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Towards Modular Testbed for Tendon-Driven Soft Robots

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Abstract. Soft robotics integrates engineering, materials science, and biology to tackle challenges that conventional robotics cannot solve. Alongside the advancements in soft robot technology, there is also a need for a standardized hardware platform that can enable benchmarking of various control methods developed for soft-bodied robots. This paper contributes to the state-of-the-art by designing a testbed that features a tendon-driven soft-bodied robot with integrated closed-loop force control.

Keywords: Soft Material Robotics · Force Control · Tendon/Wire Mechanism · Mechanism Design of Manipulators

1 Introduction

Over the past decade, the field of soft robotics witnessed the development of numerous solutions including continuum soft-bodied manipulators [1,2], soft grippers [3], soft exoskeletons [4], and soft robots with the locomotion capabilities in various terrains [5]. Being designed in a way to mimic the biomechanisms of animals and plants [6], their use is foreseen to be especially beneficial in tasks where traditional rigid-structured robots underperform. Precisely, the inherent elasticity of soft robot's body contributes not only to the robot's safety but also provides adaptability to various surroundings, making them useful for applications such as delicate manipulation and exploration [7].

While the main focus has been placed on the technological side of developing soft robots, there is still a significant gap when it comes to controlling these robots and ensuring their consistent and precise behavior. This challenge is being addressed through the range of model-free learning techniques [8] and model-based control methods [9]. However, since each control approach has been verified on different soft robot hardware platforms, there has arisen a need for a standardized hardware platform that can serve as a benchmark for testing these control approaches.

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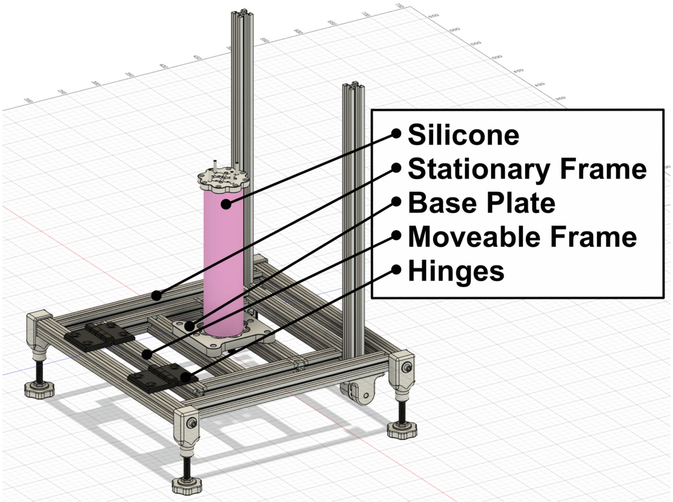

Fig. 1. The soft robot testbed, including the platform and the tendon-driven continuum soft-bodied robot

To address this challenge, openly accessible designs of test benches for both articulated and continuum soft robots have been released. An open-source and modular designs of articulated soft robots have been proposed in [10] and recently in [11]. For continuum robots, a benchmark platform for testing tendon-driven continuum soft robots has been introduced in [12] while, to support testing various tendon-driven continuum soft robot, an open-source actuation module has been proposed in [13].

Inspired by [12], the aim of this paper is to develop an tendon-driven soft robotic hardware setup that serves as an affordable testbed for research and education in soft robotics. Compared to [12], in this work we put the emphasis on modularity of the testbed. Specifically, the design of the testbed supports rod-like soft robot bodies with various lengths and cross-sectional shapes and it also enables the use of custom actuators and offers the possibility to arrange different tendon configurations.

Furthermore, the proposed soft robotic platform has a customized electronics and communication interface specifically tailored to this testbed. This design is both cost-effective and optimized for the proposed actuation system. Additionally, we implement a control system that closes the loop directly through the force feedback. Finally, we conduct experiments on a continuum soft-bodied robot mechanism with inner tendon routing to validate the platform's capabilities.

