFET. The MOSFET, or metal oxide semiconductor field effect transistor acts as a diode, allowing current to flow in just one direction (in this diagram, from right to left). Each heating pad is connected to the
Raspberry Pi. With the default settings, it is coded so that if the temperature of the bio media inside is less than 27.5°C, it will heat up the bio media until the temperature goes to 28°C. After these values are sensed by the temperature sensor, the heat pads will turn off, until the temperature is less than 27.5°C. This repeats throughout the whole print cycle. If it is necessary to adjust the minimum and maximum temperature values, refer to 1.2 maintenance on how to do that. Just be sure to account for overshoot in temperature, as the heat pads heat up very quickly.

The Raspberry Pi is connected to a stepper motor, which rotates counterclockwise or counterclockwise depending on the command from the Raspberry Pi itself, as well as the linear actuator, which moves up and down on its command. This is the extrusion mechanism for the bio media.

Post extrusion, there are UV lights connected on an angle of about 45° to the syringes, where the bio ink is extruded. These cure the bio media. Without these, the bio media will splatter everywhere after being extruded.

Power will be transferred to the device via a power supply. It has three channels.

Channel 1 goes up to 5V.
Channel 2 goes up to 30V
Channel 3 supplies negative voltage and goes up to –30V.

For the purposes of this exact device, channel 2 will be used and set to 12V.
Voltages tend to fluctuate slightly. A voltage regulator will be used to keep the voltage at 12V without the value constantly changing. Setting it up is very easy. Just connect the input to power and the output to a multimeter and adjust the potentiometer to the desired value.
Bioprintly controls the extrusion hardware as a set of preset pin names. These can be mapped to any valid GPIO pin on the Raspberry Pi and configured as inputs or outputs. Commands issued through this pane are entered into Bioprintly’s command queue to be processed by the Bioprintly background service.
Command processing occurs in first-in, first-out order. Visually, newly entered commands are added to the bottom of the command queue display. When processing is enabled, each command at the top of the queue display will be processed, then moved over to the top of the command history display and given a final timestamp.

When Bioprintly is first opened, an alignment must be completed before processing can be enabled.
Per the instructions given, the operator must visually line up the barrel syringe marked #1 with the actuator on the printhead. This gives Bioprintly a reference point from which the remainder of rotation and other commands can be done automatically.
Once manual alignment is completed, the operator can enable processing with the enable processing checkbox (not shown; behind the confirmation popup). With processing enabled, printing can proceed without interruption from the Klipper web UI pre-installed, named Mainsail.
Figure 3.2.5: Mainsail is bookmarked in the system’s default web browser under “Mainsail”. Controls are available for standard 3D printer functionalities, including homing, movement, G-code monitoring, and visualization. Extrusion controls will have no effect, as they are managed by Bioprintly.

Printing can be initiated either directly from Mainsail on the Raspberry Pi itself, or from the Mainsail web UI accessed from another device, through a Tailscale tunnel if required. Instructions for setting up networking and Tailscale can be found under section 1.4 of this guide, Device Activation. The procedure for printing is to upload a G-code file taken from 3D printing slicing software into the G-code files section of Mainsail. From there, clicking on a file should bring up a confirmation prompt (pictured below). Click “PRINT” and the print should start immediately.
With support for up to four syringes, the bioprint head supports G-code files created from up to four separate 3D models sliced at the same time. The recommended slicing software is OrcaSlicer by SoftFever, which is known to work with Bioprintly.

During the print, Klipper will communicate with Bioprintly in a synchronous manner to complete tool changes, heating, light control, and extrusion. For this reason, it is imperative that the operator NOT perform manual interactions with Bioprintly until the print is complete or paused.

