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SURF 2025 Interim Report #1

Motivation and Background

Understanding the ground reaction forces and moments at a humanoid robot's foot is essential for achieving robust, adaptable, and dynamically stable locomotion across varied terrains. This information enables control algorithms to react appropriately to foot-ground interactions, such as uneven loading between heel and toe or early loss of contact during a step. My project focuses on the development of a modular tactile sensing foot that can quantify such force distributions during walking. The long-term goal is to develop a lightweight, low-cost, replaceable sensor module that outputs real-time tactile data, contributing to the broader AMBER Lab initiative of designing a full humanoid robot platform by the end of the summer.

This work ties into the broader research within the AMBER Lab, which investigates hybrid systems theory and optimization-based control for robotic locomotion [1, 2]. Previous work has demonstrated that ground contact forces, represented as external reaction terms λ in the Lagrangian formulation, play a central role in multi-domain bipedal walking models [2]. Several prior sensor designs have been proposed to estimate these forces, including MEMS barometric sensor arrays [3], multimodal contact sensing with reconfigurable feet [4, 5], and integrated force-torque sensors [6]. These systems inspire the sensing strategies explored in this project.

Problem and Methods

The core problem is designing and integrating a sensor system that can estimate spatially distributed ground forces under the foot while remaining modular, affordable, and lightweight. Commercial force-torque sensors and pressure mats are often prohibitively expensive or unfit for onboard integration. Therefore, our approach is to prototype with Force-Sensitive Resistors (FSRs) and mechanical push buttons due to their simplicity, availability, and ease of integration. While these sensors have limitations in accuracy and drift, they offer a scalable platform for preliminary force localization, edge detection, and binary contact confirmation.

We are exploring multiple sensing modalities: barometric pressure sensors for distributed sensing, FSRs for localized force detection, and rugged push buttons for binary heel/toe contact validation. The system is being prototyped using a Teensy 4.0 microcontroller and inverting op-amp circuits for signal conditioning. Our initial integration pathway uses analog inputs and voltage dividers, with plans to transition to multiplexed digital buses (e.g., I^2C or CAN) for final integration into the robot. In parallel, we are developing a custom PCB using KiCAD and JLCPCB manufacturing constraints to create a robust, soldered version of the prototype circuit. Mechanically, the sensors are being embedded into a multilayer sole that includes silicone rubber for load distribution and protection, with manufacturer-provided pucks to concentrate forces.

Progress

Significant progress has been made across sensor selection, prototyping, mechanical design, and PCB development. We began with a review of prior foot sensor integrations, including MEMS barometers, FSRs, and six-axis force/torque sensors. We then prototyped a voltage divider circuit using Interlink FSR 406 sensors and calibrated the force-resistance relationship through known loads (Figures 1-2). The derived relationship followed a log-log trend: $F \approx 2.58 \times 10^4 \cdot R^{-1.16}$ (Figure 3), enabling real-time force estimation from analog readings. These signals were visually validated with LEDs and displayed on Arduino IDE's plotter.

We created CAD models of the force sensors, load concentrator pucks, and a multilayer foot assembly that includes recesses and cable routing (Figures 4-9). For binary detection, we wired pushbuttons to Teensy pins and assessed their behavior under simulated footfalls. Additionally, we explored edge detection by taping FSR strips to the front and rear of a Unitree G1 Humanoid robot foot (Figure 10), confirming that 1 N was a reasonable threshold for contact events. We then designed a two-FSR PCB prototype in KiCAD with surface-mounted LEDs for feedback, Teensy header footprints, resistors, and analog input wiring (Figures 11-15). We then created the manufacturing files in accordance with JLCPCB constraints. Finally, we designed a passive toe mechanism for enhanced contact area, referencing both previous AMBER designs and published work (Figures 16-17). The front toe segment rotates about a shaft constrained radially by two bushings and axially by shaft collars. A 120° torsional spring provides the restoring moment. It remains preloaded to ensure the two segments are parallel while the toe is not activated. All 3D prints have been fabricated and parts ordered for initial assembly.

