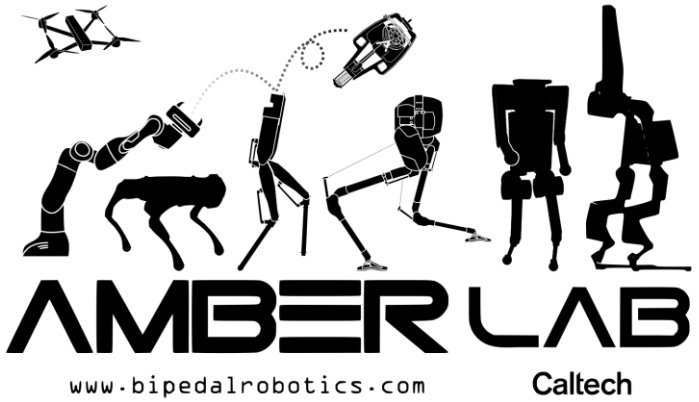

Toward Contact-Aware Humanoid Locomotion: A Modular Foot Sensing Platform

Dylan Winer[1]

Mentors: Prof Aaron Ames[2], Sergio Esteban[3], and Adrian Ghansah[3]

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[2]Bren Professor of Mechanical and Civil Engineering, Control and Dynamical Systems and Aerospace, Caltech

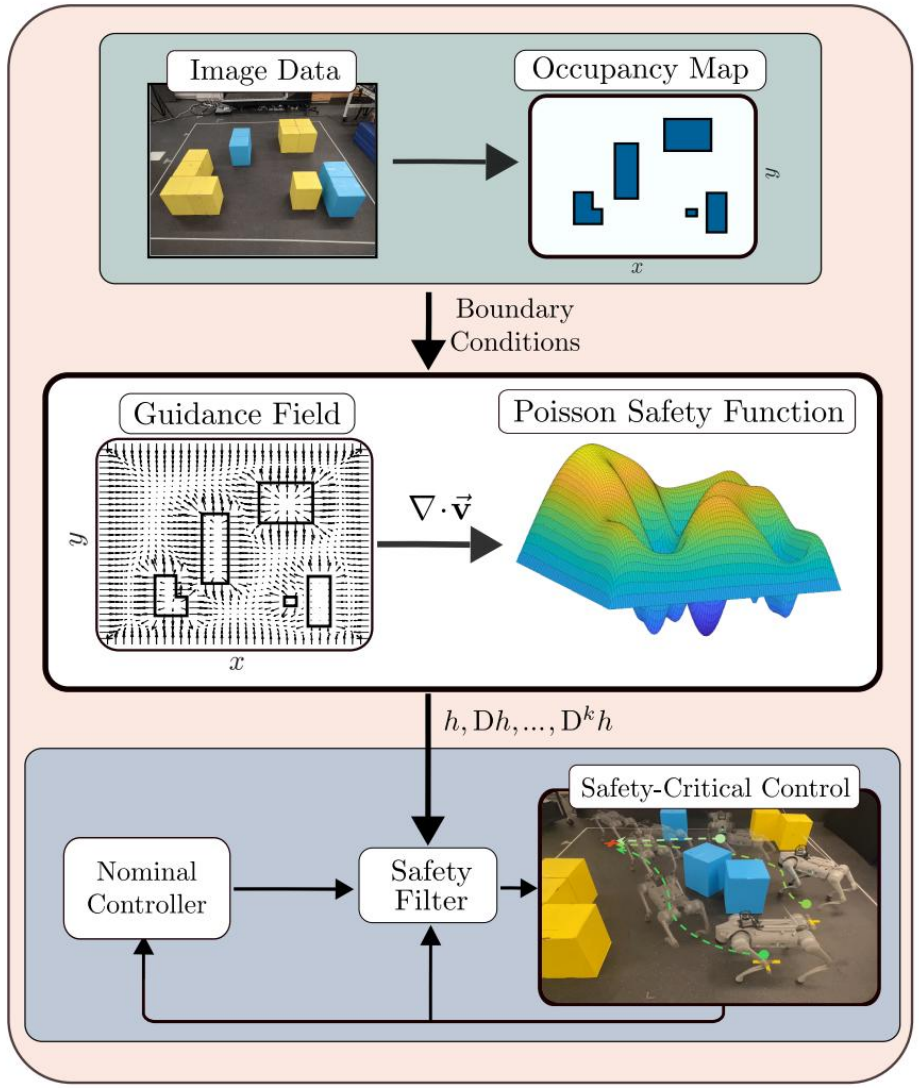
[3]Graduate Student in Robotics and Control, Caltech

