

M.Eng. MAE Final Engineering Report

To:

Mr. Matt Ulinski
Director, Master of Engineering Program
Sibley School of Mechanical and Aerospace Engineering
Cornell University

Subject: *2-D Continuum Arm for Compliant Surface Manipulation*

Dear Mr. Ulinski,

I am pleased to submit my final report, "*2-D Continuum Arm for Compliant Surface Manipulation*," in fulfillment of the requirements for the Master of Engineering program in Mechanical and Aerospace Engineering at Cornell University. This report documents my contributions to the Robot Room project, conducted under the supervision of Dr. Keith Evan Green, from Fall 2024 through Spring 2025.

My main work (Spring 2025) involved scaling and implementing a tendon-actuated robotic continuum arm to deform a compliant ceiling surface. I specifically contributed to the physical room structure, redesigned and manufactured two instances of the robotic arm, and developed the Arduino-based control software for their actuation.

I am grateful to Dr. Green for his invaluable support and guidance throughout this project. Please contact me if any additional information is required.

Sincerely,

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May 19, 2025

Title Page

Project Title: *2-D Continuum Arm for Compliant Surface Manipulation*

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Program: Master of Engineering (M.Eng.)

School: Sibley School of Mechanical and Aerospace Engineering

Institution: Cornell University

Date: May 19, 2025

Abstract

This project builds upon prior lab research involving tendon-actuated robotic armatures that deform compliant surfaces. Early prototypes aimed to use flexible tendrils to manipulate fabric surfaces but suffered from issues like tendon slack, limited torque, and restricted surface engagement. The system introduced here improves on that concept by rotating the entire motor and pulley assembly, maintaining consistent tendon tension across its range of motion and eliminating slack when changing pulling angles. Testing showed that the new design provides expressive, reliable deformation and returns close to its original position, validating its potential for use in adaptive environments. Applications include aesthetic and practical enhancements in spaces that can be achieved via compliant surfaces. This work contributes a practical solution for incorporating robotics into everyday architecture. The final prototype demonstrates the feasibility of this mechanism as a programmable robotic element in architectural spaces.

Executive Summary

Problem:

Indoor spaces often feel stagnant and confining, negatively impacting emotional well-being. To address this, Professor Keith Evan Green of Cornell University's Architectural Robotics Lab proposed dynamically reshaping ceilings to create emotionally transporting environments. However, the lab's initial robotic prototype intended to manipulate compliant surfaces suffered from limited practicality, performance, and robustness.

My project addressed these limitations by scaling and enhancing the robotic concept into a practical, full-scale system capable of reliably deforming a latex-fabric ceiling. Specifically, I:

- **Scaled and Redesigned** the original concept into a robust system.

- **Increased Structural Stiffness** of the continuum arm, allowing reliable shape recovery.
- **Enhanced Range of Motion** by improving tendon routing and motor selection.

Discoveries and Outcomes:

Iterative development revealed essential insights for successful implementation:

- **Balance of Core Stiffness and Motor Strength:** Adequate stiffness is critical for the continuum arm to counteract gravity-induced sagging, but must be carefully balanced to prevent motor stalling during actuation.

The final scaled-up system demonstrated effective and feasible robotic manipulation of a compliant surface. Informal demonstrations confirmed observers felt engaged and intrigued, validating the project's emotional and experiential objectives.

Recommendations:

To further improve the capabilities of the design, I recommend:

1. **Reducing Shear Forces with Improved Tendon Routing:**
Strategically routed tendons using pulleys will significantly reduce friction and shear forces, enhancing range of motion and structural longevity.
2. **Connecting Multiple Arms End-to-End:**
Mechanisms enabling the linking of continuum arms will dramatically increase achievable shape complexity and emotional impact.
3. **Direct Surface Attachment:**
Direct attachment of robotic arms to target surfaces will ensure maximal expressive deformation.

Implementing these recommendations will elevate robotic ceilings from prototypes to versatile and unique architectural features with compliant surfaces.

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Acknowledgments

I would like to thank Professor Keith Evan Green for his mentorship, as well as Nithesh Kumar, Katelynn Thorne, Ge Lv, and Ian D. Walker. Special thanks to the M.Eng. program staff for their guidance throughout the semester.

1. Introduction

The purpose of this project was to improve and scale a robotic mechanism capable of dynamically reshaping a compliant surface, designed to evoke positive emotional responses in occupants of indoor spaces. A prior prototype developed in Cornell University's Architectural Robotics Lab introduced the concept of tendon-actuated continuum arms for deforming architectural surfaces but faced practical limitations such as insufficient stiffness and limited expressive range.

The main objective of this project was to redesign and scale the original robotic arm concept for reliable performance at room-scale. This report discusses the previous design and its limitations, then describes my specific improvements, including mechanical design changes and control system enhancements. Finally, the report evaluates the functionality of the newly developed prototype, presenting results that demonstrate its improved capability to manipulate compliant surfaces in practical and engaging ways.

2. Background

Most rooms are static, and that can make people feel stuck or disconnected—especially in places where they spend a lot of time, like offices, hospitals, or homes. There's growing interest in making spaces that can change and adapt to help relieve some of those feelings as people go about their daily tasks.

Some architects and engineers are exploring movable walls, shifting ceilings, and shape-changing surfaces. This project focuses on developing a low-cost, easy-to-implement device that can change the shape of compliant surfaces. The system must physically reshape a surface in expressive ways. The reshaping and movement of the surface is meant to make a space feel more dynamic and, when possible, to increase the space's utility. If refined and scaled, this kind of device could be used in hotel rooms as an aesthetic feature, or in office spaces where the ceiling drops down to create private, cubicle-like zones in otherwise open environments.

3. Literature Review

This project builds on research in three main areas: **soft and continuum robotics**, **robotic/morphing surfaces**, and **architectural robotic systems**. This project takes ideas from past research and applies them into a simple mechanism to be used in a real-world scenario for architectural robotics.