Challenges and Anticipated Problems

One major challenge is the high cost and limited modularity of commercial force-torque sensors. Many high-performance options cost \$3,000–\$10,000 and must be installed at the ankle, complicating direct foot sensing. Similarly, commercial pressure mats from AMTI or Kistler are prohibitively expensive for long-term use, though we identified an affordable \$400 force plate from Vernier for validation purposes, which we may pursue further.

Another challenge involves the complexity of custom MEMS barometer sensors. These require delicate mechanical modifications, vacuum-cast encapsulation, and custom PCB designs with multiplexers. While promising, these systems demand greater resources and will be explored later in the project. PCB design also presented difficulties, as we initially began in Autodesk Eagle before switching to KiCAD due to future deprecation. Learning KiCAD workflows, adhering to JLCPCB manufacturing rules, and generating valid Gerber files required careful attention. The prototype PCB will be soldered and evaluated in the coming week.

Moving forward, we anticipate challenges in validating the sensor outputs against known force data, especially under dynamic walking conditions. Signal noise, mechanical stress shielding, and sensor drift may also introduce errors. However, our modular design approach and layered validation strategy, using both internal sensors and potentially an external plate, position us well to continue iterating toward a deployable foot module.

Appendix

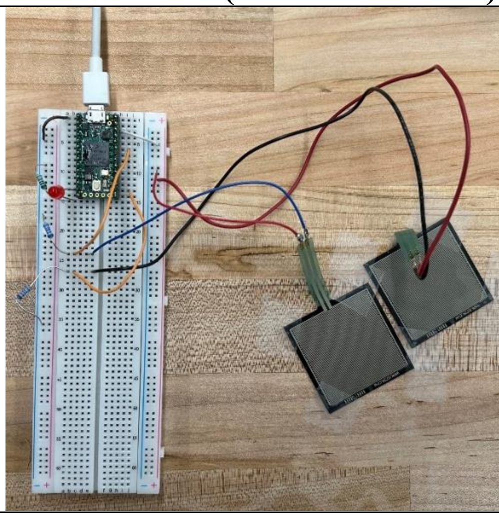
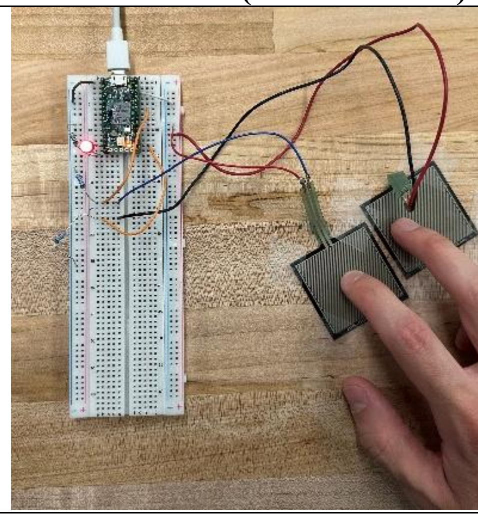
Both LEDs Off (No Force Detected)	Both LEDs On (Force Detected)
	

