

DYNAMIC BIOREACTOR FOR ENGINEERED CARTILAGE TISSUE

By

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A Thesis Submitted to The Honors College
In Partial Fulfillment of the Bachelors degree
With Honors in
Biomedical Engineering

THE UNIVERSITY OF ARIZONA

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Approved by:

Gary Redford
College of Engineering

Statement of Roles & Responsibilities

- **Dallas Altamirano** (Biomedical Engineering): The team leader, Dallas, is responsible for budgeting, ordering, and help with other tasks of other team members. He also finalized the written documents and is the main person in contact in case of questions by the sponsor and mentor.
- **Efren Barron** (Biomedical Engineering): Efren is responsible for soldering the strain gauges together.
- **Samuel Freitas** (Biomedical Engineering): With a minor in Mechanical Engineering, Samuel is responsible for designing the mechanical loads, trying out different actuators, and designing the outer box.
- **Xinyi Gu** (Electrical Engineering): Xinyi is responsible for the programming and design of the circuit.
- **Danielle Larson** (System Engineering): Danielle is responsible for printing out the scaffolds and soldering the circuits. She also performed one of the acceptance test results.
- **Trinny Tat** (Biomedical Engineering): Trinny is responsible for gathering *in vivo* results from animal studies to apply to the project and designing the small components inside the box. The *in vivo* was supposed to be given by the sponsor. However, they did not have the results ready so Trinny accessed the data and performed some analysis. Trinny also helped with building the preliminary circuits and soldering the final circuits to connect with the programming. Trinny also wrote and put the presentation poster together. What her roles fit with the Honors thesis is that she went beyond what is expected of a biomedical engineering student to help with the electrical components because one electrical engineering student would not be able to finish on her own.

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1. Abstract

Cartilage within the knee joint that is damaged in younger patients due to sports injuries and other traumatic events does not heal spontaneously. Cartilage damage leads to pain, decreased mobility and can eventually progress to diffuse cartilage degeneration and osteoarthritis of a joint. There are no current medical or surgical treatments that restore osteoarthritic joints to their native condition and patients will commonly require joint replacement. In order to develop new treatments to regenerate damaged cartilage, stem cells have been used to produce cartilage like tissues. The Dynamic Bioreactor for Engineered Cartilage Tissue shall mimic loads that are observed from humans' natural gait onto stem cell seeded scaffolds, specifically for creating tissue that will have similar histological and mechanical properties as that of native cartilage. The aim is to provide shear of 5%-10% and axial compression of up 20%, a sterile environment for cell growth, as well as regulate and record the axial strain and shear strain. For the various phases and milestones of the project, refer to *Appendix A*. This report is a comprehensive summary of our final project and its associated documentation.

2. System Block Diagram

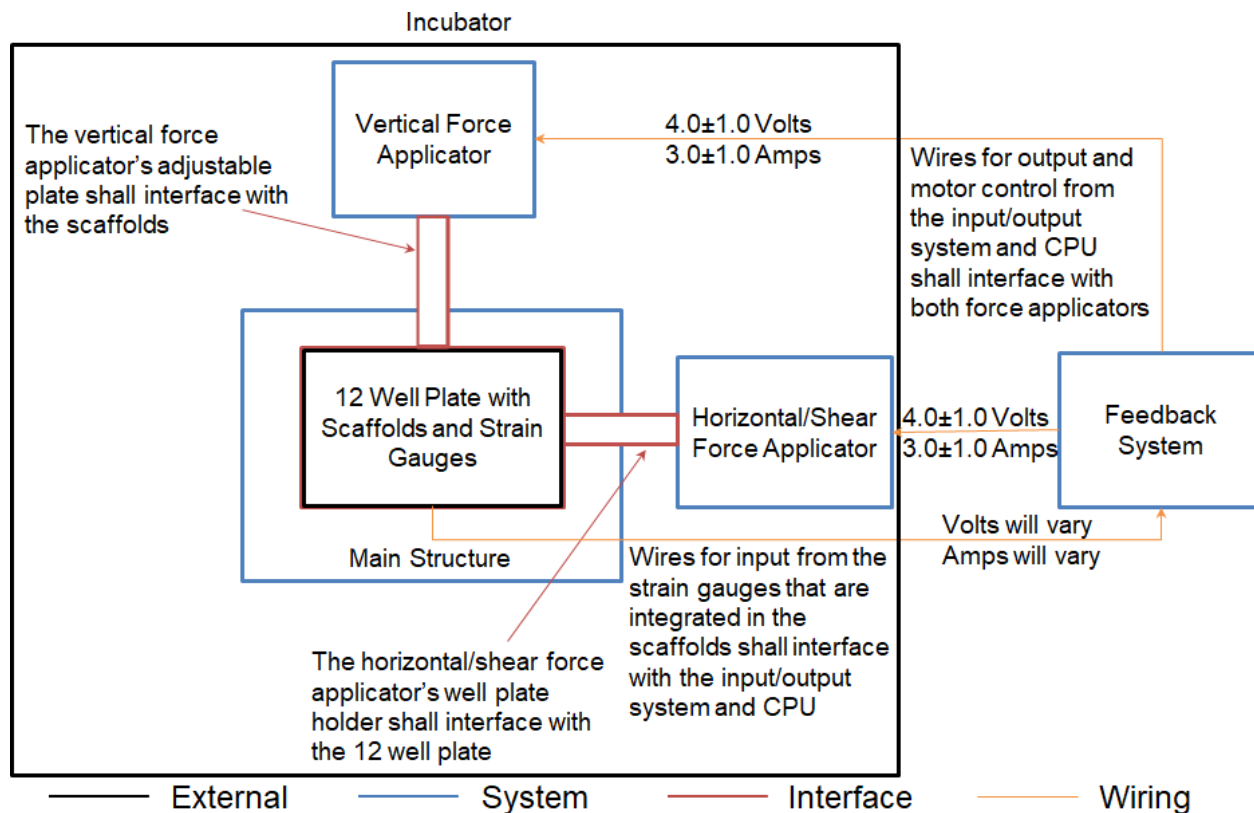


Figure 1. System Block Diagram

The entire system is centered around the 12 well plate that contains the scaffolds. The scaffolds contain strain gauges that specify how much load/strain is being currently applied. The well plate containing the scaffolds is considered the 'main structure', and both the shear and axial force applicators interact with this 'main structure'. Specifically, the shear force applicator will push/pull the 12 well plate to create a shear strain upon the scaffolds. Concurrently the axial force applicator will push straight down onto the scaffolds from a screw-adjusting interface; this will provide the proper amount of axial strain. Both force applicators are independently controlled by the feedback system - the overarching brain of the system - and will react to the amount of strain being currently applied. This will be tuned to the specific pattern required. For a breakdown of the various subcomponents refer to *Appendix B*

3. Technical Data Package

Technical Data Package, SDD

1. Scope

1.1. Identification

This Feedback System^{100,400} SDD gives the design of the software CSCI for the Dynamic Bioreactor for Engineered Cartilage Tissue^{101,000}.

1.2. System Overview

The Feedback System^{100,400} is comprised of the Sensor Connectors^{100,410}, CPU^{100,420}, and Data Input/Output^{100,430} circuitry. The requirement for the software that is flowed down from the Feedback System^{100,400} is that it displays and records accurate real-time data.

1.3. Document Overview

This document will define the software modules required to control the force applicators (Horizontal/Shear^{100,200} and Vertical^{100,100}), receive and interpret data from the Sensor Connectors^{100,410}, and display the data in a graphical interface for the user. These steps will occur continuously for the duration of testing that the sponsor specifies.

2. CSCI-Wide Design Decisions

2.1. Design Decisions Regarding Inputs the CSCI Will Accept and Outputs it will Produce, Including Interfaces with Other Systems, HWCIs, CSCIs, And Users

The input for the desired strain to apply will be given to us by the sponsor as an excel file containing the load patterns obtained from *in vivo* testing. This excel file will then be converted to a Text (MS-DOS) file which will be read by our software. The input regarding the stain actually being applied will be received as analog voltage values from the strain gauges that are in the scaffolds the sponsor provides and circuitry to provide greater accuracy. The output for controlling the motors will go to the DM556T motor driver in the form of PIN-high and PIN-low into Microstep Resolution Selection PIN, and are active when PWM signal input to P1 connector at the trig edge. The output for display will be in the form of serial outputs which can be dealt with both PC software, applications and the microcontroller to the user interface (sponsors monitor).

2.2. Design Decisions on CSCI Behavior in Response to Each Input or Condition, Including Actions the CSCI Will Perform, Response Times and Other Performance Characteristics, Description of Physical Systems

The input for the desired strain will be converted into output commands for the motor on the force applicators. The input regarding the stain actually being applied will be converted from analog voltage to strain % which will be displayed on the user interface (sponsors monitor). The data given to us regarding the desired load was taken at 22hz, however, the actual applied strain is desired to only be around 2hz. The fastest frequency that our microcontroller can command the DM556T motor drive is 400kHz (Decided by the frequency of PWM edge).

2.3. Modeled, Selected Equations/Algorithms/Rules, and Handling of

The analog input from the strain gauges will be converted to actual voltage values using the following conversion;

```
{ C0 = analogRead(A0);
Voltage0 = ((float)C0 * 5.00);
FinalVoltage0 = (Voltage0 / 1023.00);}
```

The conversion from this actual voltage value to strain will be unique to each scaffold and calibration with the scaffold will be necessary first to obtain this conversion. The Algorithm for controlling the motor is:

```
{ Initiate Timer;
  Read ( waveform file);
  Selection PIN Low/High;
  Initiate PWM freq;
  Delay(half interval);
  Enable;
  Delay(interval);
  While (File not reach end) loop{
    Read (waveform file);
    Selection PIN Low/High;
    Delay(interval);
  }
}
```

The conversion from these steps to train applied will depend upon the force applicator set up and will be obtained by modeling the force applicators and testing the strain applied with each step.