A. Soft and Continuum Robotics

These projects focus on flexible robotic arms, pneumatic actuators, and tendon-based motion systems:

- **Habibi et al. (2020)** modeled how robotic arms can deform large surfaces using a lumped-mass model.
 - **Digumarti et al. (2019)** introduced pellicular surfaces for soft robots that can morph shape.
 - **Shepherd et al. (2011)** created a soft robot with multiple gaits using silicone and air channels.
 - **Chen et al. (2018)** developed soft surfaces made from hyperelastic materials.
 - **Bhat et al. (2023)** designed soft actuators using extensible fabric-based skins.
 - **Dupont et al. (2010)** provided core modeling for tendon-driven robots (concentric tube designs).
-

B. Robotic and Morphing Surfaces

These works explore flat or curved surfaces that can change shape using actuators embedded within them:

- **Tan et al. (2022)** embedded McKibben muscles in a woven surface to shape walls and ceilings.
 - **Liu et al. (2021)** created reversible shape-morphing robotic panels.
 - **Bai et al. (2022)** developed reprogrammable surfaces that adapt in real-time.
 - **Deng et al. (2018)** and **Medina et al. (2016)** built robotic tables and manifolds that push and manipulate objects.
 - **Wang et al. (2019)** and **Lu et al. (2023)** modeled morphing surfaces and soft robotic tongues.
 - **Johnson et al. (2023)** built high-speed robotic shape displays with sensing and feedback.
-

C. Architectural Robotics and Robot Rooms

This is the most directly relevant category. It includes spatial robotics and human-centered environments:

- **Sirohi et al. (2019)** and **Tan et al. (2022)** created tendon-driven robot surfaces for ceilings and walls.

- **Kumar et al. (2024)** ran user studies on robot-room systems and what people expect from them.
 - **Houayek et al. (2014)** introduced the Animated Work Environment (AWE), merging robotics with workspace flexibility.
 - **Green (2016)** formalized the vision of architectural robotics—where rooms respond like robots.
-

4. Theory

This project uses a **tendon-actuated continuum arm** to deform a compliant ceiling surface. The arm is designed to bend in a smooth arc when a tendon (cable) is shortened, pulling the tip toward the base and creating a dome-like shape. The motion is modeled using **constant curvature kinematics**, a common method for describing the bending behavior of soft or flexible robotic arms.

4.1 Constant Curvature Assumption

The backbone of the arm is assumed to bend into a circular arc, meaning the curvature stays the same along its length. This simplifies the math and allows the arm's position and shape to be calculated from just a few parameters.

The key variables are:

- θ : angle of bending (in radians)
- κ : curvature of the arm
- s : arc length of the backbone
- Δl : change in tendon length
- r is the radial distance from the center of the arm to the tendon.

$$\kappa = \frac{\theta}{s}, \quad \Delta l = r \cdot \theta$$

You can also express the **end-effector (tip) position** as:

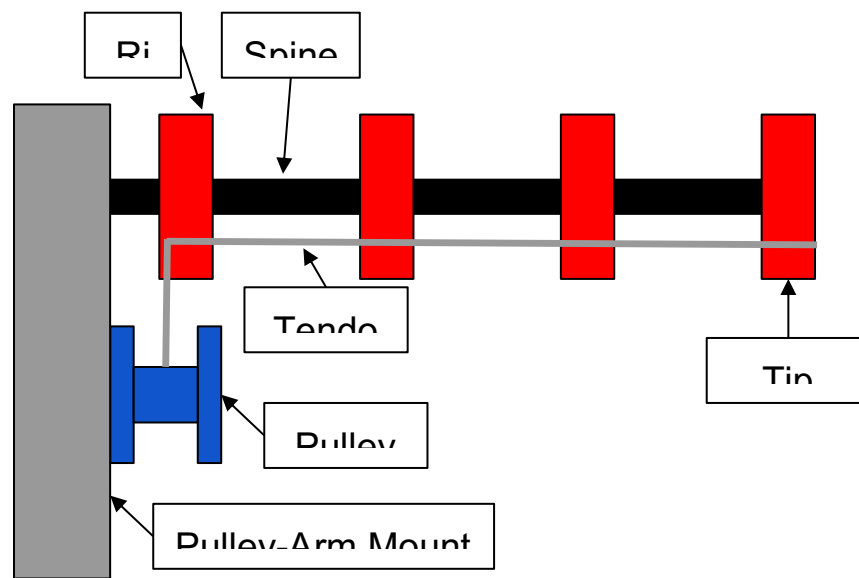
$$x = \frac{1}{\kappa} \sin(\theta), \quad y = 0, \quad z = \frac{1}{\kappa} (1 - \cos(\theta))$$

This gives the 3D position of the tip in space, assuming the arm bends in the x-z plane.

4.2 Applying to a Single Tendon Arm

In this project, the arm uses a **single tendon**, routed along one side of a carbon fiber rod (spine). When the tendon is shortened by the motor, it causes the arm to bend toward the cable side. The carbon fiber backbone provides natural spring-back, so when the cable is released, the arm returns to its neutral, straightened state without requiring a second tendon or actuator.

Unlike more complex continuum robots that use multiple tendons for 3D steering, this setup only bends in a single vertical plane. To increase range of motion, the pulley-arm assembly is mounted on a motor, which can rotate the side that has the tendon. This allows the direction of the arm's bend to be changed relative to the environment.



(Fig 1. Diagram of Device)

5. Design and Decision Criteria

Requirements

- **Reliable Tendon Actuation:** The system needed to maintain consistent tendon tension during movement to avoid slack that would reduce control and precision.
- **Compactness and Simplicity:** It had to be small enough to fit into a room environment and simple enough to be manufactured and maintained easily.

- **Enough Force to Deform the Surface:** The motor and mechanical setup had to generate enough torque to meaningfully manipulate the latex ceiling material.



(Fig 2. The original robot surface prototype. Flexible surface shown with four markers attached for quantitative measurements. Actuation package below surface.)

Constraints

- **Simplicity:** The system had to be simple, as the system is meant to work in partnership with others like it in different configurations.
- **Low Profile:** The system was designed specifically to complement other devices in the proposed robot room, and should ideally take up as little space as possible.

Design Decisions & Trade-offs

The original prototype suffered from two main issues:

- **Inconsistent tendon tension:** changing the pulling direction would introduce slack due to the fixed pulley orientation..
- **Oversized and underpowered:** the architecture took up a lot of space relative to its size and lacked the torque needed to create strong deformations.

To solve this, I redesigned the system so that the entire pulling arm assembly including the motor would rotate together, keeping the tendon path constant relative to the pulling angle. This eliminated the slack issues and improved control.

This choice introduced a trade-off in the range of motion. It was now limited to 180 degrees due to the physical constraints of rotating the motor housing.