Advanced Mechanical Bipedal Experimental Robotics LAB

AMBER Lab Overview

- Hybrid systems locomotion research
- Optimization-based control methods
- Robotics hardware & mechanisms
- Current tests on Unitree G1/Go2
- Goal: fully custom humanoid robot

G1 Humanoid



Poisson Safety Function with Go2[1]

[1] G. Bahati, R. M. Bena, and A. D. Ames, "Dynamic Safety in Complex Environments: Synthesizing Safety Filters with Poisson's Equation," arXiv.org, 2025.

Advanced Mechanical
Bipedal Experimental
Robotics LAB

Roadmap

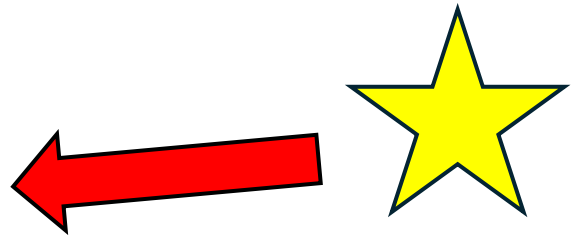
01	02	03	04	05
Motivation & Goals	Background	System overviews	Results & key findings	Future directions

Bipedal Locomotion Dynamics

$$D(q)\ddot{q} + H(q,\dot{q}) = Bu + J_c(q)^T\lambda_c$$

Euler-Lagrange Model of Robot Dynamics[2]

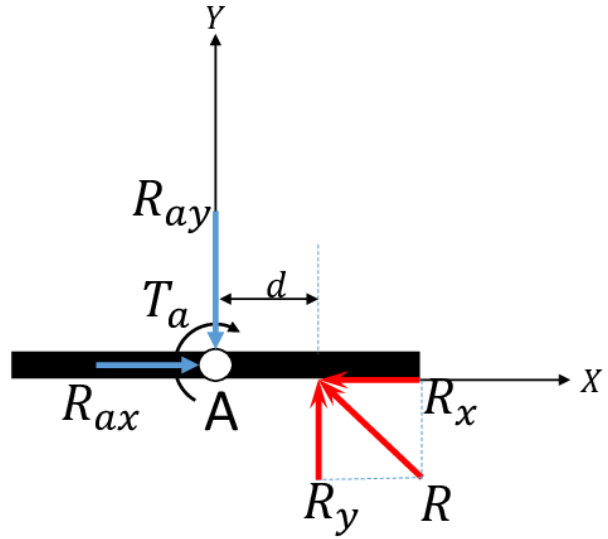
- Modeled as a rigid-link tree
- $D(q)$: mass–inertia matrix
- $H(q,\dot{q})$: Coriolis, gravity, spring forces
- B: Actuation matrix (gear ratios)
- u: Joint torque inputs
- $J_c(q)$: Contact constraint Jacobian
- λ_c: External contact forces/moments