These communications are performed through the use of G-code macros, a Klipper feature to intercept G-codes and process them in a manner tailored for bioprinting custom hardware.
4. TROUBLESHOOTING

Experiencing difficulties? Refer here

4.1 General troubleshooting

- Electrical and Mechanical Troubleshooting:
  - Check the following in this order:
    1. Double check that everything is assembled correctly (refer to the maintenance section for help)
    2. Check the voltages on the breadboard when powered on (refer to the maintenance section for help)
    3. Ensure all equipment is in working condition. If any equipment is not operable, refer to the replacement parts section (below) to obtain replacement parts

4.2 Replacement parts

- Replacement parts
  - Contact the manufacturer for replacement parts. Attempting to fix faulty equipment by hand can lead to serious injury and premature failure of the device.
  - Common equipment breaks/faults that would require replacement parts
    1. Ensure everything is secured prior to printing. Loose wires, short circuits, and improper setup will damage the device
    2. Polyimide heating pads burn out from being on too long. If on too long, it will also smell like it, and it is a good indication to replace it.
    3. Rotating barrel can melt from heat of heating pads. Look out for holes or indications of deflection.
    4. If exposed to too much heat at once, the plastic to a syringe can start to melt, losing its function.
    5. Improper setup of wires/resistors can cause a short and can lead to electrical hazards. Always be ready to turn the device off at any given moment.
    6. Ensure the bio media is within the required temperature range. If the same bio media is used amongst all four syringes, ensure the temperature sensors are set up the same way. Improper care of bio media will result in product failure.
    7. Ensure everything is dry prior to usage. Any wet areas can cause permanent damage to the circuitry or the various components. Involved
    8. Do not add any additional weight to the device aside from the bio ink inside the syringes. Excessive weight can cause stress and deformation, which affects the product’s performance
    9. Do not fill the syringes beyond 5mL of bio media. Doing so prevents the syringes from fitting into the rotating barrel

4.3 Troubleshooting Raspberry Pi

- Troubleshooting Raspberry Pi functionality:
  - General:
1. Klipper (administrated through the Mainsail interface) oversees printing and controls the Ender 3 V2 directly. It has registered G-code macros that enqueue commands with Bioprintly for syringe changes, heat/UV changes, and extrusion changes.
2. Bioprintly controls the bioprint hardware by accepting commands coming from Klipper/Mainsail into a “command queue”, and executing them one at a time. This process can be viewed using the Bioprintly GUI, which should run at startup. It can be started and stopped with its icon on the top-left of the Raspberry Pi desktop.

- Raspberry Pi Not Booting:
  1. Ensure the power supply is securely connected and providing adequate power. Check for any loose connections.
  2. Verify the microSD card containing the Raspberry Pi OS is inserted correctly. Try reseating the card if necessary.
  3. If the green LED indicator on the Raspberry Pi remains solid or fails to blink, it may indicate a hardware issue. Contact technical support for further assistance.

- Unable to Connect to Wi-Fi:
  1. Double-check the Wi-Fi network credentials to ensure they are entered correctly. Pay close attention to uppercase and lowercase characters.
  2. Test the Wi-Fi network with another device to confirm its functionality.
  3. Restart the Raspberry Pi and attempt to reconnect to the Wi-Fi network.
  4. If utilizing Tailscale for remote access, ensure it is running and properly configured to connect to the internet.

- Issues with Tailscale:
  1. Check the status of the Tailscale service by running `sudo systemctl status tailscale` in the terminal.
  2. Verify that the configuration settings for Tailscale are accurate and that the Raspberry Pi has internet connectivity.
  3. Install any available updates for Tailscale to ensure compatibility and stability.

- Mainsail Interface Not Accessible:
  1. Confirm that both the Raspberry Pi and the accessing device are connected to the same network.
  2. Check the status of the Mainsail interface through its web interface or by accessing it via SSH.
  3. Review network firewall settings and ensure there are no restrictions preventing access to the Raspberry Pi.
  4. If using Tailscale, ensure that the accessing device is logged in to the same Tailscale account to facilitate remote access.

- Bioprintly GUI Not Launching:
  1. Check the Raspberry Pi OS configuration to ensure that Bioprintly is set to run at startup.
  2. Examine system logs for any errors that may be preventing Bioprintly from launching properly.
  3. Attempt to manually launch Bioprintly from the terminal using the appropriate command.

- Issues with G-code Execution:
  1. Validate the formatting and compatibility of G-code files with the printer.
  2. Monitor the Mainsail interface or terminal output for any errors encountered during G-code execution.
  3. Ensure that the printer hardware is correctly configured and operational.