Figure 1. Two-FSR and LED Prototype Circuit

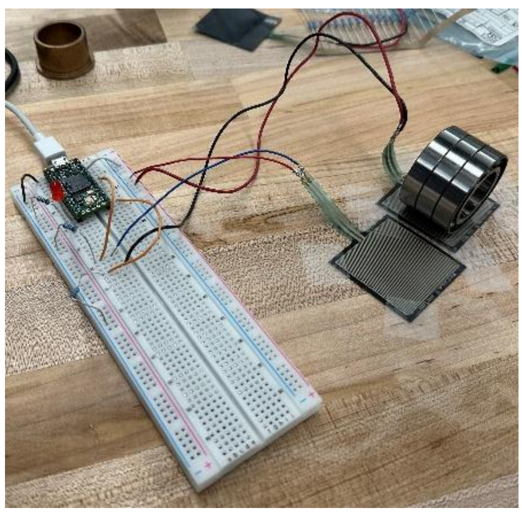
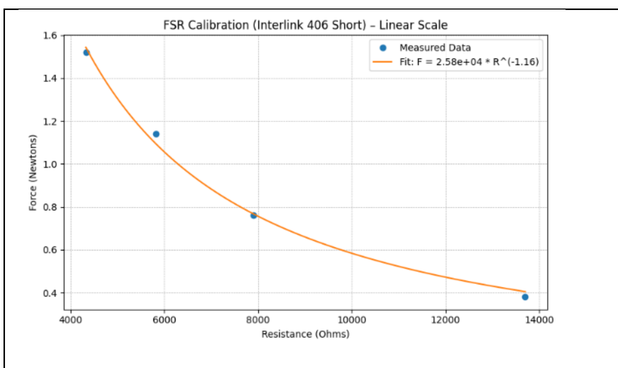