2.4. Unallowed Inputs or Conditions

From the user manual of DM556T, there are three unallowed input for motor driver which will trigger the protection of the driver.


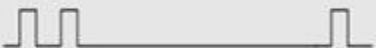
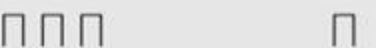
Priority	Time(s) of Blink	Sequence wave of red LED	Description
1st	1		Over-current protection activated when peak current exceeds the limit.
2nd	2		Over-voltage protection activated when drive working voltage is greater than 60VDC
3rd	3		Reserved.

Figure 2. Unallowed Inputs

We will embed an algorithm when we generate the PWM from the input data of strain wave (the text file imported from user) to avoid the input like the wave shown above.

2.5. Design Decisions on How Databases/Data Files Will Appear to the User

The data will appear to be a graph of the strain waveform to the user through a mobile phone applicator/ PC software.

2.6. Selected Approach to Meeting Safety, Security, and Privacy Requirements

Bluetooth module should be embedded an algorithm to do an authentication. It should be paired with an bluetooth device to avoid someone else got our measured data from strain gauges. Since we are not connecting our bioreactor to internet, the security problem is much easier to be solved.

2.7. Other CSCI-Wide Design Decisions Made in Response to Requirements, Such as Selected Approach to Providing Required Flexibility, Availability, and Maintainability

The input for desired strain is converted from an excel file to a text (MS-DOS) file which will be read by our software. This is because the sponsors desired load patterns obtained from *in vivo* testing are in excel files. This will allow the sponsor to easily change which patten he would like to utilize since the only necessary step would be saving the excel file as a text file. The frequency at which data is acquired and output is provided to the motors can also be easily customized by the sponsor by changing the desired frequency. Included in our deliverables will be an instruction manual for the sponsor on the specifics regarding these customizations, however, the software will be designed to make this change as easy as possible.

3. CSCI Architectural Design

3.1. CSCI Component's Identification, Static Relationship, Purpose, Status, Planned Computer Resources, and Library

Table 1. Component Properties Included in Microcontroller

Component properties included in Microcontroller			
<u>Component</u>	<u>Relationship / Characteristics</u>	<u>Purpose</u>	<u>Library</u>
Microcontroller Board (Mega 2560)	The main board with 54 digital I/O pins, 16 analog inputs, which is used to download the arduino code, output digital and analog signal and get back digital input signal.	Control and monitor the stepper motor and strain gauges	avr/io.h Arduino.h
Stepper Driver (DM556T)	This module has three parts used to controlled the signal connection, power supply and the microstep resolution.	Receive command and control the stepper motor	avr/io.h Arduino.h
Stepper Motor	Controlled by analog input, rotate and move the force applicator, so that we can apply forces on the scaffolds.	Movement apply forces on the scaffolds.	none
Analog/Digital Multiplexer (CD74HC4067)	The chip connected to the board to make an extension of analog input pins. Occupies 1 analog input pin only while collect 16 analog/digital inputs from devices.	Extend the analog input pins.	avr/io.h Arduino.h
Gauges	Realized by Wheatstone Bridges. When the strain changes, the resistor in the bridge structure will also change with it. By measure the voltage of the resistor, we can calculate the resistor value and then get the strain value.	Input a voltage value analog input pin of CD74HC4067, feedback the value of strain	none
Bluetooth Module (HC-05)	The chip has pins to read the serial signal received from PC and pass it to MCU or get the signal from MCU and send out the serial signal which can be read by PC.	Send the measured value to the PC and also get control information from PC, pass it to MCU and help MCU decide the control signals.	avr/io.h Arduino.h

3.2. Concept of Execution

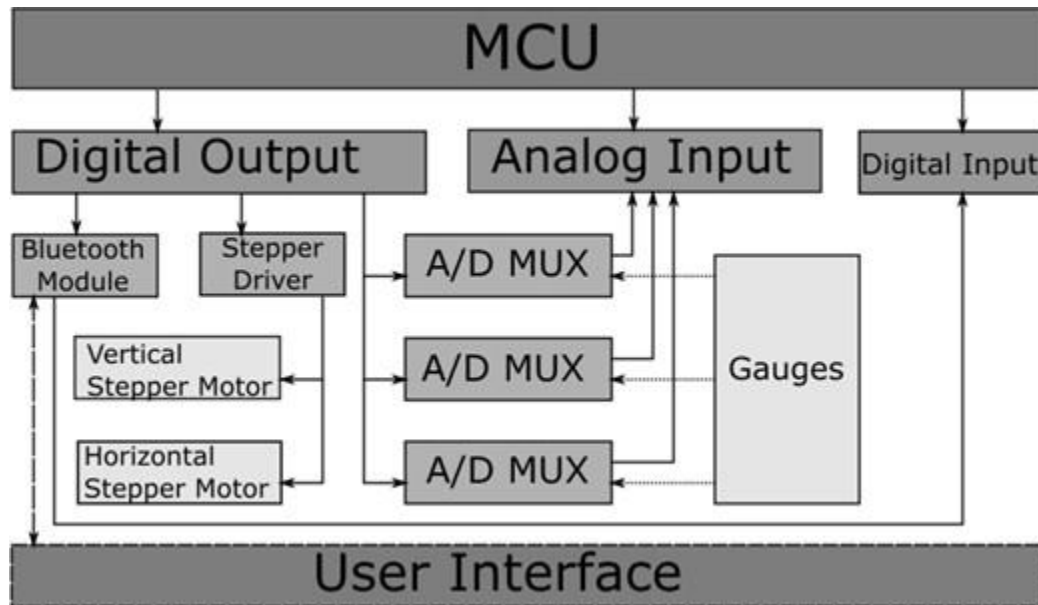


Figure 3. Concept of Execution

3.3. Interface Design: Identification and Diagrams, Priority, Type, Individual Characteristics, Assembly Characteristics, Communication Characteristics, Protocol Characteristics, and Other Characteristics

The data- machine interface will be realized by microcontroller and bluetooth module. PC will use bluetooth to convey the data of the desired waveform, decided by user's input. Another interface is machine- human interaction. The software in PC/ mobile will complete the interface.

4. CSCI Detailed Design

<Pseudocode below>

Bluetooth Drive1:

PC software: C/C++

```

{
  Read force change/force measurement freq (User input of desired Accuracy/ Freq)
  If (Start enabled){
    Read file ( Desired waveform text file);
    while loop{
      Bluetooth send(command send out);
      Bluetooth read(get the measurement of gauges from another bluetooth
      module);
      delay(interval);
    }
  }
}

```

```

Microcontroller Part
Motor Driver: Arduino
{
  Initiate Timer;
  Read ( waveform file);
  Selection PIN Low/High;
  Initiate PWM freq;
  Delay(half interval);
  Enable;
  Delay(interval);
  While (File not reach end) loop{
    Read (waveform file);
    Selection PIN Low/High;
    Delay(interval);
  }
}

```

```

Strain Measurement Part
Multiplexer : Arduino
{
  While loop{
    Selection PIN (i%n'th input);
    Enable;
    Read Analog voltage;
    Analog Digital Converter;
    Bluetooth send data;
    I+1;
  }
}

```

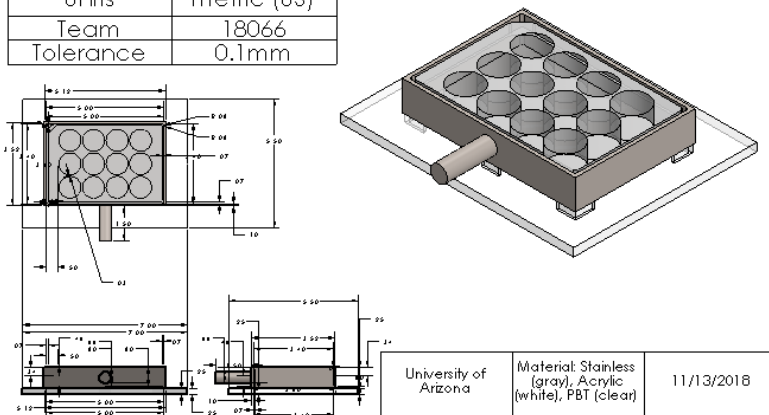
5. Requirement Traceability

Table 2. Feedback System Verification Matrix

Feedback System Verification Matrix			
<u>SRD #:</u>	<u>Requirement:</u>	<u>Verification:</u>	<u>Description:</u>
5.1.3	Display and Recording of Real-Time Data: Accuracy of software reading $\pm 2\%$ Strain	Test	Load Cell Test (Refer to ATP)

Drawing: Well Plate Assembly

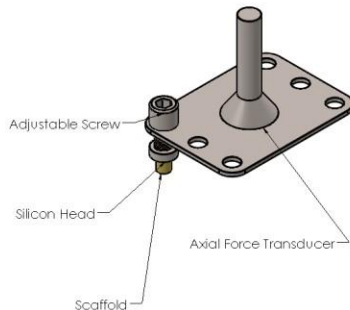
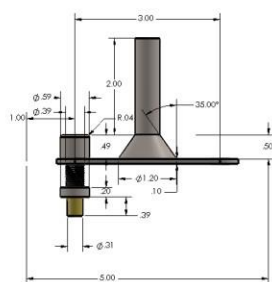
Title	Dynamic Bioreactor
Drawing	Well plate assembly
Units	metric (US)
Team	18066
Tolerance	0.1mm



Notes: This is a standard 12-well plate sitting on a free moving platform. This platform is situated around the shear transducer to allow a shear strain to be applied to the scaffolds. The shear force transducer takes the linear force and converts it into shear strain.