The main contributions of this paper are the following: 1) a design of a soft robot platform shown in Fig. 1 that serves as a testbed that can be used for benchmarking various control approaches; 2) the experimental results that demonstrate the performance of a soft robot with inner-routed tendons.

2 Hardware Development and Design

This section provides a detailed description of the hardware components, including the design of the platform frame, universal plate, plate holder, casting molds, soft robot's body, and its actuation mechanism.

2.1 Platform Frame Design

The frame of the soft robot platform needs to fulfill the following criteria:

- The frame must be able to support a silicon-made soft-bodied robot along with the associated electronics and actuators;
- The frame should offer a design that is easily configurable, allowing the smooth installation of different actuators and soft-bodied robots;

To meet the first two criteria, the frame of the soft robot platform is constructed using the extruded aluminum profile, whose width and height are 20 mm each. The motivation for selecting this profile was its flexibility when it comes to changing the actuators, adjusting their position or mounting electronics, as well as due to its availability at the market and low-cost. The final design of the frame is illustrated in Fig. 2.

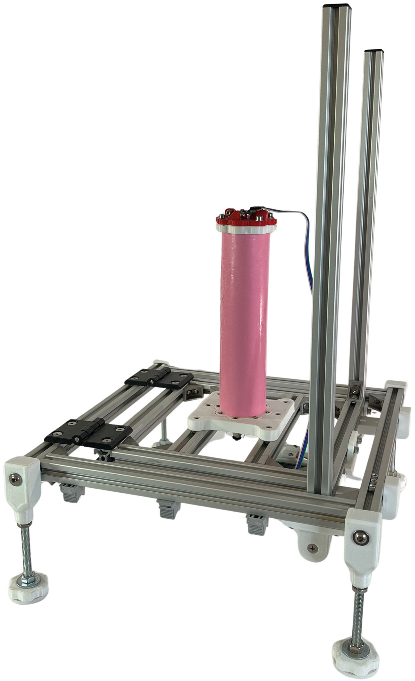

Fig. 2. Aluminum Frame Design (Horizontal Position) – Horizontal position of the aluminum frame.

2.2 Actuation Mechanism

The soft robot uses a tendon-driven actuation system, which requires actuators capable of achieving necessary output torque, while also being compact and easy for control. Therefore, we have selected Pololu geared brushed direct current (DC).

While initially we have considered using a current controller, being motivated by the proportional current-torque relation, this approach proved to be infeasible due to the slack in motor's gearbox and sensor noise. Therefore, we used a 10 kg load cell that provides direct measurements of the tendon tension and can be later used for feeding the control algorithm. The final design of this actuation mechanism is shown in Fig. 3.

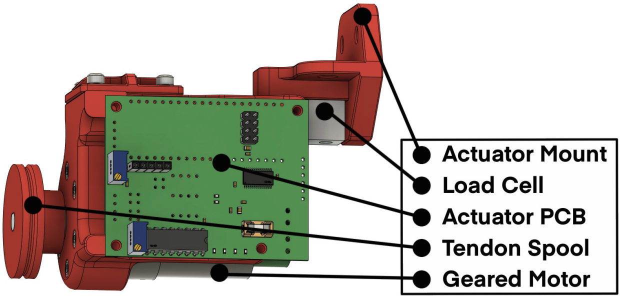

Fig. 3. Force Feedback Actuator – Three-dimensional depiction of the model of the actuator. The red parts are 3D printed.

3 Electronics and Software Development

Each actuator in this setup functions as an independent unit but can also be daisy-chained via the Inter-Integrated Circuit (I2C) interface when multiple actuators are needed. The circuitry was developed to perform a range of critical functions: reading signals from the load cell, controlling the brushed DC motor in both directions, supporting daisy-chaining for communication and power distribution, managing the power supply, and reading user input. The load cell, a piezoresistive element that acts as a resistive bridge and varies resistance with applied force, requires an amplifier circuit for its signals to be read accurately by a microcontroller. For motor control, a driver capable of handling at least 5A is necessary in order to match the motors' rated stall current. The DRV8842 driver was chosen for this purpose.