- SSH Access Not Working:
  1. Review the SSH configuration settings on the Raspberry Pi to ensure they are configured correctly.
  2. Verify that SSH is enabled in the Raspberry Pi OS settings.
3. Check network firewall settings to ensure that SSH traffic is not being blocked.
4. If using Tailscale, ensure that SSH access is permitted through Tailscale settings and that the accessing device is connected to the same Tailscale network.

4.4 Troubleshooting Rotary System:

a. Problem Statement:
   o When using a multi-material bioprinter, precise control over the rotation of the syringe barrel is crucial. The bioprinter utilizes a slicer to generate G-code that instructs the stepper motor to switch between different syringes (e.g., from syringe one to syringe two, etc.). Each switch requires an exact angular rotation corresponding to a specific number of steps by the stepper motor. Misalignment can occur due to inaccuracies in these steps, leading to the linear actuator failing to properly engage with the syringe plunger through the pre-designed opening atop the barrel. This misalignment impedes the extrusion process and may accumulate over multiple switches, exacerbating angular errors.

b. Troubleshooting Steps:
   1. Understand the Stepper Motor Mechanics: Familiarize yourself with the operational mechanics of the stepper motor that drives the rotary barrel's motion. Recognize that the motor converts sequences of electrical pulses into discrete angular movements.
   2. Examine Script and Step Counts: Using a Raspberry Pi, review the script that controls the stepper motor. Record the number of steps taken by the motor for each syringe switch from the rotary system's origin point to each subsequent syringe position.
   3. Determine Gear Ratios: Calculate the gear ratio by noting the number of teeth on the pulley of the stepper motor and the gear rotating the barrel. This will help you understand the theoretical angular displacement per step and match it to the required angular positions for syringe alignment.
   4. Experimental Verification: Set up a mounted camera to visually record the barrel's position before and after each commanded rotation. This visual record will serve as evidence of the actual angular change.
   5. Comparison of Actual vs. Theoretical Angles: Compare the experimental angular changes (as captured by the camera) to the theoretical expectations (as calculated from the stepper steps and gear ratio). Look for any deviations that might indicate errors in step counts or mechanical slippage.
   6. Adjust and Recalibrate: Adjust the number of steps in the script based on the discrepancies noted between the experimental and theoretical angular changes. This might involve increasing or decreasing the step count to achieve the desired alignment.
   7. Iterative Testing: Re-run the adjusted script to test the new settings. Continue adjusting and testing until the syringe alignment is consistent and accurate, ensuring reliable extrusion.
   8. Documentation for Reproducibility: Document the final settings, the process used for calibration, and any observations made during testing. This documentation will help maintain the bioprinter's accuracy and assist in troubleshooting future issues.

4.5 Troubleshooting Extrusion Rates for Optimized Print Fidelity:

a. Problem Statement:
   o Accurate control of extrusion rates is essential in multi-material bioprinting to ensure high print fidelity. Inappropriate extrusion rates can result from imprecise steps of the linear actuator stepper motor, leading to issues such as pooling of media, oversized bead widths relative to the
nozzle, clogging, and inconsistent bead lines. These issues compromise the structural integrity and the aesthetic of the printed object.

b. Troubleshooting Steps:
   1. Establish a Baseline Extrusion Rate: Conduct a preliminary test to establish a baseline by setting the stepper motor to perform a predetermined number of steps (e.g., 2000 steps in 10 seconds). Position a beaker beneath the syringe and extrude a known medium like water to measure the extruded volume. Weigh the extruded water on a precision scale, and convert the mass to volume, leveraging the known density of water at room temperature (approximately 1 g/cm³).
   2. Record Baseline Data: Document the volume extruded and the corresponding stepper motor steps. This initial data is crucial for comparing and adjusting extrusion rates.
   3. Adjust Stepper Motor Settings:
      i. For Pooling or Over-Extrusion: Reduce the number of steps per unit time in the script, decreasing the extrusion rate. This adjustment aims to align the extruded bead width with the nozzle diameter and prevent excess material deposition.
      ii. For Clogging or Under-Extrusion: Increase the number of steps per unit time. This helps to ensure a smoother and more continuous flow, addressing issues like skipped beads or incomplete lines.
   4. Experimental Calibration: After adjusting the script based on the identified issues, rerun the same test under controlled conditions to validate the changes. Measure the new volume of extruded medium to ensure it aligns with the desired extrusion rate.
   5. Validate with a Calibration Print: Print a standard calibration model to evaluate the practical effects of the adjustments.
   6. Observe the extrusion quality:
      i. Ensure there are no breaks or skips in the bead.
      ii. Verify that the width of the extruded bead matches the nozzle diameter.
   7. Iterative Testing and Adjustment: If discrepancies persist, continue to refine the step adjustments, repeating the testing and validation steps. This iterative process ensures precise control over the extrusion process, critical for achieving desired print outcomes.
   8. Documentation for Reproducibility: Document all successful settings, procedures, and outcomes from the tests. This documentation should be detailed to ensure that the process can be replicated and results are consistent across different runs and setups.