Drawing: Axial Force Transducer

Title	Dynamic Bioreactor
Drawing	Axial force transducer
Units	Metric (mm)
Team	18066
Tolerance	.09mm



University of Arizona	Material: Aluminum (gray), 316 Stainless steel (brushed), PLA (black)	11/13/2018
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Notes: This assembly is a singular model assembly for the adjustable screw, silicon head and scaffold. The Axial force transducer takes the linear force and converts it into compressive strain.

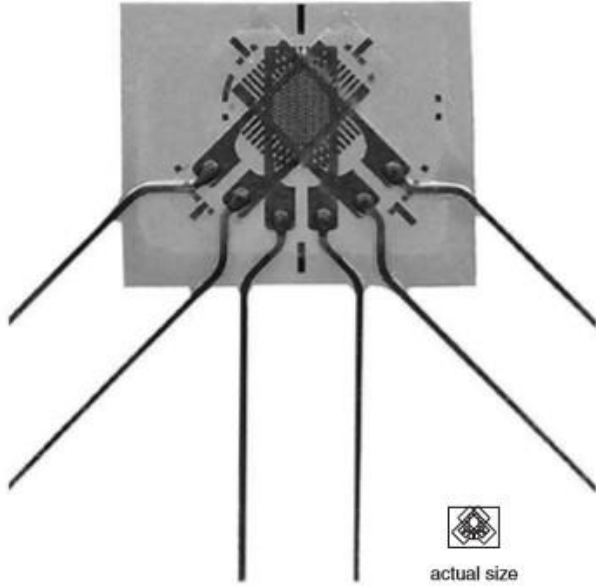
Technical Data Package, Specification Sheets

SA-06-060WR-120:



060WR

General Purpose Strain Gages – Rectangular Rosette

GAGE PATTERN DATA						
	GAGE DESIGNATION See Note 1, 2	RESISTANCE (OHMS)	OPTIONS AVAILABLE See Note 2			
	WA-XX-060WR-120 WK-XX-060WR-120 WK-XX-060WR-350 WK-XX-060WR-10C SA-XX-060WR-120 SK-XX-060WR-120 SK-XX-060WR-350 SK-XX-060WR-10C	120 ± 0.5% 120 ± 0.5% 350 ± 0.5% 1000 ± 0.5% 120 ± 0.5% 120 ± 0.5% 350 ± 0.5% 1000 ± 0.5%				
DESCRIPTION Small three-element 45° rectangular stacked rosette						
GAGE DIMENSIONS		Legend ES = Each Section S = Section (S1 = Section 1)			CP = Complete Pattern M = Matrix	inch millimeter
Gage Length	Overall Length	Grid Width	Overall Width	Matrix Length	Matrix Width	
0.060 ES	0.24 M	0.060 ES	0.30 M	0.24	0.30	
1.52 ES	6.1 M	1.52 ES	7.6 M	6.1	7.6	

GAGE SERIES DATA — See Gage Series datasheet for complete specifications			
Series	Description	Strain Range	Temperature Range
WA	Fully encapsulated constantan gages with high-endurance leadwires.	±2%	-100° to +400°F (-75° to +205°)
WK	Fully encapsulated K-alloy gages with high-endurance leadwires.	±1.5%	-452° to +550°F (-269° to +290°C)
SA	Fully encapsulated constantan gages with solder dots.	±2%	-100° to +400°F (-75° to +205°C)
SK	Fully encapsulated K-alloy gages with solder dots.	±1.5%	-452° to +450°F (-269° to +230°C)

Note 1: Insert desired S-T-C number in spaces marked XX.

Note 2: Products with designations and options shown in bold are not RoHS compliant.



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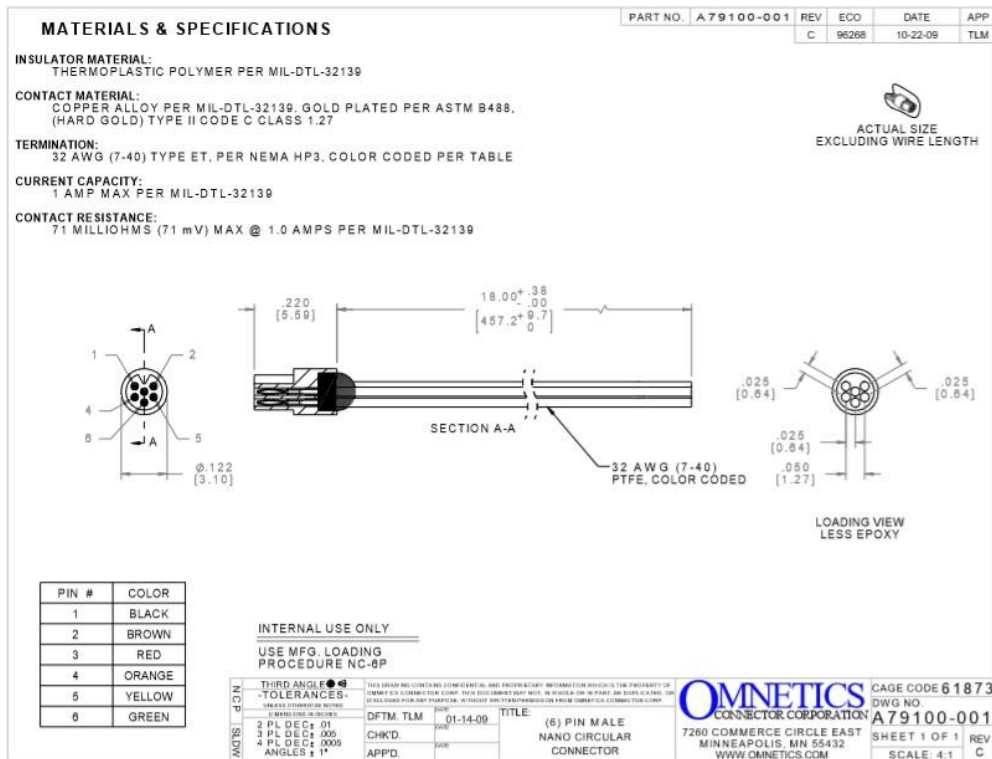
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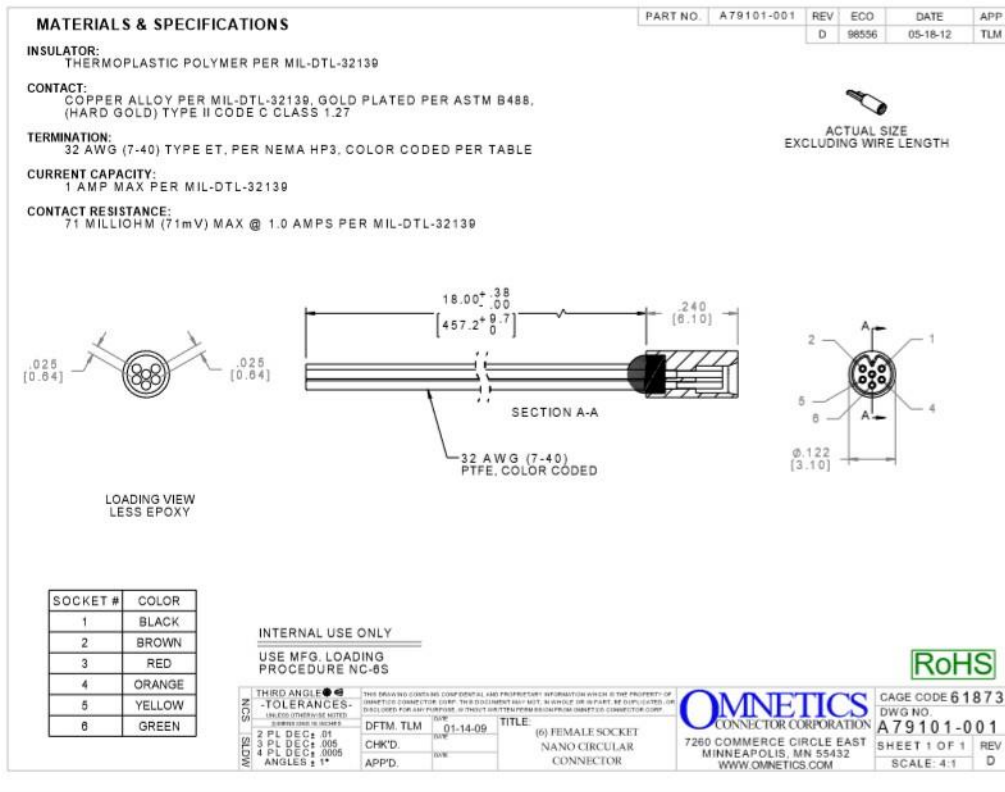
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Micro-connector (Male):



Micro-connector (Female):



4. Acceptance Test Procedure

1. Display of Real-Time Data Tests

1.1 Introduction

Feedback System^{100,400} shall utilize Sensor Connectors^{100,410} which connect to a Wheatstone bridge and Op-Amp circuit where the microcontroller shall read the outputs and record the live data in conjunction with the Data Input/Output^{100,430} and CPU^{100,420} which display real-time data.