(Fig 3. Circled in red, the tendon routing in the old prototype does not allow for constant tension as the device rotates.)

Evaluation Metrics

- **Range of Motion:** Measured how far the arm could deform the surface within its rotation limits.
 - **Surface Response:** Observed the quality and predictability of surface deformation during actuation.
 - **Ease of Assembly and Repeatability:** Assessed whether the design could be replicated affordably and integrated into future versions.
-

6. Materials and Apparatus

This section lists the primary mechanical, electrical, and structural components used in the construction of the tendon-actuated continuum arm system. To see the drawing of the parts look at Appendix B.

6.1 Structural Components

- **Carbon Fiber Rods (.125 in diameter, 48 in length)**
Used as the flexible backbone of each continuum arm. Glued into the receiving hole in the Pulley-Arm Mount. Chosen for high stiffness-to-weight ratio and spring-back behavior.

- **3D-Printed Ribs (x26) (x1 Rib Cap) (PLA)**
Custom-designed ribs. Held in place when spaced out at 1.6 in until no more can fit on the outside of the Arm-Frame mount. More details in assembly.
- **3D Printed Pulley**
Slides onto the motor and spools the tendon.
- **3D Printed Pulley-Arm Mount**
Custom-built to hold the arm, the pulley for the arm, and the motor to drive the pulley.
- **3D Printed Arm-Frame Mount (PLA)**
Custom-built to hold the motor the Pulley Arm Mount is attached too. Allows for 180 degrees of motion. Attached the whole unit to the robot room frame.
- **Stainless Steel Cable – Bare 7x19, Commercial Grade**
Acts as the tendon to ensure it does not snap and slides smoothly through the ribs to actuate the arm.

6.2 Control and Electronics

- **Motor: (2x)** 5202 Series Yellow Jacket Planetary Gear Motor (188:1 Ratio, 30 RPM, 3.3 - 5V Encoder) Chosen for high torque to allow arm to keep position even after turning off.
Motor Controller: (x2) Pololu G2 High-Power Motor Driver 24v13
- **Microcontroller:** Arduino Mega 2560. Used to read the encoder from the motor and control the motor via the motor controller.
- **Battery:** Mighty Max Battery ML5-12
- **Breadboard + Jumper Cables:** Used to power the encoder, and motor controller with 5v from the arduino.
- **Power Distribution Blocks:** Used to distribute power to many motors (for many mechanisms in total)

6.3 Surface Material

- **Spandex Fabric:** Chosen for its ability to visibly deform under tendon force while remaining flexible enough to spring back. Used for the anecdotal use case.

6.4 Assembly

- Step One: Use (x4) M4 x 0.7 (10mm max length) screws to attach a motor to the Arm-Frame Mount
- Step Two: Use a mallet and some kind of metal pole to gently press fit the Pulley-Arm Mount onto the Arm-Frame motor shaft.
- Step Three: Use (x4) M4 x 0.7 (10mm max length) screws to attach a motor to the Pulley-Arm Mount
- Step Four: Press fit the pulley onto the Pulley-Arm motor
- Step Five: Put the carbon fiber rod in its mounting hole and use a dot of hot glue to secure, then use WeldBond (Epoxy).

- Step Six: Slide all spacers down the shaft, leaving two near the pulley and behind the Arm-Frame mount and the rest in front.
- Step Seven: Thread the steel wire through all the ribs and securely wrap and tie to pulley and Rib Cap.
- Step Eight: Pull on string in its downward direction to align the rib caps hole with the pulley. Use a dot of hot glue to secure the RibCap, then apply WeldBond (Epoxy). Space each rib 1.6 in away from the last (Inside to Inside), secure with a dot of hot glue and then apply epoxy. When you reach the last two, space .1 inches away from one another, and position them to best meet the wire coming from the pulley. Glue and Epoxy like the others. Ensure that all rib holes are aligned by applying tension to the tendon.



(Fig 4. Final Assembly)

6.5 Wiring

The electronic components of the system were wired according to standard Arduino-compatible practices, ensuring robust signal and power delivery across the entire system.

Motor Wiring (Each Motor Setup):

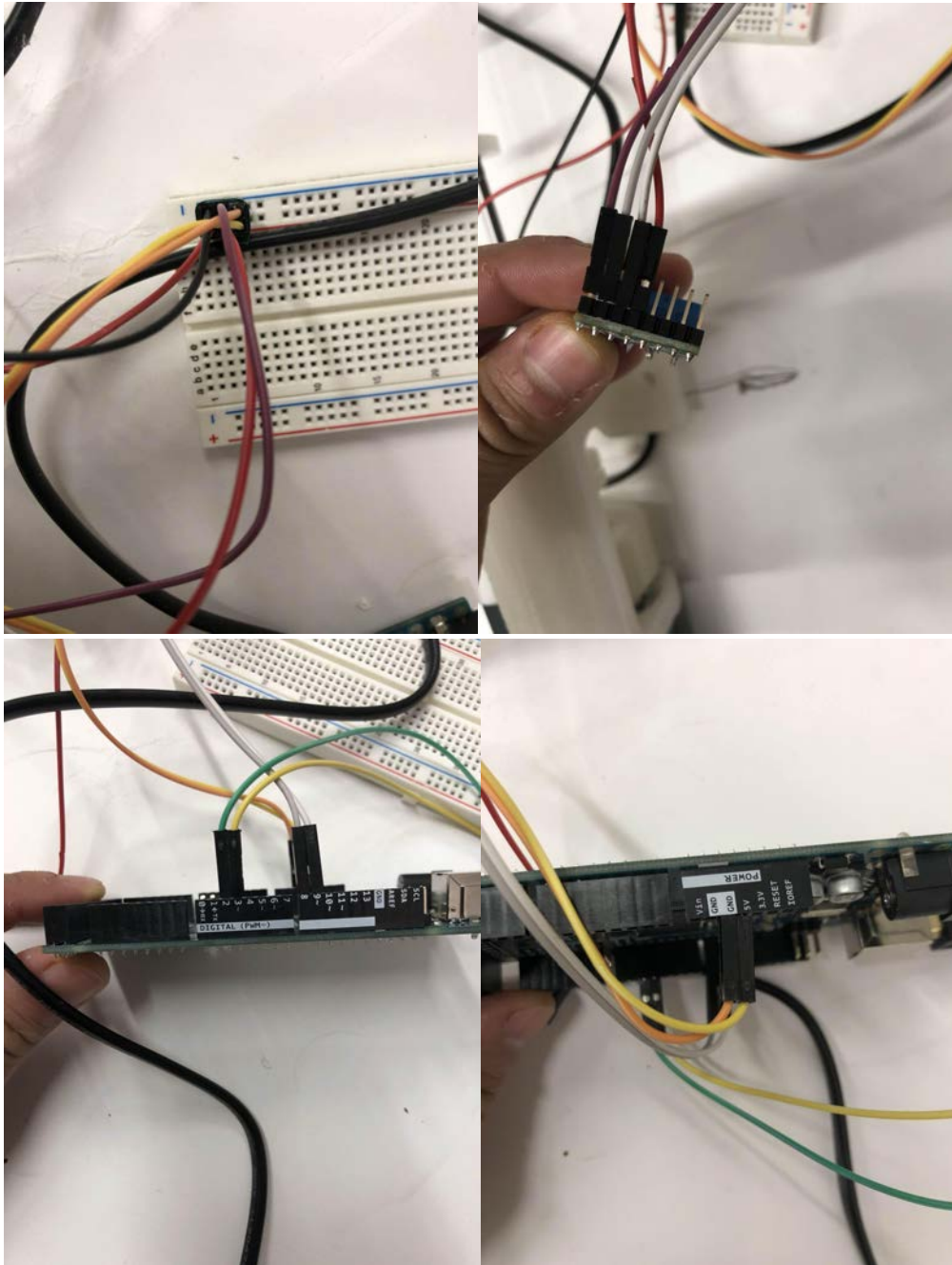
- **Motor Power:**
 - Red wire (Motor +) → M+ terminal on Pololu G2 Motor Driver
 - Black wire (Motor -) → M- terminal on Pololu G2 Motor Driver
- **Motor Driver Control Lines** (from Arduino Mega 2560):