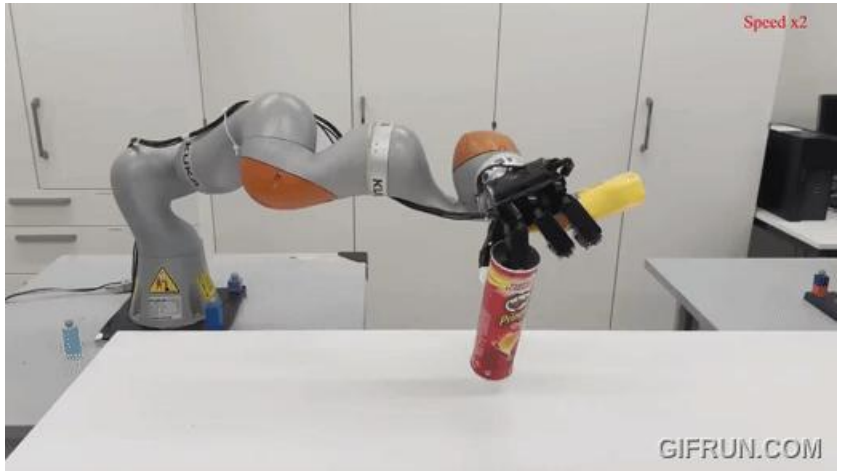
[2] J. Reher and A. D. Ames, “Control Lyapunov Functions for Compliant Hybrid Zero Dynamic Walking,” arXiv.org, 2021.

Motivation & Goal

- Goal: Modular foot sensing platform
- Measure foot forces & moments (λ_c)
- Distinguish heel, toe, dispersed loads
- Foundation for a future full humanoid
- Manipulate objects in environment



"Free body diagram of biped robot stance foot in single support phase"[3]



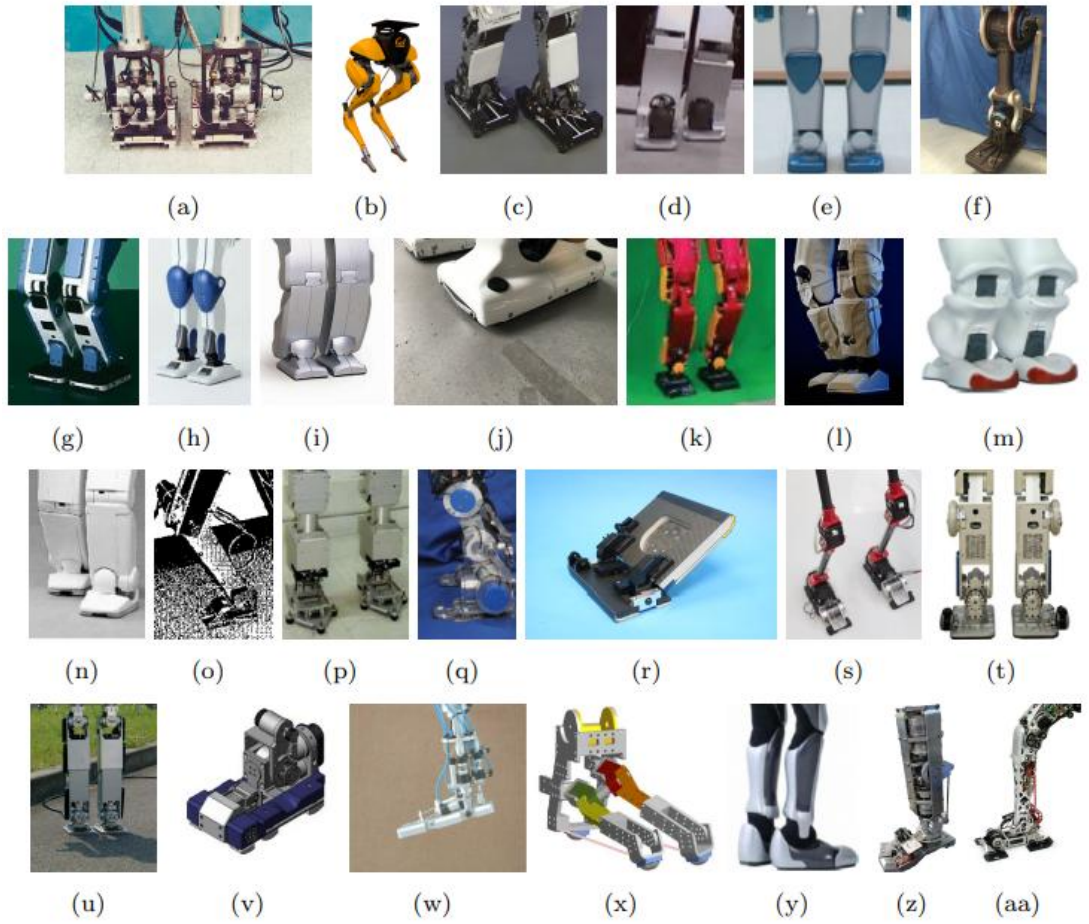
Robotic Grasping[4]