1.2 Required Test Equipment

Description	Model Number	Accuracy
Digital Multimeter	Craftsman 3482146	+/-0.1 A (at range of 0-25 A) +/-0.1 V (at range of 0-250 V)
Load Cell	Degraw 5 kg	+/-0.05% (at range of 2.7-5 V)
Monitor	Arduino Mega 2560	+/-2 V (at range of 0-5 V)

1.3 Table of Tests

Table 3. Tests for Display of Real-Time Data

Test #	Test	Requirement
1.1	Shear Force Applicator	Load up to 10% strain with an accuracy of +/- 3% strain or greater.
1.2	Axial Force Applicator:	Load up to 20% strain with an accuracy of +/-5% strain or greater.
1.3	Load Cell Test	Maximum load voltage 2.7 V with 3% Agros medium distributed among 6 scaffolds

1.4 Step-by-Step Procedure

1. Begin by having the shear and axial force applicators connected to the load cell plate.
2. Run GUI interface on the feedback system to display a voltage, which then can be calculated to display a force read output.
3. Compare the real time force value outputs from the load cell to the inputs used for the horizontal and shear force applicator.
4. Ensure that each motor will output the correct value of force we need, as this value will denote how accurate we are loading each scaffold.
5. If real time output data is not correct, go back and adjust the input coding found in the microcontroller feedback system.

1.5 Support Requirements

Feedback system should be calibrated and effectively record live output data in conjunction to our real time data.

1.6 Data Sheet

Table 4. Display of Real-Time Data Test Data Sheet

Display of Real-Time Data Test Data Sheet			
Referenced ATP Paragraph Number: 1.1			
Analysis Referenced (for verification by T/A): Axial Load and Shear Load			
Name of Test: Display of Real-Time Data Tests			
Unit Under Test (UUT): Name: Feedback System Part Number: 100400 Serial Number: n/a			
Results (Pass / Fail):		Date of Test:	
Recording of Test Measurement: 1.1 voltage change (experimental % strain) = 1.2 voltage change (experimental % strain) = 1.3 voltage change (experimental % strain) =	Requirement (SRD, with Tolerances): < 10 % < 20 % 2 N	Test Equipment Error: ● +/-3% ● +/-3% ● +/- 0.06N	Adjusted Test Limit: < 10% - std < 20% - std 1.94 N - 2.06 N
<p>Computations, (Include Analyses Results, if any):</p> <p>For actual % strain:</p> <ul style="list-style-type: none"> ● Diameter of scaffold (m) = ● Height of scaffold (m) = ● % strain wanted = ● Weight (N) = <p style="text-align: center;"><i>Amount of Force to Apply Given Strain to a Scaffold = Area of Scaffold × Compression Modulus × Desired Strain × # of Scaffolds</i></p> <p>Measure the Voltage Change from the Strain Gauge to get Experimental % Strain</p>			
Signatures:			
Tester _____			
Customer _____			

2. Sterile Environment Tests

2.1 Introduction

Inner Sterile Box^{100,310} shall be a polycarbonate chamber that allows for easy cleaning to ensure long term tissue culture. It shall seal and have a small port for gas exchange that filters incoming gas preventing microbe exchange.

2.2 Required Test Equipment

Description	Model Number	Accuracy
Incubator	Symphony VWR	+/- 1°C +/-0.1% CO ₂
DMEM Media	Gibco DMEM	[+] 1 g/L D-Glucose [+] L-Glutamine [+] 110mg/L Sodium
Pyruvate		
Agar Plate	Thermo Scientific™ Blood Agar (TSA w/ 5% Sheep Blood) / MacConkey Agar Plate	n/a

2.3 Table of Tests

Table 5. Tests for Sterile Environment

Test #	Test	Requirement
1.1	Agar Plate Test ²	Zero growth

2.4 Step-by-Step Procedure

1. Clean the inside of bioreactor with 70% ethanol and allow for it to sit in sterile environment under UV light for a minimum of 30 minutes.
2. Place sterile well plate into bioreactor with DMEM media in each well, approximately 5 mL per well.
3. Seal bioreactor.
4. Spray outside of bioreactor with 70% EtOH and place into incubator.
5. Every 24 hours, take bioreactor out and run a simple loading pattern for 30 min. (Repeat this for 3 days).
6. After 3 days, swab media onto agar plates and place agar plates into incubator.
7. After 24 hours, look at agar plates under microscope to see if there are any bacteria colonies.

2.5 Support Requirements

Sterility test shall be run before placing cells in the bioreactor.

2.6 Data Sheet

Table 6. Sterile Environment Test Data Sheet

Sterile Environment Test Data Sheet							
Referenced ATP Paragraph Number: 2.1							
Analysis Referenced (for verification by T/A): Operating Conditions							
Name of Test: Sterile Environment Test							
Unit Under Test (UUT): Name: Main Structure Part Number: 100300 Serial Number: n/a							
Results (Pass / Fail):		Date of Test:					
Recording of Test Measurement:	Requirement (SRD, with Tolerances):	Test Equipment Error:	Adjusted Test Limit:				
Number of colonies =	Zero Growth	n/a	n/a				
Computations, (Include Analyses Results, if any):							
<ul style="list-style-type: none"> ● Observe the color of the cell media ● Record the number of colonies grown (if any). <table> <tr> <td><u>Day</u></td> <td><u>number of colonies</u></td> </tr> <tr> <td>3</td> <td></td> </tr> </table>				<u>Day</u>	<u>number of colonies</u>	3	
<u>Day</u>	<u>number of colonies</u>						
3							
Signatures:							
Tester _____							
Customer _____							

5. Models / Analyses (summary, docs in appendix)

The max strain required of our force applicators are 20% Strain and 10% Strain for the Axial and Horizontal/Shear respectively. The torque needed to provide a max strain of 10% required is $0.117 \pm 0.0096(\text{N}\cdot\text{m})$. The torque needed to provide a max strain of 20% required is $0.235 \pm 0.019(\text{N}\cdot\text{m})$. Both of our force applicators can provide a torque of $3.0(\text{N}\cdot\text{m})$. The accuracy required of our force applicators are $\pm 5\%$ Strain and $\pm 3\%$ Strain for the Axial and Horizontal/Shear respectively. Both of our force applicators have an accuracy between 0.1485% Strain and 0.1815% Strain.

All requirements were met or exceeded (refer to *Appendix E, (Verification)*).


6. Acceptance Test Results (completed data sheets)
Acceptance Test Results, Display of Real-Time Data Test

Table 7. (COMPLETED) Display of Real-Time Data Test Data Sheet

Display of Real-Time Data Test Data Sheet			
Referenced ATP Paragraph Number: 1.1			
Analysis Referenced (for verification by T/A): Axial Load and Shear Load			
Name of Test: Display of Real-Time Data Tests			
Unit Under Test (UUT): Name: Feedback System Part Number: 100400 Serial Number: n/a			
Results (Pass / Fail): PASS		Date of Test: 04/14/19	
Recording of Test Measurement: 1.1 voltage change (experimental % strain) = 22.6% 1.2 voltage change (experimental % strain) = 22.6% 1.3 voltage change (experimental % strain) = 2.7 kg (or 26.5 N)	Requirement (SRD, with Tolerances): < 10 % < 20 % 2 N	Test Equipment Error: ● +/-3% ● +/-3% ● +/- 0.06N	Adjusted Test Limit: < 10% - std < 20% - std 1.94 N - 2.06 N
Computations, (Include Analyses Results, if any): For actual % strain: <ul style="list-style-type: none"> ● Diameter of scaffold (m) = 0.008 ± 0.001 ● Height of scaffold (m) = 0.01 ± 0.001 ● % strain wanted = 20% ● Weight (N) = 23.5 ± 1.90 Amount of Force to Apply Given Strain to a Scaffold = $\left(\frac{\text{Diameter of Scaffold}^2}{2}\right) \times (\text{Compression Modulus}) \times \pi \times \text{Expected Strain \%}$ Measure the Voltage Change from the Strain Gauge to get Experimental % Strain			
Signatures: Tester: <u>Xinyi Gu</u> Customer: <u>David Margolis</u>			

Acceptance Test Results, Sterile Environment Test

Table 8. (COMPLETED) Sterile Environment Test Data Sheey

Sterile Environment Test Data Sheet					
Referenced ATP Paragraph Number: 2.1					
Analysis Referenced (for verification by T/A): Operating Conditions					
Name of Test: Sterile Environment Test					
Unit Under Test (UUT): Name: Main Structure Part Number: 100300 Serial Number: n/a					
Results (Pass / Fail): PASS		Date of Test: 04/19/19			
Recording of Test Measurement:	Requirement (SRD, with Tolerances):	Test Equipment Error:	Adjusted Test Limit:		
Number of colonies = 0	Zero Growth	n/a	n/a		
Computations, (Include Analyses Results, if any):					
<ul style="list-style-type: none"> Observe the color of the cell media Record the number of colonies grown (if any). 					
<table border="0"> <tr> <td><u>Day</u></td> <td><u>number of colonies</u></td> </tr> <tr> <td align="center">3</td> <td align="center">0</td> </tr> </table>	<u>Day</u>			<u>number of colonies</u>	3
<u>Day</u>	<u>number of colonies</u>				
3	0				
Signatures:					
Tester: <u>Danielle Larson</u>					
Customer: <u>David Margolis</u>					

7. Final Budget

We completed our project within the budget provided. Our final budget was \$3,899.29, while we were provided with \$4000.00 for the project. For a breakdown of the costs of each item purchased refer to *Appendix G*.