4 Experimental Results

Based on the contributions described in the previous sections, the platform shown in Fig. 1 has been constructed. This section will focus on testing the soft robotic platform. To validate the actuation mechanism, a sawtooth force reference, ranging from 10 to 50 N, has been commanded and the results obtained are shown in Fig. 4. It can be observed that the tendon forces accurately follow the desired reference within the whole range.

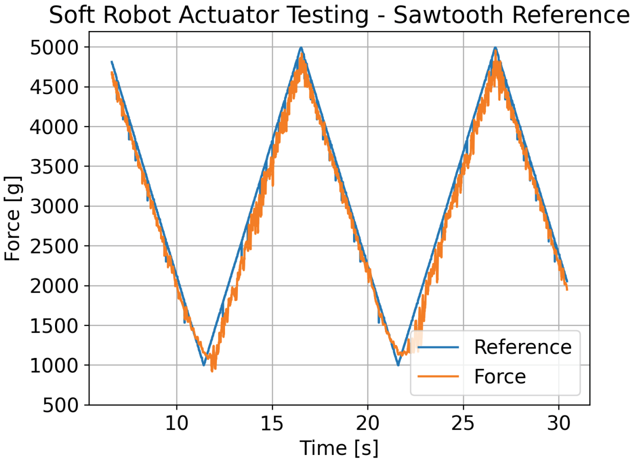

Fig. 4. Sawtooth Reference and Measured Force - The reference went between 1000 g and 5000 g.

When the actuators apply tension to the tendons, the silicone-made soft robot's body inclines towards the corresponding side. The applied force is limited to 50N (5000g), as exceeding this threshold risks the tendons behaving like a cutting edge against the silicone material. The robot's configuration under tendon tension is depicted in Fig. 5.

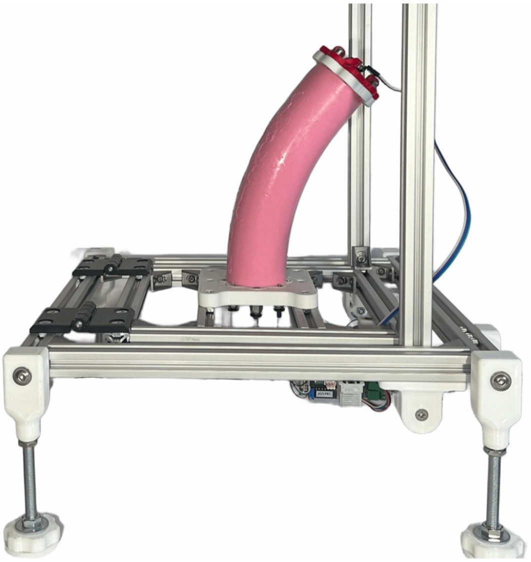

Fig. 5. Robot Static Reference – Robot tilts to a side where the force is applied to the tendons.

Next, we have attached an IMU MPU6050 sensor on top of the robot, which is calibrated such that the 0° value matches the robot's vertical upright position, while 90° describes the robot when its tip is bent to the horizontal position. Figure 6 presents the evolution of the robot's tip angle, obtained when the tendon force are following the previously described reference.

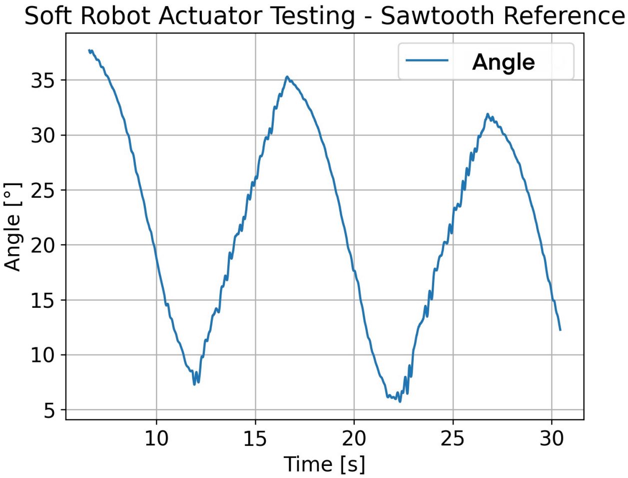

Fig. 6. IMU Angle Measurement - IMU was zeroed out before the start of the experiment, 0° is when the robot is vertical, and 90° would be when the robot's tip is bent to be horizontal.