- Gray wire (DIR) → Digital Pin
- White wire (PWM) → Digital Pin
- Purple wire (GND) → Arduino GND
- Red Wire (SLP) (5V from Arduino Mega)
- **Motor Power Supply:**
 - Motor power supplied by the **Mighty Max 12V battery** through a **power distribution block**. (To account for more assemblies being used together.)

Encoder Wiring (Each Encoder):

- **Red** = VCC (5V from Arduino Mega)
- **Black** = GND
- **Yellow** = Channel A → Digital Pin
- **Green** = Channel B → Digital Pin

Note: 5v and Ground Shared through breadboard for power distribution.



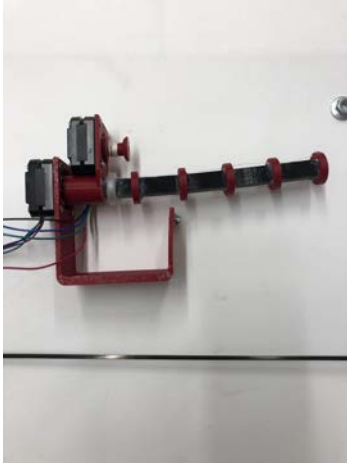
(Fig 5,6,7,8: Pictures of Wiring)

7. Procedure

Prototype Development

1. Initial Scale Prototype – Stepper Motor Test

A small-scale prototype was constructed using NEMA 17 stepper motors to evaluate motor placement feasibility and test tendon-driven actuation. Although the setup allowed for conceptual validation, the stepper motors lacked sufficient torque to rotate themselves or deform the arm reliably.



(Fig 9. Stepper Prototype)

2. Glass Fiber Rod Prototype

The second prototype used a 42-inch long, 0.062-inch diameter glass fiber rod to assess the feasibility of using a lightweight, flexible backbone. The newly selected gear motors (Yellow Jacket 5202, 188:1) successfully actuated the arm, but the rod was too compliant to support its own weight or meaningfully and controllably deform itself or a fabric ceiling.



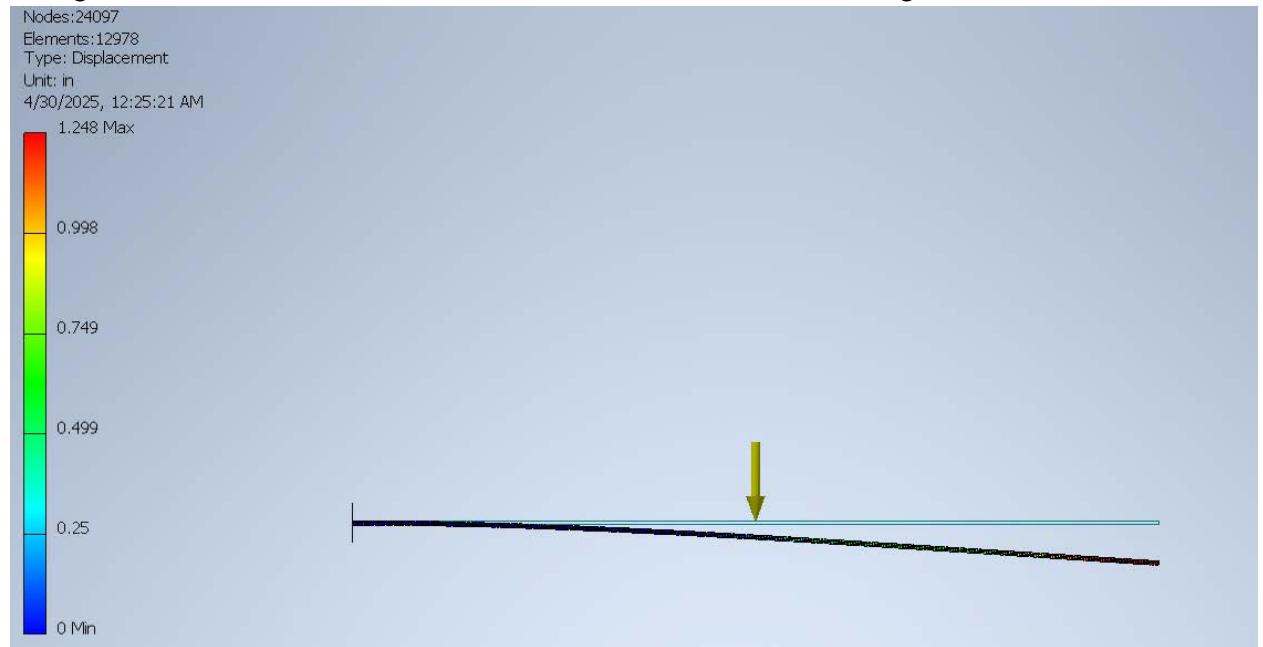
(Fig 10. Glass Rod Prototype)

3. Material Selection and Simulation

To address the lack of stiffness, a material search was conducted with the goal of identifying a rod capable of cantilevered support while remaining bendable by the motor-actuated tendon. Carbon fiber was selected for its high stiffness-to-weight ratio.