Table 9. Cost of Bioreactor

Part	Total Cost
Vertical Force Applicator^{100,100}	\$224.92
V Stepper Motor (Power Supply & Controller Included) ^{100,110}	\$103.15
V Rod/Shaft ^{100,120}	\$14.68
V Sliding Rail ^{100,130}	\$72.99
V Brace ^{100,140}	
Adjustable Plate ^{100,150}	\$34.10
Horizontal/Shear Force Applicator^{100,200}	\$213.83
H/S Stepper Motor (Power Supply & Controller Included) ^{100,210}	\$100.15
H/S Rod/Shaft ^{100,220}	\$14.68
H/S Sliding Rail ^{100,230}	\$64.90
H/S Brace ^{100,240}	
Well Plate Holder ^{100,250}	\$34.10
Main Structure^{100,300}	\$163.22
Inner Sterile box ^{100,310}	\$101.29
Stage ^{100,320}	\$31.99
Wiring System ^{100,330}	\$15.95
Removable Top/Side ^{100,340}	\$13.99
Feedback System^{100,400}	\$1,292.27
Sensor Connector ^{100,410}	\$413.52
CPU ^{100,420}	\$13.99
Data Input/Output ^{100,430}	\$864.76
Dynamic Bioreactor for Engineered Cartilage Tissue^{101,000}	\$1,894.24

8. Lessons Learned

The thing that put the project most at risk was the time it took for some of the parts to come in. This delayed assembly and testing for quite some time. Therefore, in the future we will order parts much further ahead of schedule to ensure it does not cause delays.

We also learned that it is important to order more supplies and parts than we anticipate using as we found that sometimes the parts break in the process of assembly or we ended up remaking our circuit, which required more of one item than originally expected. Through this trial and error process, we found that it was very beneficial to order an excess amount of various parts.

Appendix A

Scope

Our customer, Dr. Margolis has asked us to design, build, and test a working “Dynamic Bioreactor for Engineered Cartilage Tissue”.

Key capabilities include:

- Providing a sterile environment for cell cultures
- Interfacing with strain gauges
- Applying a controlled axial load within a given range to scaffolds
- Applying a controlled horizontal/shear load within a given range to scaffolds
- Being corrosive resistant in a warm and humid environment
- Displaying and recording real time data from the sensors on a user-friendly interface

The effort we will perform consists of the following four phases:

Phase 1 – Activities up to & including the delivery/signing of the proposal

Phase 2 – Activities up to and including the PDR

Phase 3 – Activities up to and including the CDR

Phase 4 – The remaining activities to test and deliver a working prototype.

The project efforts consist of the following major milestones:

09/11/18 Proposal due	Completed
10/02/18 SRD due	Completed
11/06/18 PDR due	Completed
12/05/19 CDR due	Completed
04/25/19 FAR due	Completed
04/30/19 Design Day	Completed
05/07/19 Final Report due	Completed

Appendix B System Block Diagram

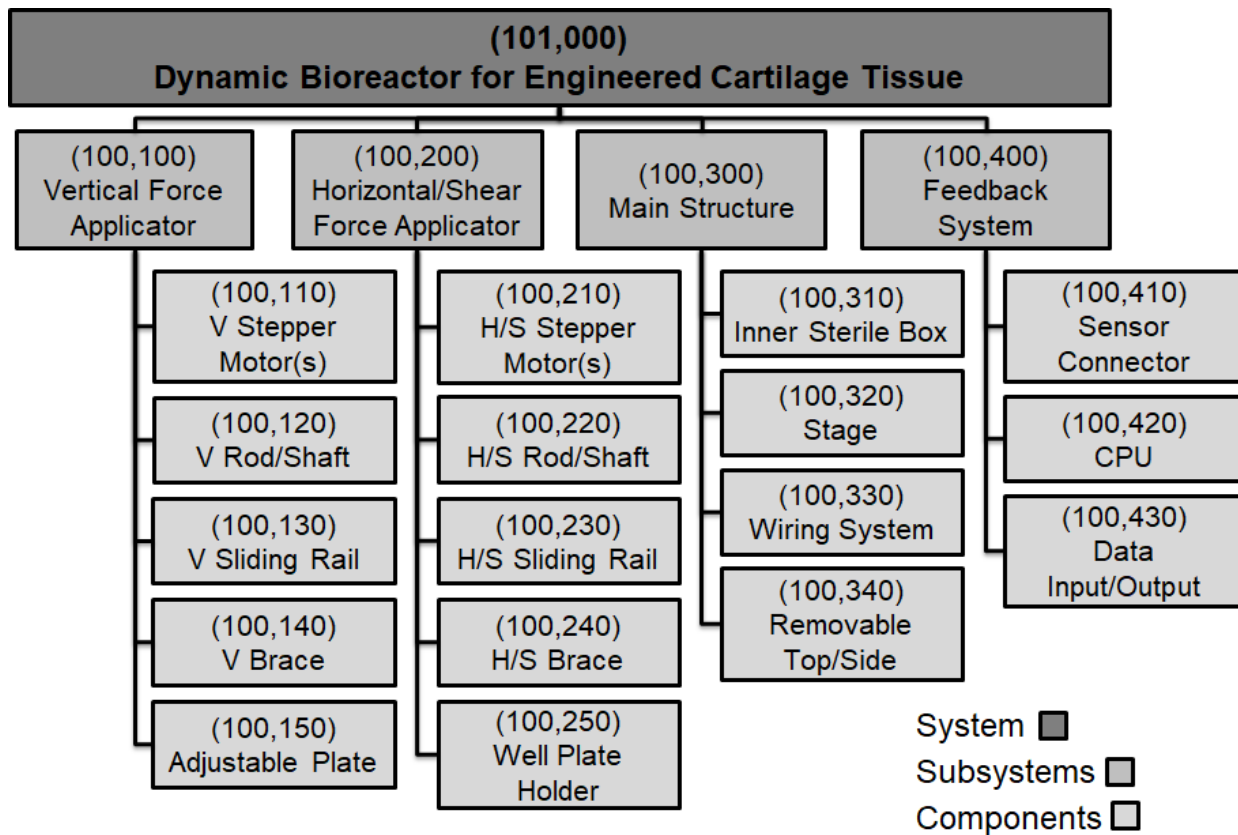


Figure 4. System Architecture Diagram

Appendix C
Technical Data Package

N/A

Appendix D
Acceptance Test Procedure

N/A

Appendix E

Models / Analyses. Accuracy of Force Applicators

Parameters of Designed Force Applicator:

$$\begin{aligned} \text{Distance per Revolution} &= 0.33 \frac{\text{(cm)}}{\frac{\text{(revolution)}}{\text{(steps)}}} \\ \text{Steps per Revolution} &= 200 \frac{\text{(revolution)}}{\text{(revolution)}} \\ \text{or} \\ \text{Revolutions per Step} &= \frac{1 \text{ (revolution)}}{200 \text{ (steps)}} \end{aligned}$$

Dimensions of Scaffold:

$$\begin{aligned} \text{Height of Scaffold} &= 1 \pm 0.1 \text{(cm)} \\ \text{Radius of Scaffold} &= 0.004 \pm 0.0005 \text{(cm)} \end{aligned}$$

Calculations:

$$\begin{aligned} &0.33 \text{ (cm)} \qquad \qquad \qquad \text{(cm)} \\ \text{Distance per Step} &= \frac{0.33 \text{ (cm)}}{200 \text{ (step)}} = 0.00165 \frac{\text{(cm)}}{\text{(step)}} \\ \text{Strain \%} &= \frac{\Delta H}{H_0} = \frac{0.00165 \text{ (cm)}}{1 \pm 0.1 \text{(cm)}} \times 100\% = (0.165 \pm 0.0165)\% \end{aligned}$$

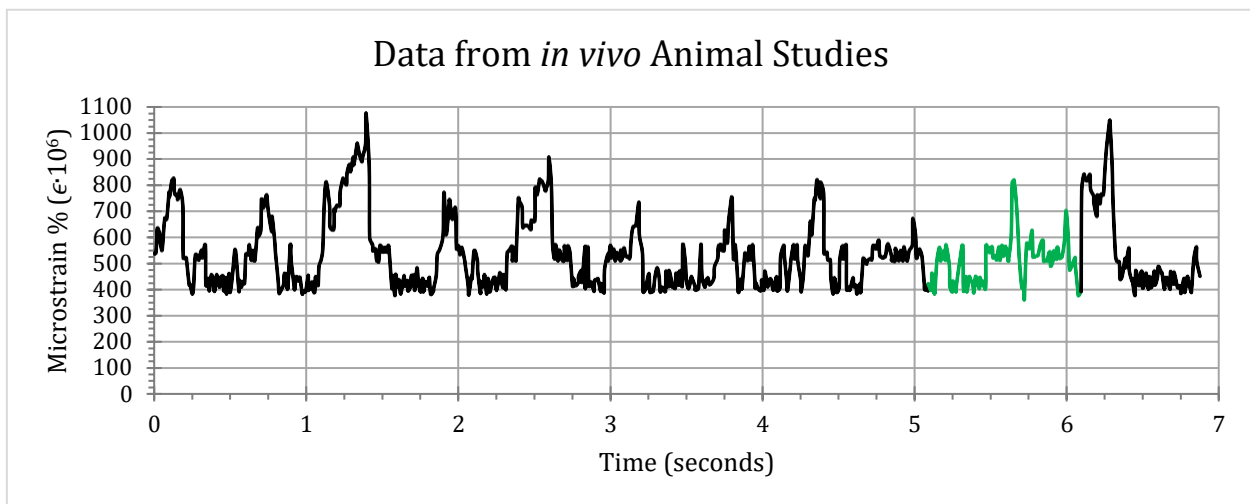


Figure 5. In-Vivo Data

This pattern of strain that is desired to replicate.