Figure 2. Calibrating the Interlink FSR 406 Using Scale and Bearings



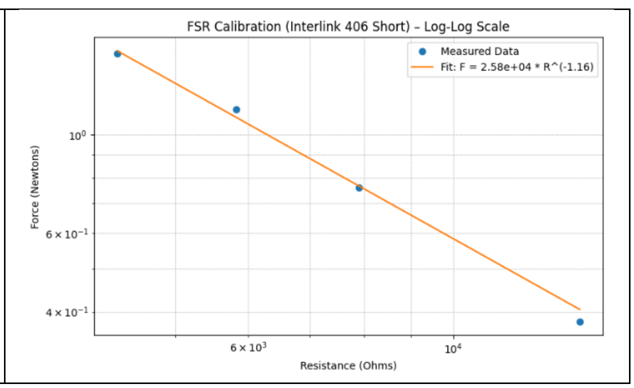


Figure 3. Calibration Plots Generated with Scikit Library

Figure 4. CAD Model of FlexiForce A201 Sensor

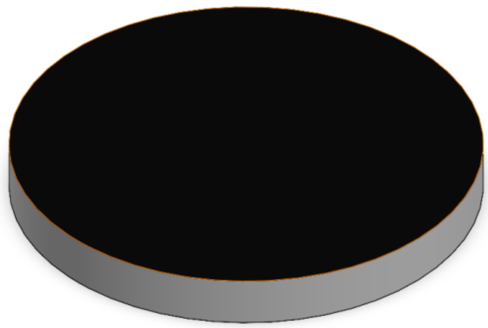


Figure 5. CAD Model of FLXLC-A Puck for A201 Sensor

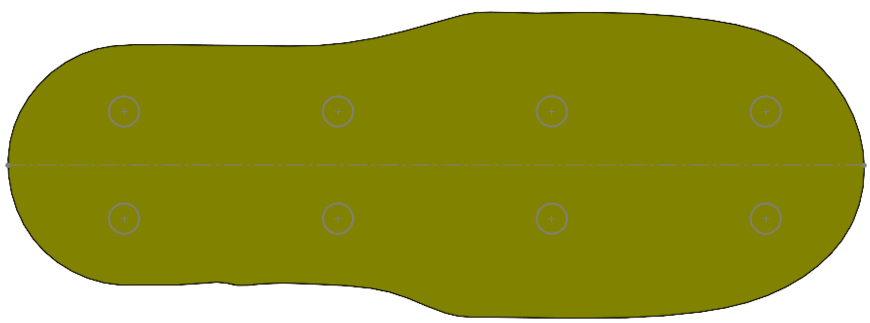


Figure 6. CAD Model of Top of Preliminary Sensing Module Assembly

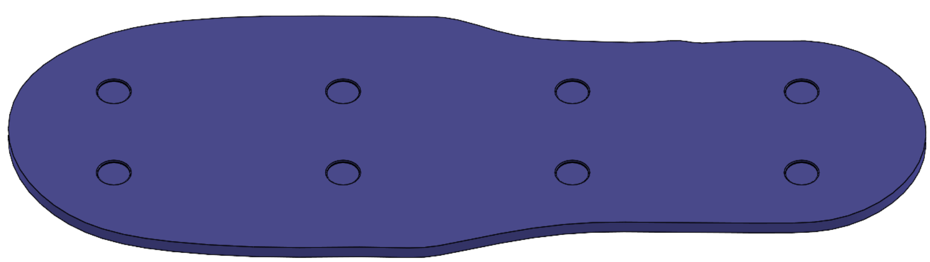


Figure 7. CAD Model of Bottom of Preliminary Sensing Module Assembly

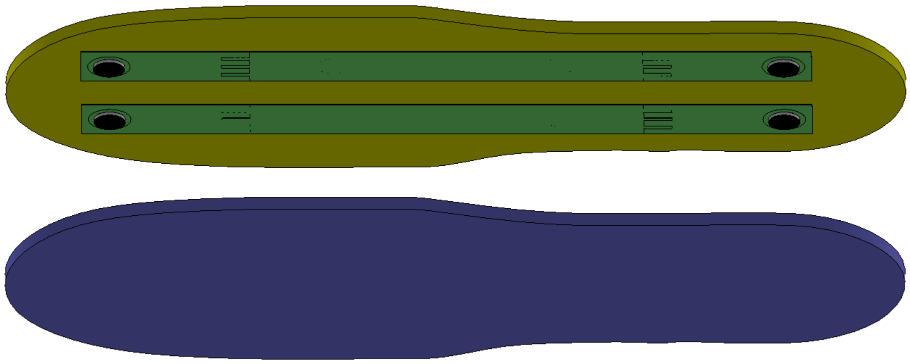


Figure 8. Exploded View of Underside of Sensing Module Assembly

Figure 9. Side View of Fastened Sensing Module Assembly