A simplified cantilever simulation was performed to estimate self-weight displacement for rods of varying diameters. The target was to keep tip displacement under 1.5 inches. The selected .125 in diameter carbon fiber rod met this criterion while remaining actuatable. No other weight like the

rib or wire were modeled under the assumption that they were negligible. This was a bad assumption, as the sag due to the weight of those items were way greater than expected, but still manageable. The selected carbon fiber rod met this criterion while remaining actuatable.



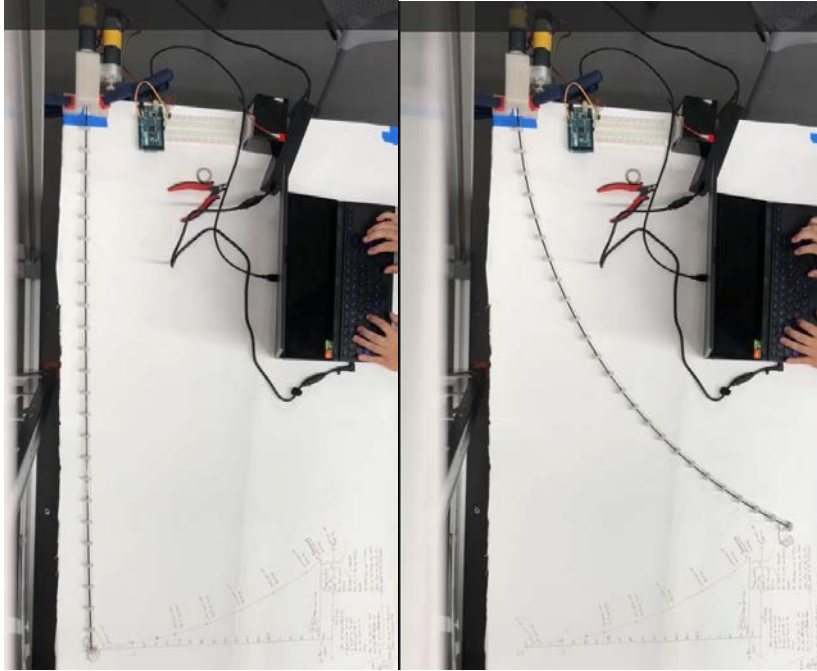
(Fig 11. Displacement Test .125 in)

Physical Testing and Experimentation

Static Deformation Mapping

The current full-scale arm was mounted horizontally to a table. A large sheet of paper was placed underneath to record motion. The motorized pulley was commanded to rotate in 20° increments, and the resulting tip position of the arm was marked manually. This process produced a deformation profile for the arm in free space. The distance from point to point was made to approximate the deformation that

occurred per set amount of turns on the pulley.



(Fig 12,13 . Arm in Initial State Freespace Test (Left), Arm at Recommended Max bend state (Right))

Anecdotal Fabric Deformation Test

To assess real-world performance, the arm was mounted on the robot room frame and positioned above a taut, mounted piece of spandex fabric. The arm was actuated downward without direct attachment to the fabric. This test confirmed that the arm could visibly deform the fabric through applied force alone, validating its ability to interact with compliant surfaces in an architectural context.



(Fig 14. Test Rig for Fabric Deformation)

8. Work Plan

Week(s)	Phase	Key Activities and Milestones
1	Project Planning & Literature Review	Defined scope. Reviewed tendon-actuated continuum robots, morphing surfaces, and architectural robotics.
2	Initial Design Sketches & CAD Models	Developed early CAD designs. Prepared first arm prototype geometry using small-scale parts.
3	Prototype 1: NEMA 17 Stepper Test	Built small-scale prototype. Evaluated tendon actuation concept. Determined motors were underpowered.
4	Prototype 2: Glass Fiber Rod	Constructed 42" glass rod prototype. Verified actuation with Yellow Jacket motors. The identified rod was too flexible.
5	Simulation of Backbone Candidates	Ran cantilever simulations in Inventor. Selected carbon fiber rod with <1.5" deflection under own weight.
6–7	Fabrication of Final Arm	Manufactured ribs, arm mount, pulley, and supports. Epoxied and spaced components on the carbon rod.
8	Assembly & Mechanical Integration	Mounted motors and arm assembly. Installed tendon cable and verified tension across ribs.
9	Wiring & Electronics Integration	Wired encoders and motor drivers to Arduino Mega. Set up breadboard power distribution. Verified control loop.

10	System Debugging & Calibration	Ran functional tests on motor control. Adjusted encoder thresholds and tendon slack.
11	Free-Space Deformation Mapping	Mounted arm horizontally. Ran 20° incremental rotations. Traced arm positions on paper to evaluate arc shape.
12	Fabric Interaction Test	Mounted arm to robot room frame. Evaluated surface deformation of taut spandex fabric in-place.
13	Photo Documentation & Analysis	Captured images of each prototype and setup. Began compiling figures and captions for the final report.
14	Writing Final Report Draft	Finalized technical sections: Theory, Materials, Procedure. Polished wiring diagrams and CAD screenshots.
15	Submission & Presentation	Submitted report. Delivered in-lab demo showing arm deforming ceiling fabric in real-time.

(Table 1: Work Plan)

9. Results

9.1 Free Space Motion

The Carbon Fiber Rod Met stiffness goal (<1.5" displacement under gravity in simulation) without any of the ribs or steel wire attached. In reality, the sag of the prototype was around 6.35 in.

In the freespace movement test, the device was clamped to a table with the plane of bending parallel to the surface of the table. In the cereal monitor, I put in a command over and over to rotate the pulley by 20 degrees. These are the results.