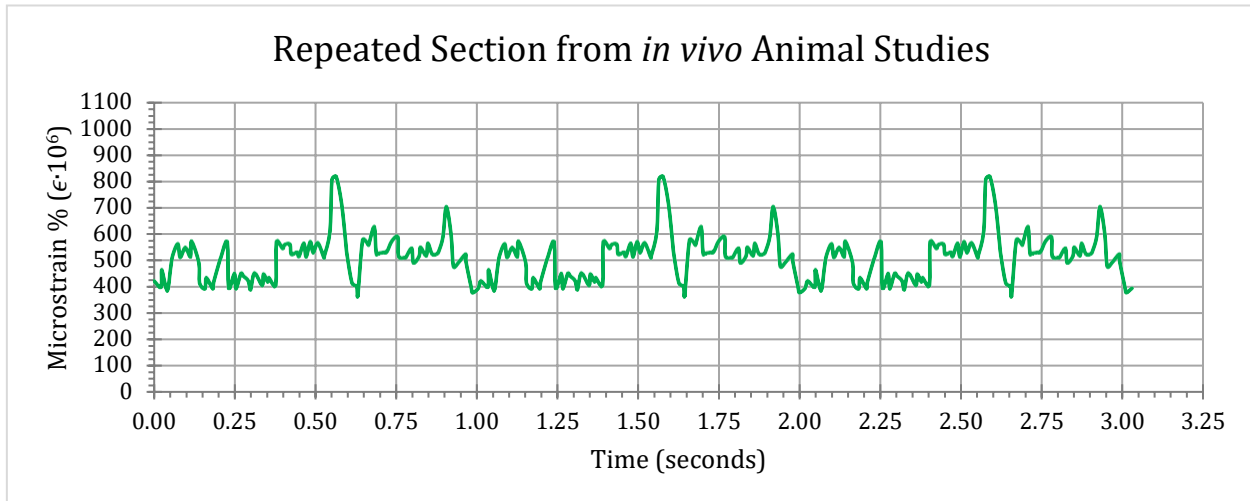


Figure 6. Repeat of Highlighted Section from *In-Vivo* Data

This pattern of strain is what the force applicators will replicate using the calculations shown previously. Since this can be repeated indefinitely, this was used so that run time was customizable.

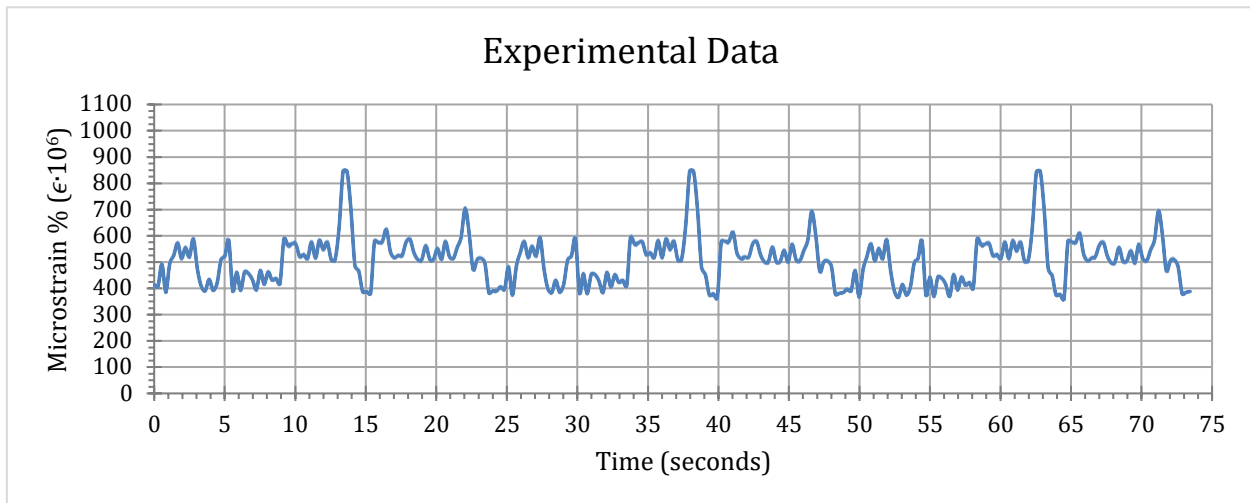


Figure 7. Experimental Data

This pattern of strain that the force applicators produced.

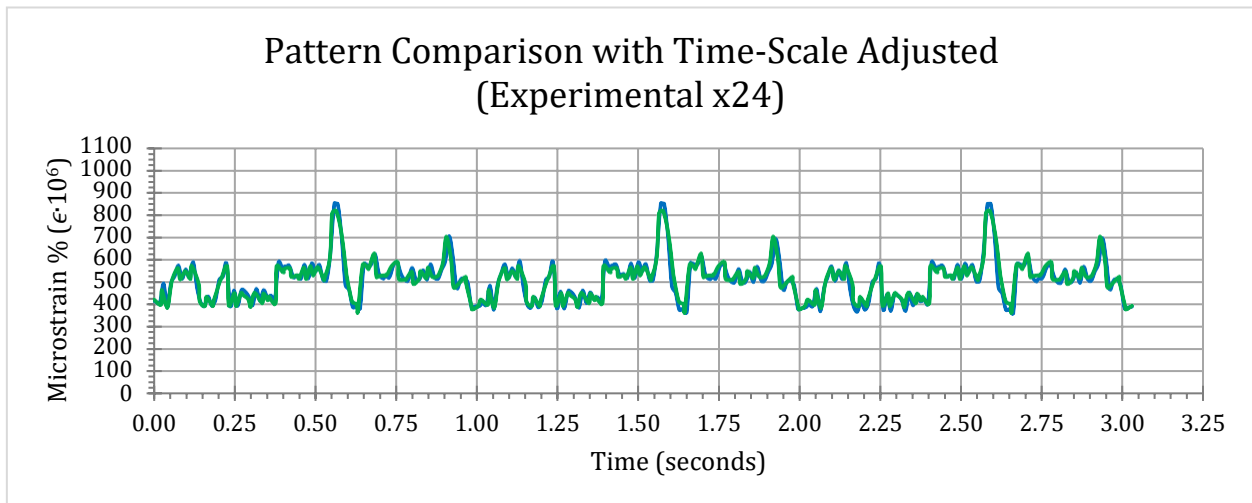


Figure 8. Comparison of Experimental vs. *In-Vivo* with adjusted time scale

This shows both the desired pattern and actual pattern executed with the time scale of the experimental data multiplied by 24.

Models / Analyses, Torque Needed from Force Applicators

Dimensions of Scaffold:

$$\begin{aligned} \text{Height of Scaffold} &= 1 \pm 0.1(\text{cm}) \\ \text{Radius of Scaffold} &= 0.4 \pm 0.05(\text{cm}) \end{aligned}$$

Compression Modulus:

$$\begin{aligned} 2.5\% \text{ Agarose} &= 0.254 \pm 0.020(\text{MPa}) \\ 5\% \text{ Agarose} &= 0.929 \pm 0.048(\text{MPa}) \end{aligned}$$

Extrapolation and Conversion for 3% Agarose:

$$\begin{aligned} X\% \text{ Agarose} &= (0.270x - 0.421) \pm (0.0112x - 0.008)(\text{MPa}) \\ 3\% \text{ Agarose} &= 0.389 \pm 0.0256(\text{MPa}) \end{aligned}$$

or

$$3\% \text{ Agarose} = 38.9 \pm 2.56 \left(\frac{\text{N}}{\text{cm}^2} \right)$$

Calculations:

$$\begin{aligned} \text{Surface Area of 1 Scaffold} &= \pi(0.4 \pm 0.05(\text{cm}))^2 \\ &= 0.503 \pm 0.008(\text{cm}^2) \\ \text{Surface Area of 6 Scaffolds} &= 3.016 \pm 0.047(\text{cm}^2) \\ \text{Force Required} &= 0.0003015929 \pm 0.0000047124(\text{cm}^2) \times 38.9 \pm 2.56 \left(\frac{\text{N}}{\text{cm}^2} \right) \\ &= 117.320 \pm 9.554(\text{N}) \end{aligned}$$

Calculations for 10% Strain:

$$(117.320 \pm 9.554(\text{N}))(0.001(\text{m})) = 0.117 \pm 0.0096(\text{N} \cdot \text{m})$$

Calculations for 20% Strain:

$$(117.320 \pm 9.554(\text{N}))(0.002(\text{m})) = 0.235 \pm 0.019(\text{N} \cdot \text{m})$$

Models / Analyses, Verification

Table 10. Requirement Verification Table

Requirement	Method	Limit/ Reference	Model/ Analysis	Measured/ Ref Value			
1. Interface Requirements	-	-	-	-			
a. Strain Gauge Interface	D, I	Drawings: Strain Gauge to System Connector, System to Strain Gauge Connector	Drawings: Strain Gauge to System Connector, System to Strain Gauge Connector	Strain Gauges Successfully Integrated			
2. Environmental Requirements	-	-	-	-			
a. Operating Conditions	A, I	$\leq 80\%$ Humidity $\leq 50^{\circ}\text{C}$	Materials used: PLA, PBT, Aluminum, Acrylic, Stainless Steel	No Degradation Observed			
3. Customer Constraints	-	-	-	-			
a. Size	I	L \leq 43.18 cm W \leq 38.10 cm H \leq 60.96 cm	L = 42.01 cm W = 19.05 cm H = 39.29 cm	Fits Upon Inspection			
b. Cost	A	\leq \$4,000	\$3936.23	\$1894.24			
c. Display of Real-Time Data	T, D	Display Live Data (ATP 1.7)	SDD 4.2	Displays Properly			
4. Performance Requirements	-	-	-	-			
a. Sterile Environment	T, I	0 Bacterial growth (ATP 2.7)	Drawing: Full Build	0 Bacterial Growth			
b. Axial Load	A, D	$\leq 20\%$ Strain Accuracy of $\pm 5\%$	$\leq 21.41\%$ Strain Accuracy of 0.165%	$\leq 22.6\%$ Strain Accuracy of 0.084%			
c. Shear Load	A, D	$\leq 10\%$ Strain Accuracy of $\pm 3\%$	$\leq 21.41\%$ Strain Accuracy of 0.165%	$\leq 22.6\%$ Strain Accuracy of 0.084%			
Key							
A = Analysis		D = Demonstration	I = Inspection	T = Test	Pass	Fail	Not Checked/Tested