Figure 10. Side View of G1 Foot with Taped FSR Sensors on Toe and Heel

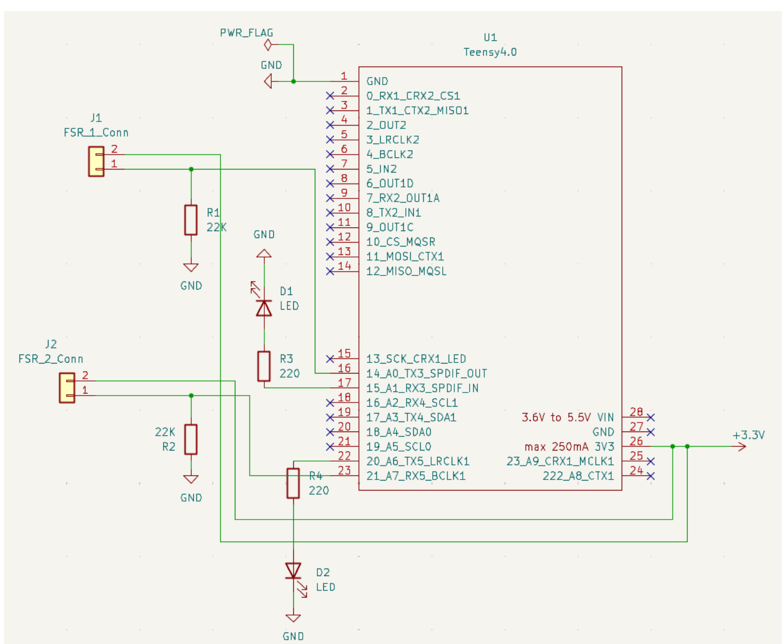


Figure 11. Schematic for Two-FSR + LED Prototype PCB

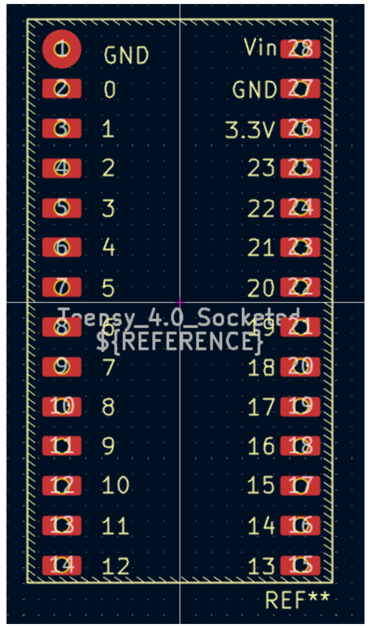


Figure 12. Custom Footprint Created for Teensy Through-Holes

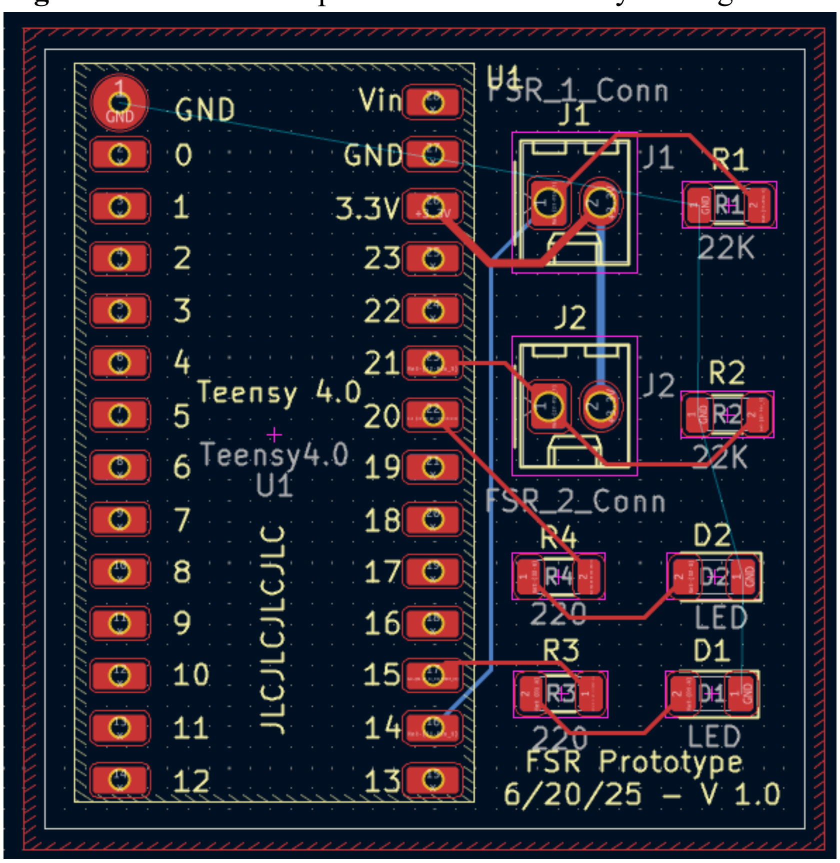


Figure 13. FSR Prototype PCB Sketch with Traces and Components

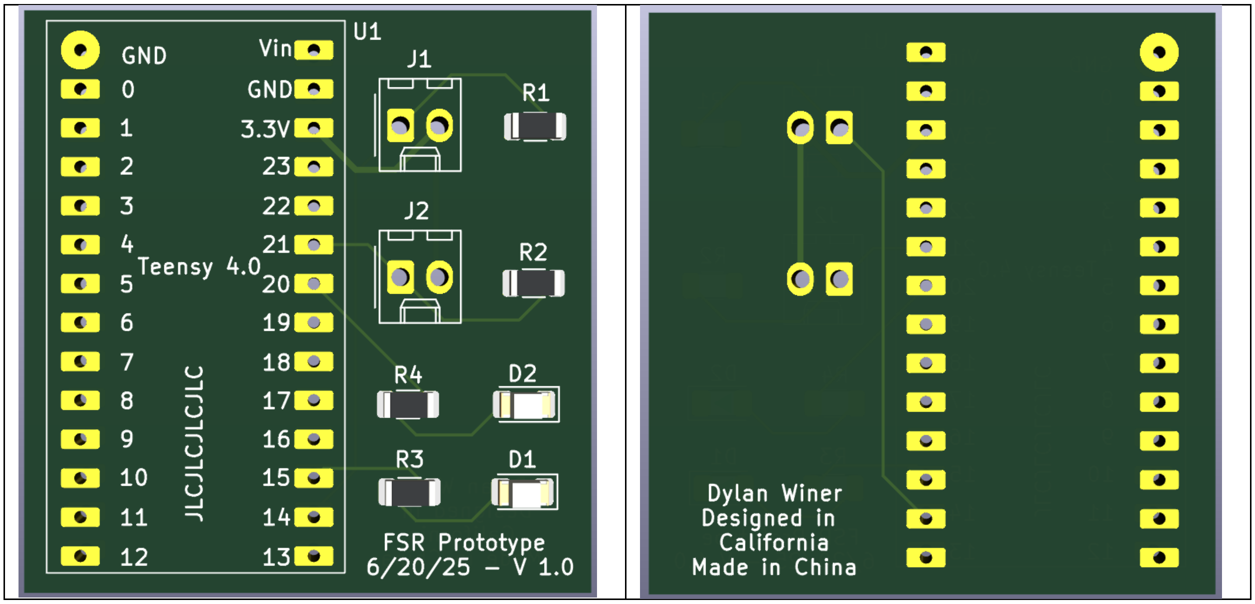


Figure 14. Front and Back View of Prototype PCB 3D Render

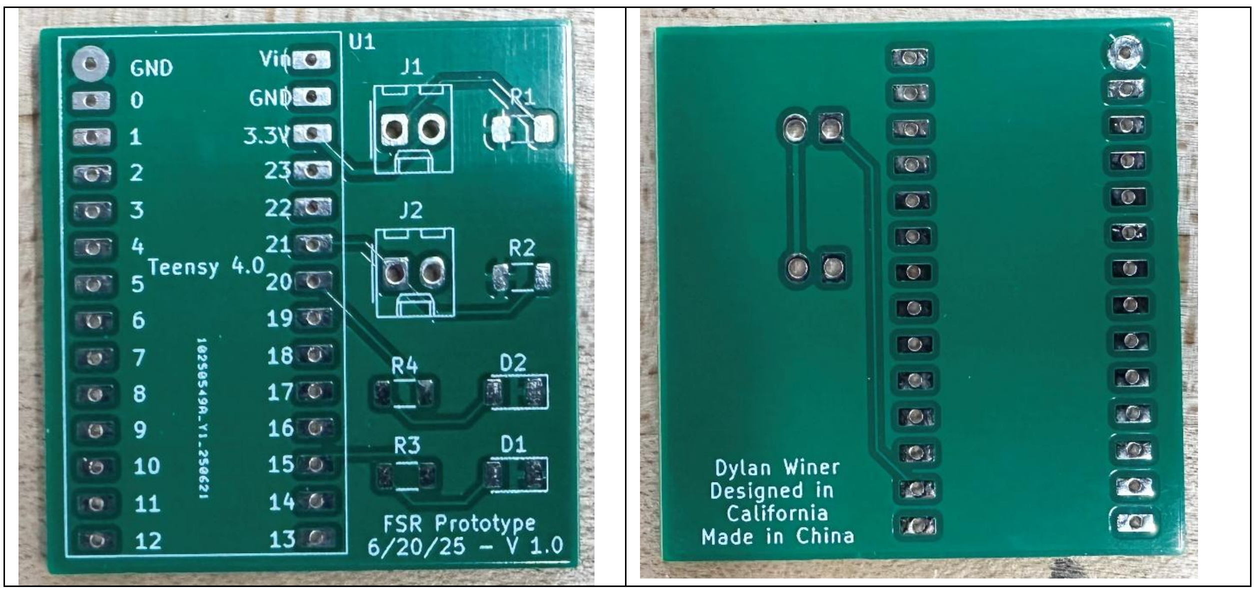


Figure 15. Front and Back View of Prototype PCB In-Person

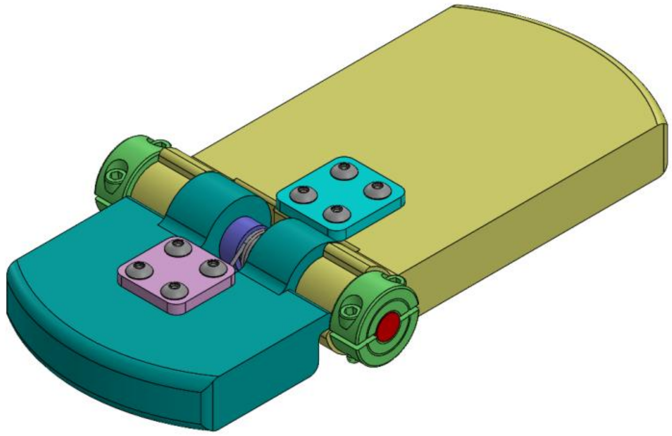


Figure 16. Isometric View of Prototype Passive Toe Assembly