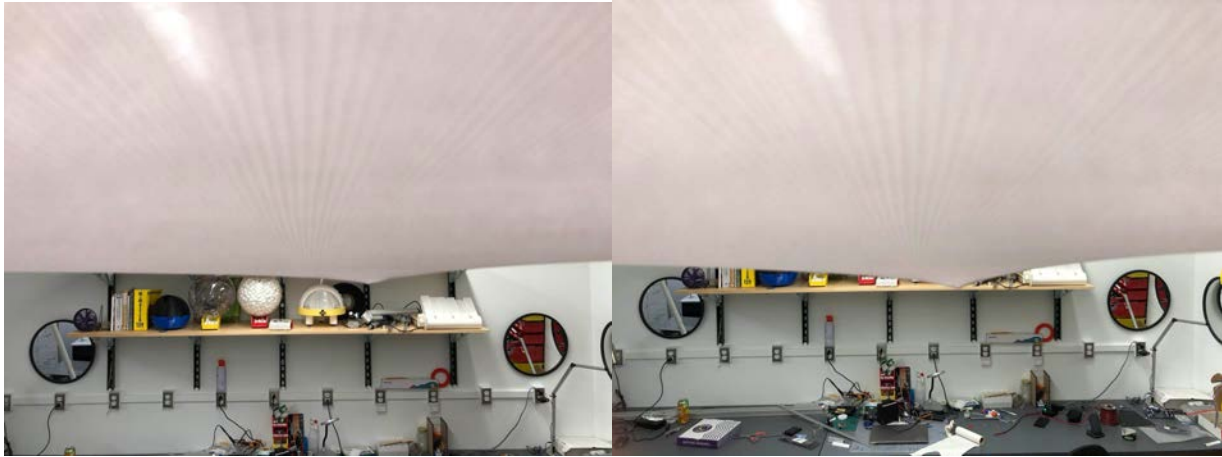
The actuator system achieved smooth and progressive tip deformation with increasing pulley rotation. As the system was commanded from 0° to 140°, the arm tip underwent a cumulative displacement of ~21.18 inches. Displacements between each 20° increment averaged 2.65 inches, with a maximum single step change of 3.64 inches. Encoder feedback closely matched the commanded angles (within ~0.5° error), confirming control accuracy. Deformation gains diminished slightly past 120°, likely due to the wire pushing up against the archway for the Arm-Frame mount.

Angle Commanded (deg)	Angle Read (deg)	Encoder Count	Distance Between Points (in)	Cumulative Tip Displacement (in)
0	0	0	0	0
20	19.83	289	3.013	3.013
40	39.73	580	3.6385	6.6515
60	59.7	872	2.9095	9.561
80	79.54	1162	3.033	12.594
100	99.23	1450	3.3825	15.9765
120	119	1740	3.412	19.3885
140	138.49	2024	1.789	21.177500000000002

(Table 2: Free Movement Results)

9.2 Fabric Interaction Test (Unbound Contact)

To evaluate the arm's ability to deform a compliant surface without direct attachment, an informal test was conducted using a **taut sheet of spandex fabric**. The images below are how well it performed.



(Fig 15, 16. Arm at rest below fabric(Left), Arm at 140 degrees pulley rotation below fabric (Right))



(Fig 17, 18. Arm at rest above fabric(Left), Arm at 140 degrees pulley rotation above fabric (Right))

10. Discussion

The continuum arm system achieved its primary objective: enabling expressive deformation of a compliant surface using a single tendon-actuated mechanism. The measured cumulative tip displacement of 21.18 inches across a 140° range of motion marked a substantial improvement over earlier prototypes, validating the mechanical redesign and material selection.

Theoretical simulations of the rod, which assumed no additional rib or cable weight, underestimated real-world deflection. The observed sag of ~ 6.35 inches (versus <1.5 inches in simulation) highlights the need to include passive load contributions in future models.

A slight drop-off in displacement per degree was observed after 120° , likely due to mechanical interference. The tendon rubbing against the arch of the Arm-Frame mount is the main culprit. This

revealed a geometric constraint that could be mitigated with improved tendon path design or offset pulley routing.

Although the encoder reliably translated commands into angular motion (with $<0.5^\circ$ average error), the tip displacement was not perfectly uniform across all increments. This was attributed to friction between the ribs and the tabletop surface during testing, and possibly to internal cable friction within the rib holes.

In the fabric interaction test, the arm produced visible surface deformation despite being unbound to the fabric. While the force output was not quantified, the test demonstrated that the mechanism is capable of unanchored interaction with compliant surfaces. However, the extent of deformation was limited by the resistance of the fabric exceeding the arm's spring force, which could be mitigated by bounding the arm to the compliant surface.

11. Conclusion

This project successfully developed and validated a single-tendon continuum robotic arm capable of deforming compliant architectural surfaces in expressive ways. Through simulation, prototyping, and iterative mechanical refinement, a practical room-scale actuator was realized.

Key achievements include:

- Verified actuation across 140° pulley motion with precise angular tracking via encoder feedback.
- Demonstrated smooth arc-shaped deformation and ~ 21 -inch cumulative tip displacement.
- Achieved interaction with a taut fabric surface using unbound force-only contact.
- Identified practical design limitations, including gravity-induced sag and tendon path interference.

Overall, the project fulfills its goal of delivering a lightweight, low-profile robotic element that can be installed in architectural spaces.

12. Recommendations

To extend the capabilities and reliability of the design, several improvements are recommended:

1. **Include Passive Loads in Simulation:** Model the weight of ribs, wire, and epoxy during bending simulation to better match real-world performance and avoid underestimating sag.
 2. **Remove Obstacles from tendon path:** Modify the pulley geometry or arch mount clearance to prevent tendon binding at angles $>120^\circ$.
 3. **Implement a Routeing Pulley:** A routeing pulley for the tendon will reduce sheer forces on the carbon fiber rod, allowing for steeper angles without risking delamination.
 4. **Quantify Tip Force Output:** Add load cells or simple force sensors at the tip to measure how much force the mechanism can exert, especially for future vertical interaction tasks.
 5. **Improve Rib Sliding Interface:** Consider adding low-friction bushings or coating inside rib holes to reduce cable friction and variance in tip movement.
 6. **Explore Modular Deployment:** Design brackets or linkages that allow multiple arms to be daisy-chained, enabling richer deformation effects and surface shaping.
 7. **Implement Fabric Attachment Options:** Add optional hooks, Velcro, or soft adhesives to allow the arm to engage fabric directly when greater deformation is required.
 8. **User-Centric Testing:** Conduct observational or user studies on how dynamic ceilings impact occupant emotion, comfort, and space perception.
-

Appendices

Use appendices to include supporting material that would clutter the main report but is still useful for understanding your work.