Appendix F
Acceptance Test Results

N/A

Appendix G Final Budget

Table 11. Units Cost

Item/Part #:	Description:	Quantity:	Unit Price:	Amount:	Shipping:	Tax:	Order #	Order Total:
B01CJJKSU6	HiLetgo Mega2560 R3 ATMEGA16U2 CH340 Microcontroller Board Develo Product Link: https://www.amazon.com/HiLetgo-ATMEGA16U2-Micro	1	\$ 13.99	\$ 13.99				
B01DLHKLNE	HiLetgo CD74HC4067 CMOS 16 Channel 16 CH Digital Analog Multiplexer Product Link: https://www.amazon.com/HiLetgo-CD74HC4067-Chann	3	\$ 5.29	\$ 15.87				
B00IF93H6W	3DMakerWorld Switching Power Supply 24V 400W Product Link: https://www.amazon.com/gp/product/B00IF93H6W/ref	1	\$ 54.39	\$ 54.39				
B074TBMC7N	STEPPERONLINE Digital Stepper Driver 1.8~5.6A 20-50VDC for Nema 23, 2 Product Link: https://www.amazon.com/gp/product/B074TBMC7N/re	1	\$ 39.95	\$ 39.95	\$ -	\$ -	1	\$ 248.19
B074JJ6NGQ	Nema 23 Stepper Motor 4.2A 3.0Nm (425oz.in) 100mm Length for CNC Mi Product Link: https://www.amazon.com/gp/product/B074JJ6NGQ/ref	1	\$ 36.00	\$ 36.00				
B01JFDHXCK	3D Printer Filament Black PLA 1.75 mm 1 KG Spool (2.2 lb) Dimensional A Product Link: https://www.amazon.com/Printer-Filament-Black-Dime	1	\$ 15.00	\$ 15.00				
B01N3U8B6F	100mm Travel Length Linear Stage Actuator DIY CNC Router Parts X Y Z Lin Product Link: https://www.amazon.com/Actuator-Sfu1605-Stepper-B	1	\$ 72.99	\$ 72.99				
B07DC42DLW	100mm Travel Length Linear Rail Guide Ballscrew Sfu1605 DIY CNC Router Product Link: https://www.amazon.com/gp/product/B07DC42DLW/re	1	\$ 64.90	\$ 64.90				
B00D7OL1AE	316 Stainless Steel Sheet, Unpolished (Mill) Finish, Annealed, ASTM A24 Product Link: https://www.amazon.com/gp/product/B00D7OL1AE/ref	2	\$ 68.19	\$ 136.38				
B07HMC5RR6	Stainless Steel Lab Frame Rods.5 Diameter, Round rods (6") Product Link: https://www.amazon.com/gp/product/B07HMC5RR6/re	4	\$ 14.68	\$ 58.72				
B00844SOSE	Source One Premium 1/4 Clear Acrylic PlexiGlass Sheet 12 x 12 Inches (S1 Product Link: https://www.amazon.com/gp/product/B00844SOSE/ref	7	\$ 12.99	\$ 90.93	\$ 17.49	\$ -	2	\$ 399.84
B003HNFLMY	SCIGRIP 16 10315 Acrylic Cement, Low-VOC, Medium bodied, 5 Ounce Tu Product Link: https://www.amazon.com/gp/product/B003HNFLMY/re	2	\$ 7.22	\$ 14.44				
B01GUG2Q4U	EarthOx Sterile Tissue Culture Plate 12 Well -Surface Treated (4 Plates) Product Link: https://www.amazon.com/gp/product/B01GUG2Q4U/re	1	\$ 6.99	\$ 6.99				
B0716CSWHJ	Red Blood Agar (RBA), (10-Pack) Tryptic Soy Agar with 5% Sheep Blood, P Product Link: https://www.amazon.com/gp/product/B0716CSWHJ/ref	1	\$ 9.99	\$ 9.99				
A79100-001	Nano 360® Plastic Circulars - Straight. 6 contact with color coded discrete Product Link: https://www.omnetics.com/products/micro-and-nano	10	\$ 16.23	\$ 162.30				
A79101-001	Nano 360® Plastic Circulars - Straight. 6 contact with color coded discrete Product Link: https://www.omnetics.com/products/micro-and-nano	10	\$ 16.38	\$ 163.80	\$ -	\$ -	3	\$ 326.10
B07JQXQ8S5	DC Power Supply Variable, Tacklife 4 digital LCD display (0-30V/0-5A) Swi Product Link: https://www.amazon.com/gp/product/B07JQXQ8S5/ref	1	\$ 63.97	\$ 63.97				
B00B4ZQ3L0	Hook up Wire Kit (Stranded Wire Kit) 22 Guage (6 different colored 25 Fo Product Link: https://www.amazon.com/gp/product/B00B4ZQ3L0/ref	1	\$ 15.95	\$ 15.95				
B07GXFRX1W	18AWG UL1007 PVC Stranded Tinned Copper Wire, Hook Up Wire 6 Color Product Link: https://www.amazon.com/gp/product/B07GXFRX1W/re	1	\$ 13.99	\$ 13.99				
B01EV6LJ7G	Elegoo EL-CP-003 3pcs MB-102 Breadboard 830 Point Solderless Prototyp Product Link: https://www.amazon.com/gp/product/B01EV6LJ7G/ref	1	\$ 9.99	\$ 9.99				
B072BL2VX1	Elegoo 17 Values 1% Resistor Kit Assortment, 0 Ohm-1M Ohm (Pack of 52 Product Link: https://www.amazon.com/gp/product/B072BL2VX1/ref	1	\$ 10.86	\$ 10.86	\$ -	\$ -	4	\$ 146.72
B07K1W6XWJ	(Pack of 50 Pieces) MCIGICM Im358 ic SMD op-amp Im358 Operational A Product Link: https://www.amazon.com/gp/product/B07K1W6XWJ/re	2	\$ 7.99	\$ 15.98				
B07K34QQZN	TREONYIA 63/37 Tin Lead Rosin Core Solder Wire for Electrical Soldering Product Link: https://www.amazon.com/gp/product/B07K34QQZN/re	1	\$ 6.99	\$ 6.99				
B072PCQ2LW	560PCS Heat Shrink Tubing 2:1, Eventronic Electrical Wire Cable Wrap Ass Product Link: https://www.amazon.com/gp/product/B072PCQ2LW/re	1	\$ 8.99	\$ 8.99				
CON-1200	12 PIN CONNECTOR Product Link: https://www.allelectronics.com/item/con-1200/12-pin-	8	\$ 3.70	\$ 29.60				
CON-640	6-CONDUCTOR LOCKING CONNECTOR W/ LEADS Product Link: https://www.allelectronics.com/item/con-640/6-condu	8	\$ 2.60	\$ 20.80	\$ -	\$ -	5	\$ 50.40