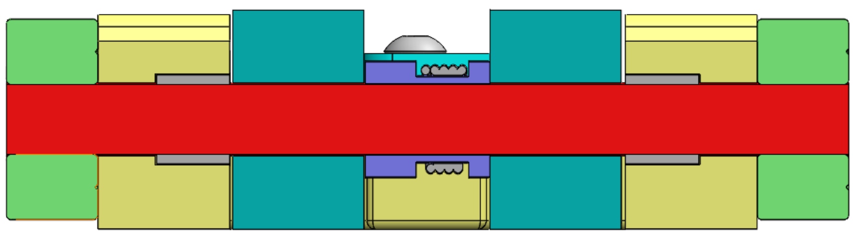


Figure 17. Cross-Section View of Center Shaft, Segments, Bushings, and Spring

References

[1] M. Dai, J. Lee, and A. D. Ames, “Multi-Domain Walking with Reduced-Order Models of Locomotion,” *2022 American Control Conference (ACC)*, pp. 2830–2837, Jul. 2024, doi: https://doi.org/10.23919/acc60939.2024.10644270.

[2] H. Zhao, A. Hereid, W. Ma, and A. D. Ames, “Multi-contact bipedal robotic locomotion,” *Robotica*, vol. 35, no. 5, pp. 1072–1106, Dec. 2015, doi: https://doi.org/10.1017/s0263574715000995.

[3] X. Guo *et al.*, “Soft Foot Sensor Design and Terrain Classification for Dynamic Legged Locomotion,” pp. 550–557, May 2020, doi: https://doi.org/10.1109/robosoft48309.2020.9115990.

[4] T. Tyler, V. Malhotra, A. Montague, Z. Zhao, F. L. Hammond III, and Y. Zhao, “Integrating Reconfigurable Foot Design, Multi-modal Contact Sensing, and Terrain Classification for Bipedal Locomotion,” *IFAC-PapersOnLine*, vol. 56, no. 3, pp. 523–528, 2023, doi: https://doi.org/10.1016/j.ifacol.2023.12.077.

[5] Risto Koiva, T. Schwank, G. Walck, M. Meier, R. Haschke, and H. Ritter, “Barometer-based Tactile Skin for Anthropomorphic Robot Hand,” Oct. 2020, doi: https://doi.org/10.1109/iros45743.2020.9341691.

[6] K. Fondahl *et al.*, “An adaptive sensor foot for a bipedal and quadrupedal robot,” Jun. 2012, doi: https://doi.org/10.1109/biorob.2012.6290735.