Suggested Appendices for Your Project:

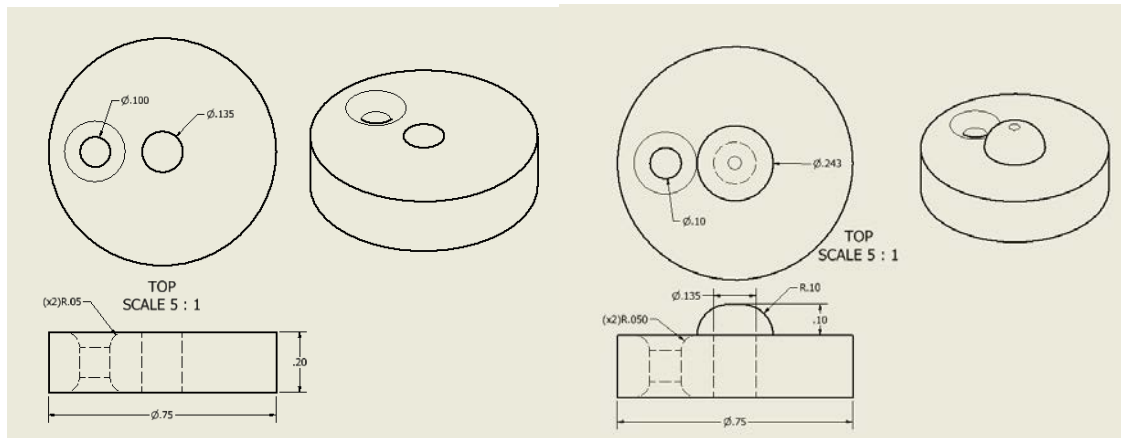
- **Appendix A: Arduino Code**
// MOTOR DRIVER
- **#define DIR_PIN 8**
- **#define PWM_PIN 9**
-
- // ENCODER
- **#define CHA_PIN 2**
- **#define CHB_PIN 3**
-
- **volatile long encoderPos = 0;**
- **volatile uint8_t lastEncoded = 0;**
- **long targetPos = 0;**
- **bool motorActive = false;**

- `String inputString = "";`
-
- `const float COUNTS_PER_DEGREE = 5264.0 / 360.0; // Adjust to your gear ratio and encoder`
- `const int MOTOR_PWM = 26; // 10% speed (26/255)`
-
- `void setup() {`
- `Serial.begin(9600);`
-
- `pinMode(DIR_PIN, OUTPUT);`
- `pinMode(PWM_PIN, OUTPUT);`
- `pinMode(CHA_PIN, INPUT);`
- `pinMode(CHB_PIN, INPUT);`
-
- `attachInterrupt(digitalPinToInterrupt(CHA_PIN), readEncoder, CHANGE);`
- `attachInterrupt(digitalPinToInterrupt(CHB_PIN), readEncoder, CHANGE);`
-
- `Serial.println("Enter commands like 20f or 45b (degrees + direction):");`
- `}`
-
- `void loop() {`
- `// Handle serial input`
- `if (Serial.available()) {`
- `char c = Serial.read();`
-
- `if (isDigit(c) || c == '-') {`
- `inputString += c;`
- `} else if (c == 'f' || c == 'F' || c == 'b' || c == 'B') {`
- `int angle = inputString.toInt();`
- `long delta = angle * COUNTS_PER_DEGREE;`
-
- `// Reverse f and b behavior`
- `if (c == 'f' || c == 'F') {`
- `delta = -delta;`
- `}`
-
- `targetPos = encoderPos + delta;`
- `motorActive = true;`

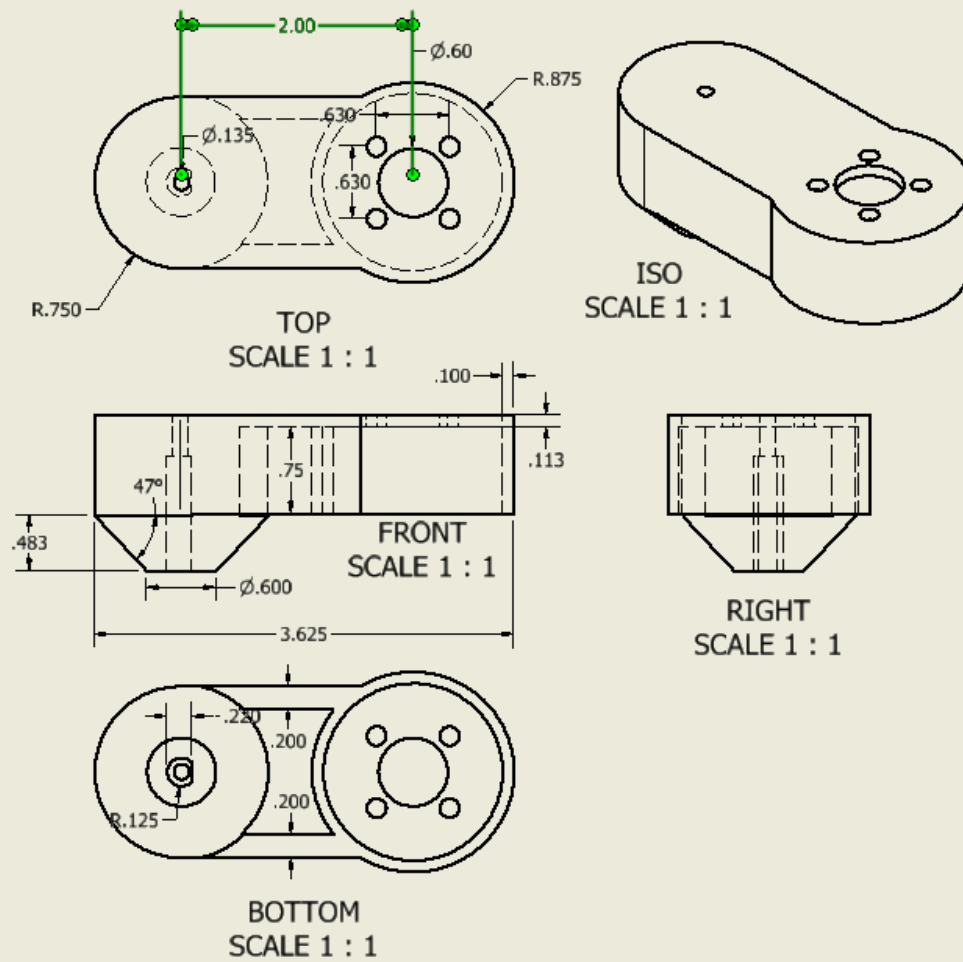
- inputString = "";
-
- Serial.print("Moving ");
- Serial.print(angle);
- Serial.println((c == 'f' || c == 'F') ? "° backward" : "° forward");
- } else if (c == '\n' || c == '\r') {
- inputString = "";
- }
- }
-
- // Motor control loop
- if (motorActive) {
- long error = targetPos - encoderPos;
-
- if (abs(error) <= 3) {
- analogWrite(PWM_PIN, 0);
- motorActive = false;
- Serial.println("Target reached.");
- Serial.print("Current encoder count: ");
- Serial.println(encoderPos);
- Serial.print("Current position in degrees: ");
- Serial.println(encoderPos / COUNTS_PER_DEGREE);
- } else {
- digitalWrite(DIR_PIN, error > 0 ? HIGH : LOW);
- analogWrite(PWM_PIN, MOTOR_PWM);
- }
- }
- }
-
- // Quadrature encoder decoder
- void readEncoder() {
- uint8_t MSB = digitalRead(CHA_PIN);
- uint8_t LSB = digitalRead(CHB_PIN);
- uint8_t encoded = (MSB << 1) | LSB;
- uint8_t sum = (lastEncoded << 2) | encoded;
-
- if (sum == 0b1101 || sum == 0b0100 || sum == 0b0010 || sum == 0b1011)