B07G2ZFQBW	BIDE T Handle Tap Wrench Kit Alloy Steel 6pcs Tap Set Metric (M6 M7 M8)	1	\$ 11.95	\$ 11.95					
	Product Link: https://www.amazon.com/gp/product/B07G2ZFQBW/ref								
B07BVCBS71	SBDs (Pack of 10): 3/8" - 7/16" Round Black Vinyl Flexible End Cap Bolt Scr	1	\$ 7.50	\$ 7.50					
	Product Link: https://www.amazon.com/gp/product/B07BVCBS71/ref								
B07FDWJW6N	SBDs (Pack of 10): 1/4" - 5/16" Round Black Vinyl Flexible End Cap Bolt Scr	1	\$ 6.45	\$ 6.45					
	Product Link: https://www.amazon.com/gp/product/B07FDWJW6N/r								
B00394F9K0	Whatman 1003-055 Quantitative Filter Paper Circles, 6 Micron, 26 s/100m	1	\$ 15.51	\$ 15.51	\$ -	\$ -	6	\$ 110.01	
	Product Link: https://www.amazon.com/gp/product/B00394F9K0/ref								
B07CQGR9SP	M12-1.75 x 40mm Hex Head Cap Screws, Steel Metric Class 8.8, Zinc Platin	1	\$ 27.97	\$ 27.97					
	Product Link: https://www.amazon.com/gp/product/B07CQGR9SP/re								
B00HYLYWDE	The Hillman Group 2468 M12-1.75 - Metric Pitch Hex Nut, 20-Pack	1	\$ 9.99	\$ 9.99					
	Product Link: https://www.amazon.com/gp/product/B00HYLYWDE/re								
B013JKQRVI	Uxcell a14051000ux0286 30 Piece 1W 120 Ohm Resistance Metal Oxide Fil	4	\$ 7.66	\$ 30.64					
	Product Link: https://www.amazon.com/gp/product/B013JKQRVI/ref								
B074JJ6NGQ	Nema 23 Stepper Motor 4.2A 3.0Nm (425oz.in) 100mm Length for CNC Mi	1	\$ 33.00	\$ 33.00					
	Product Link: https://www.amazon.com/gp/product/B074JJ6NGQ/ref								
B074TBMC7N	STEPPERONLINE Digital Stepper Driver 1.8~5.6A 20-50VDC for Nema 23, 2	1	\$ 39.95	\$ 39.95					
	Product Link: https://www.amazon.com/gp/product/B074TBMC7N/re								
B00W8FQJR8	POW PowerBoard Box3 Kit - KBOX3-AL-BK-POW, Black Enclosure with 5 C	1	\$ 32.99	\$ 32.99					
	Product Link: https://www.amazon.com/gp/product/B00W8FQJR8/re								
B0040Z6OYC	POW3U PowerBoard-3U with Power Rails, 1 Sided PCB, 3.94 x 6.30 in (100	3	\$ 10.78	\$ 32.34					
	Product Link: https://www.amazon.com/gp/product/B0040Z6OYC/ref								
B06XFRJD56	Rubber Sheets, Black, (Pack of 3) 6x6-Inch by 1/8 (+/-10%) Neoprene, Plu	1	\$ 11.43	\$ 11.43	\$ -	\$ -	7	\$ 236.27	
	Product Link: https://www.amazon.com/gp/product/B06XFRJD56/ref								
B0719PSZVK	Rubber Sheets, Black, (Pack of 3) 6x6-Inch by 1/4 (+/-5%) High Grade Shor	1	\$ 15.83	\$ 15.83					
	Product Link: https://www.amazon.com/gp/product/B0719PSZVK/ref								
B001C4SJ7Y	Big Horn 19100 5/8" Conveyor Roller Ball Transfer Bearings, Set of 6	1	\$ 13.83	\$ 13.83					
	Product Link: https://www.amazon.com/gp/product/B001C4SJ7Y/ref								
B000OQ03KM	Bertech ESD Mat Kit with a Wrist Strap and a Grounding Cord, 18" Wide x	1	\$ 56.90	\$ 56.90					
	Product Link: https://www.amazon.com/gp/product/B000OQ03KM/re								
MMF309321	SA-06-060WR-120 STACKED ROSETTE (5/PK)	4	\$ 123.38	\$ 493.52	\$ -	\$ -	8	\$ 493.52	
	Product Link: N/A								
B078VTCDK1	uxcell 8mmx12mm Clamp Tight Motor Shaft 2 Diaphragm Coupling Coupl	2	\$ 15.89	\$ 31.78					
	Product Link: https://www.amazon.com/gp/product/B078VTCDK1/ref								
B00C32ME6G	Starbond EM-02 Super Fast Thin, PREMIUM Instant CA (Cyanoacrylate Ad	2	\$ 10.79	\$ 21.58					
	Product Link: https://www.amazon.com/gp/product/B00C32ME6G/re								
B01KO48D5K	Texas Instrumen UA741CP OP Amp Single General Purpose 18V 8-Pin Pla	2	\$ 9.67	\$ 19.34					
	Product Link: https://www.amazon.com/gp/product/B01KO48D5K/ref								
B078WT94S7	DC Power Supply Variable, LIUMY LM7005 Adjustable Switching Regulate	2	\$ 59.99	\$ 119.98	\$ -	\$ -	9	\$ 243.90	
	Product Link: https://www.amazon.com/gp/product/B078WT94S7/ref								
B078VR9V7J	uxcell 8mmx10mm Clamp Tight Motor Shaft 2 Diaphragm Coupling Coupl	2	\$ 13.62	\$ 27.24					
	Product Link: https://www.amazon.com/gp/product/B078VR9V7J/ref								
B01HICVLG4	Texas Instruments 20 Pieces UA741CP IC OPAMP GP 1MHZ SGL LP 8DIP 74	2	\$ 11.99	\$ 23.98					
	Product Link: https://www.amazon.com/gp/product/B01HICVLG4/ref								
2055808	POLO GREY	8	\$ 31.92	\$ 255.36	\$ -	\$ -	10	\$ 255.36	
	Product Link: N/A								
B000HBM6PE	Source One Premium 1/4 Clear Acrylic PlexiGlass Sheet 12 x 12 Inches (\$	8	\$ 13.99	\$ 111.92					
	Product Link: https://www.amazon.com/gp/product/B00844SOSE/ref								
B01DBVB8KK	uxcell 8mm to 10mm Shaft Coupling 25mm Length 19mm Diameter Stepp	2	\$ 6.83	\$ 13.66					
	Product Link: https://www.amazon.com/gp/product/B06X99VXPV/ref								
B07B4DNJ2L	Source One Premium 1/4 Clear Acrylic PlexiGlass Sheet (12" X 24")	1	\$ 31.99	\$ 31.99					
	Product Link: https://www.amazon.com/gp/product/B01FIMWAHU/r								
B01FIMWAHU	4pcs 50KG Load Cell Half-Bridge Human Body Scale Weight Weighting Se	1	\$ 9.99	\$ 9.99	\$ -	\$ -	11	\$ 206.73	
	Product Link: https://www.amazon.com/gp/product/B07B4DNJ2L/ref								
B06X99VXPV	Shop Craft 37722 12" x 20" x 1/32" High Temperature Gasket Material	1	\$ 5.29	\$ 5.29					
	Product Link: https://www.amazon.com/gp/product/B01DBVB8KK/re								
B00844SOSE	Permatex 99070 The Right Stuff Gasket Maker, 5 oz. - 2 Pack with Caulkin	1	\$ 33.88	\$ 33.88					
	Product Link: https://www.amazon.com/gp/product/B000HBM6PE/re								

B004026QYC	POW3U PowerBoard-3U with Power Rails, 1 Sided PCB, 3.94 x 6.30 in (100 x 160 mm) Product Link: https://www.amazon.com/gp/product/B004026QYC/ref=ox_sc_act_title_1?smid=A2BKGEIGG4B1JT&ps	3	\$ 10.78	\$ 32.34					
B00W8FQJRB	POW PowerBoard Box3 Kit - KBOX3-AL-BK-POW, Black Enclosure with 5 Card Guides and a Size 3 PCB Product Link: https://www.amazon.com/gp/product/B00W8FQJRB/ref=ox_sc_act_title_2?smid=A2BKGEIGG4B1JT&ps	1	\$ 32.99	\$ 32.99					
B0185FHFSQ	E-Projects 100EP514120R 120 Ohm Resistors, 1/4 W, 5% (Pack of 100) Product Link: https://www.amazon.com/gp/product/B0185FHFSQ/ref=ox_sc_act_title_3?smid=AQDFMQUHD0RBM&ps	2	\$ 6.37	\$ 12.74					
B072BL2VX1	Elegoo 17 Values 1% Resistor Kit Assortment, 0 Ohm-1M Ohm (Pack of 525) RoHS Compliant Product Link: https://www.amazon.com/gp/product/B072BL2VX1/ref=ox_sc_act_title_4?smid=A2WwHQ25ENKwJ18&ps	3	\$ 10.86	\$ 32.58					
B01MY5QKH1	30ft Wireless Bluetooth RF Transceiver Module serial RS232 TTL HC-05 for arduino Product Link: https://www.amazon.com/gp/product/B01MY5QKH1/ref=ox_sc_act_title_5?smid=A1CAGQ66D4VwJF&ps	2	\$ 11.00	\$ 22.00	\$ 34.02	\$ -		12	\$ 221.44
B07K7JF3HX	Ximimark 5Pcs 16CH Analog Digital Multiplexer Breakout Board Module CD74HC4067 CMOS Precise Module For Arduino Product Link: https://www.amazon.com/gp/product/B07K7JF3HX/ref=ox_sc_act_title_6?smid=A1D0D0TVUQPH3B&ps	1	\$ 6.99	\$ 6.99					
B01M70EDCW	BNTECHGO 30 Gauge Silicone Wire Kit Ultra Flexible 10 Color High Resistant 200 deg C 600V Silicone Rubber Insulation Product Link: https://www.amazon.com/gp/product/B01M70EDCW/ref=ox_sc_act_title_7?smid=AITZQ53LNBA1K&ps	3	\$ 9.48	\$ 28.44					
B01K048D5K	Texas Instrumen UA741CP OP Amp Single General Purpose 18V 8-Pin Plastic Dip Tube (Pack of 20) Product Link: https://www.amazon.com/gp/product/B01K048D5K/ref=ox_sc_act_title_1?smid=ATVPOKIKX0DER&ps	2	\$ 9.67	\$ 19.34					
B01DLHKLNE	HiLetgo CD74HC4067 CMOS 16 Channel 16 CH Digital Analog Multiplexer Breakout Module for Arduino Product Link: https://www.amazon.com/gp/product/B01DLHKLNE/ref=ox_sc_act_title_1?smid=A30QSGQJ8L MxA&ps	6	\$ 5.29	\$ 31.74	\$ 13.16	\$ -		13	\$ 164.75
B074TBMC7N	STEPPERONLINE Digital Stepper Driver 1.8°5.6A 20-50VDC for Nema 23, 24 Stepper Motor Product Link: https://www.amazon.com/gp/product/B074TBMC7N/ref=ox_sc_act_title_2?smid=AwQBCGwSS7BL&ps	3	\$ 39.95	\$ 119.85					
B06XH648M7	Clear Polycarbonate Lexan Sheet - 1/4" (12" x 24") for window replacements, signage, display cases, aquarium covers, gr Product Link: https://www.amazon.com/gp/product/B06XH648M7/ref=ox_sc_act_title_1?smid=A1Q76FERHQHXA&ps	7	\$ 33.78	\$236.46	\$ 53.20	\$ -		14	\$ 235.66
N/A	Machining of Polycarbonate Product Link: http://mwc.arizona.edu/	1	\$ 295.00	\$295.00	\$ -	\$ -		15	\$ 295.00
CON-1200	12 PIN CONNECTOR Product Link: https://www.allelectronics.com/item/con-1200/12-pin-connector/1.html	12	\$ 3.45	\$ 41.40	\$ 79.00	\$ -		16	\$ 120.40
N/A	Poster Printing Product Link: N/A	1	\$ 85.00	\$ 85.00	\$ -	\$ -		17	\$ 85.00