4.6 Troubleshooting Thermal Regulation System:

   a. Problem Statement
      o In bioprinting setups, maintaining an accurate temperature is critical for ensuring the viability and consistency of printed biological materials. A common problem encountered involves the thermal regulation system either overheating or underheating relative to the set parameters on the control module. This discrepancy can arise from inaccuracies in the digital thermometer readings, improper settings on the thermal control module, or issues with the physical heating components.
   b. Troubleshooting Steps
      1. Setup and Initial Testing:
         i. Prepare the System: Configure the bioprinting setup for a normal operation, initiating the preheating process to reach the typical operational temperature.
ii. Install a Physical Thermometer: Place a calibrated physical thermometer close to the heating element within the fluid media to verify the temperature readings provided by the digital thermometer of the W1209 module.

2. Familiarization with the W1209 Module [1]:
   i. Consult the Manual: Thoroughly review the user manual for the W1209 thermal control module to understand its various settings, including temperature adjustment, switching between heating and refrigeration modes, and other configurable parameters.

3. Calibration and Adjustment Procedures:
   i. Adjust Temperature Settings: Use the module's interface to modify the target temperature settings by either raising or lowering them based on initial observations.
   ii. Modify Hysteresis Settings: Fine-tune the hysteresis setting to compensate for any lag between the sensor readings and the actual temperature. This is particularly useful if the sensor persistently reads temperatures that deviate from actual values, such as being consistently cooler by a measurable degree.
   iii. Implement Temperature Correction: Activate the temperature correction feature to align the digital sensor readings more closely with those observed on the physical thermometer.

4. Voltage Divider Configuration:
   i. Examine the Circuit Configuration: Understand the function of the voltage divider in the system, which affects the voltage supplied to the heating element and therefore its heat output.
   ii. Adjust the Voltage Divider: If necessary, recalibrate the voltage divider to alter the voltage input to the heating pad, controlling its maximum operational temperature.

5. Iterative Testing and Measurement:
   i. Conduct Iterative Adjustments: After each adjustment, allow the system to stabilize, then measure and record the temperature as indicated by both the digital and physical thermometers.
   ii. Continuous Comparison and Adjustment: Keep refining the settings on the W1209 module until the digital readings accurately reflect the physical thermometer’s measurements.

6. Documentation and Standardization:

7. Record Final Settings: Document the settings that yielded accurate and consistent temperature control, noting any changes made to hysteresis and voltage settings.

8. Develop Standard Operating Procedures (SOPs): Establish detailed SOPs for the setup and calibration of the thermal regulation system for all future operations to ensure reproducibility and reliability in bioprinting processes.
References


Andrew’s Contributions

Andrew certainly had a heavy hand in writing a large sum of this report, writing parts of chapters 2.2 and 2.3. His next contributions come in chapter 3, having done the tables shown throughout the chapter and helping the entire design team write the whole chapter. He also wrote chapters 4.5, 4.7, and 4.8 in chapter 4. In chapter 5, he wrote 5.4 and helped on the overall effort in chapter 6.

His next major comes in the operator’s manual, writing nearly half of it. He wrote all of chapter 1, with the exceptions coding and assembly instructions, all of chapter 2, The first part of chapter 3, and the first half of chapter 4.

In terms of physical contributions, Andrew developed the “calibration bio media” used in the final product (because real biomaterials were too expensive) and helped test many of the individual components on the final design.