- `encoderPos++;`
- `if (sum == 0b1110 || sum == 0b0111 || sum == 0b0001 || sum == 0b1000)`
- `encoderPos--;`
-
- `lastEncoded = encoded;`
- `}`

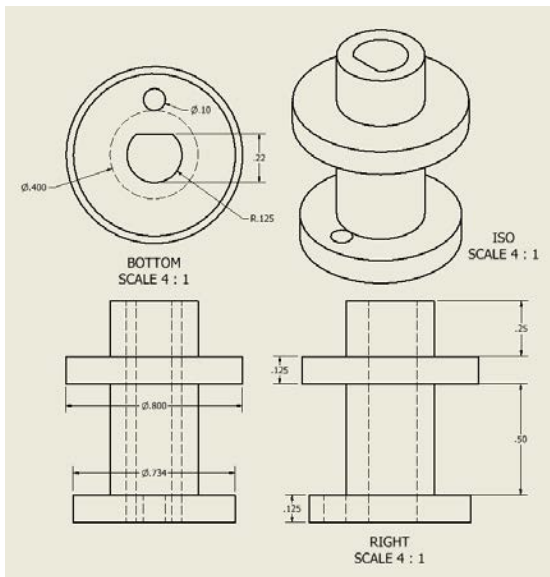
- **Appendix B: CAD Files or Diagrams**



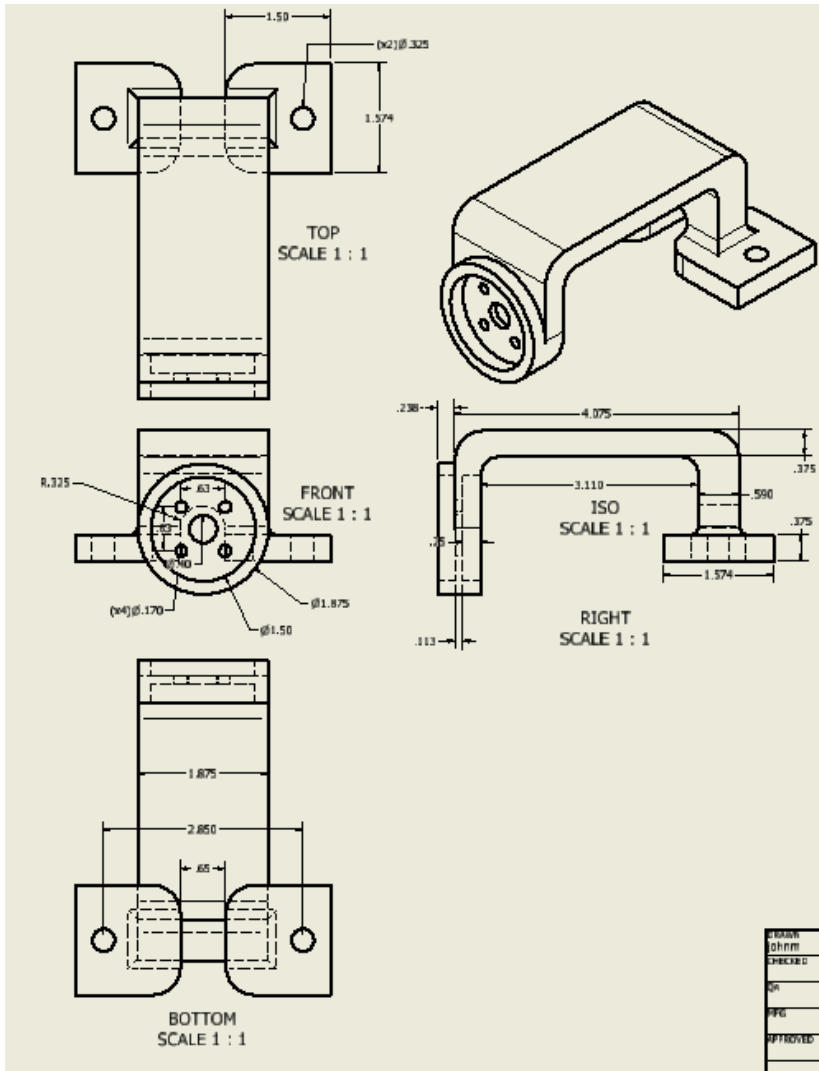
(Fig 19. (left) Rib & Fig 20. Rib Cap (right))



(Fig 21. Pully-Arm Mount)



(Fig 22. Pulley)



(Fig 22. Arm-Frame Mount)

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