Furthermore, our aim was to establish the mapping between the tendon force and the achieved robot's tip bending angle in order to enable a more intuitive control, i.e., a control of the robot's angle instead of the tendon forces. To that purpose we exploited the rising edge of the sawtooth signal, which was recorded from the 12th to the 17th second. The related values of the tip angle and the tendon forces were collected and presented in Fig. 7, along with the fitted line, obtained by using the least square method.

Finally, using the parameters of the fitted line, the estimated angle was compared to the IMU values, as shown in Fig. 8. It can be observed that the error is larger along the falling edge of the sawtooth signal, which can be explained by the existence of hysteresis.

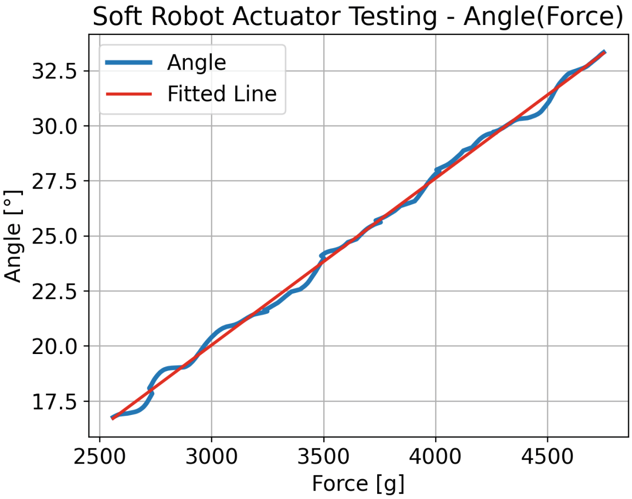

Fig. 7. Measured Angle based on the Tendon Force - This data was used from the rising edge of the central sawtooth peak.

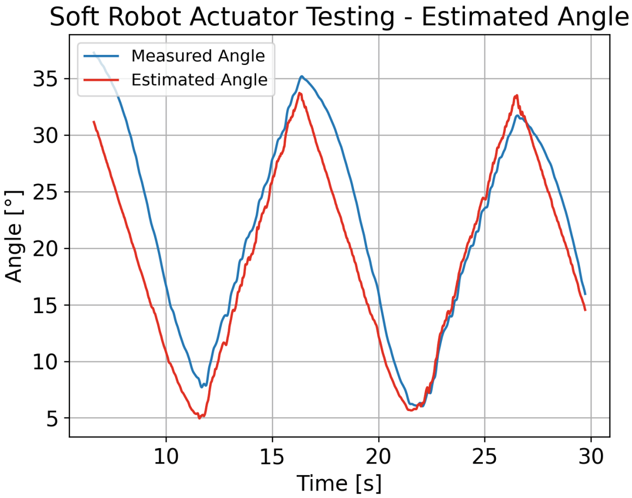

Fig. 8. IMU Angle Compared to Calculated Angle - Parameters for the calculated angle are line parameters of the fitted line.

5 Conclusion

The paper has presented the design and development procedure for each component of the soft robotic hardware setup, including the aluminium frame, silicone mold, actuation mechanism, electronics and software. We have experimentally validated the tendon force control and demonstrated that an accurate tracking of a sawtooth reference force signal is achieved. Furthermore, a relation between the tendon force and soft robot's tip angle has been numerically derived. Future research will tackle the challenge of preventing the tendons to cut through the silicone, as well as enabling the soft robot control by using Robot Operating System and Matlab.

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