[3] V. Janardhan and R. Prasanth Kumar, "Online trajectory generation for wide ditch crossing of biped robots using control constraints," *Robotics and Autonomous Systems*, vol. 97, pp. 61–82, Nov. 2017

[4] Xiao GAO, "Beyond Manual Dexterity: Designing a Multi-fingered Robotic Hand for Grasping and Crawling," YouTube, Oct. 04, 2024.

Humanoid Foot Sensing

- Humans use heel-toe rolling
- Many robots have rigid feet (one segment)
- Limited distributed sensing
- Existing force-torque sensors costly/complex



"Robotic feet with a one segment structure"[5]

[5] I. Frizza, K. Ayusawa, A. Cherubini, H. Kaminaga, P. Fraisse, and G. Venture, "Humanoids' Feet: State of the Art & Future Directions," 2022

Force Sensitive Resistors (FSR)

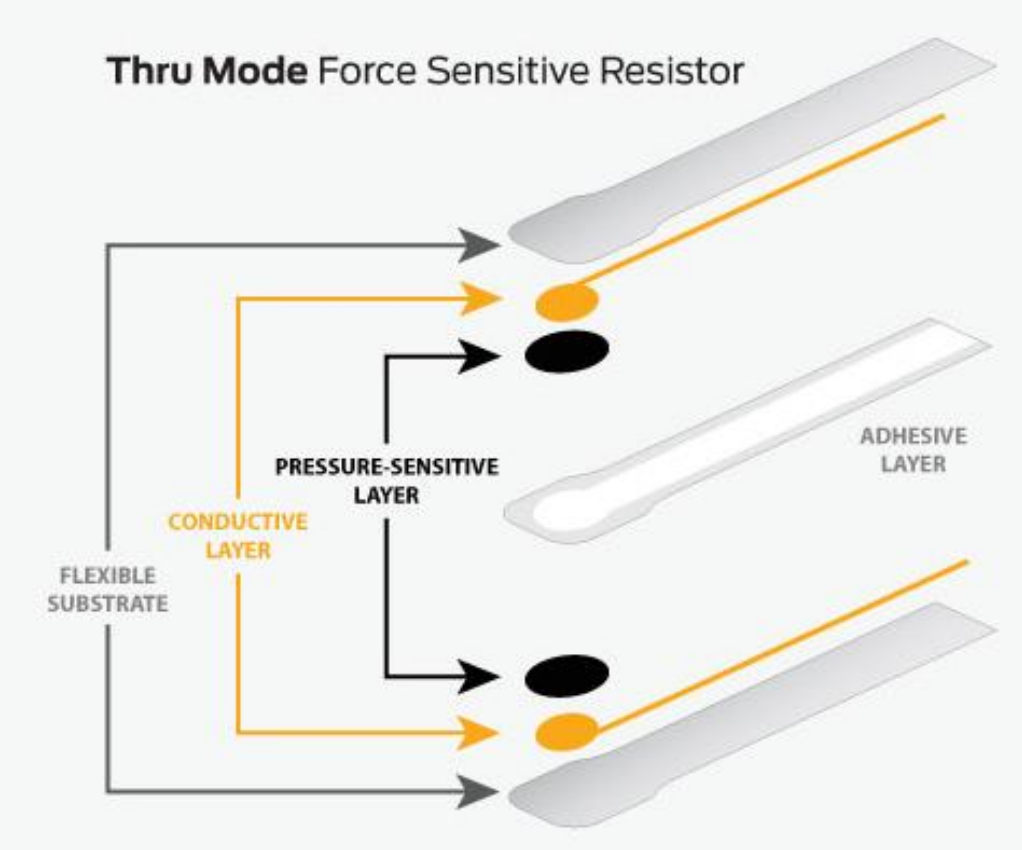
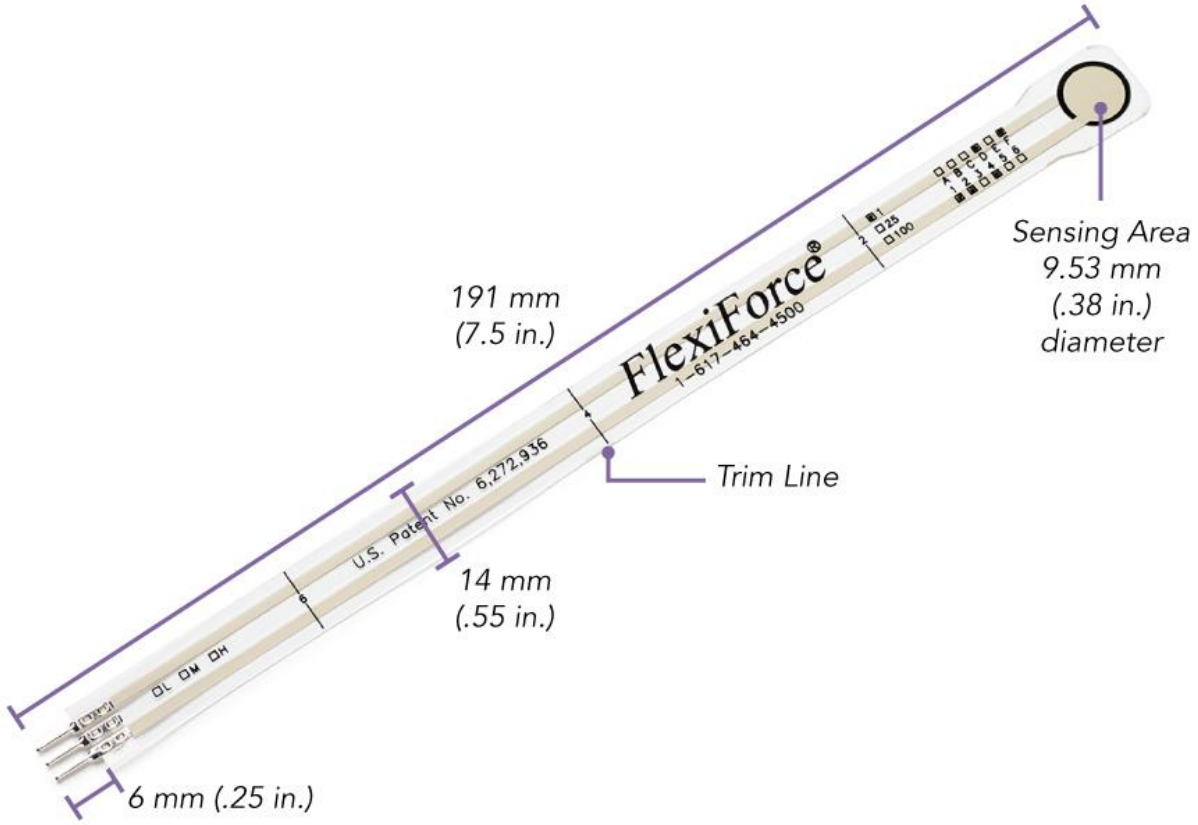


Diagram of FSR Structure[6]

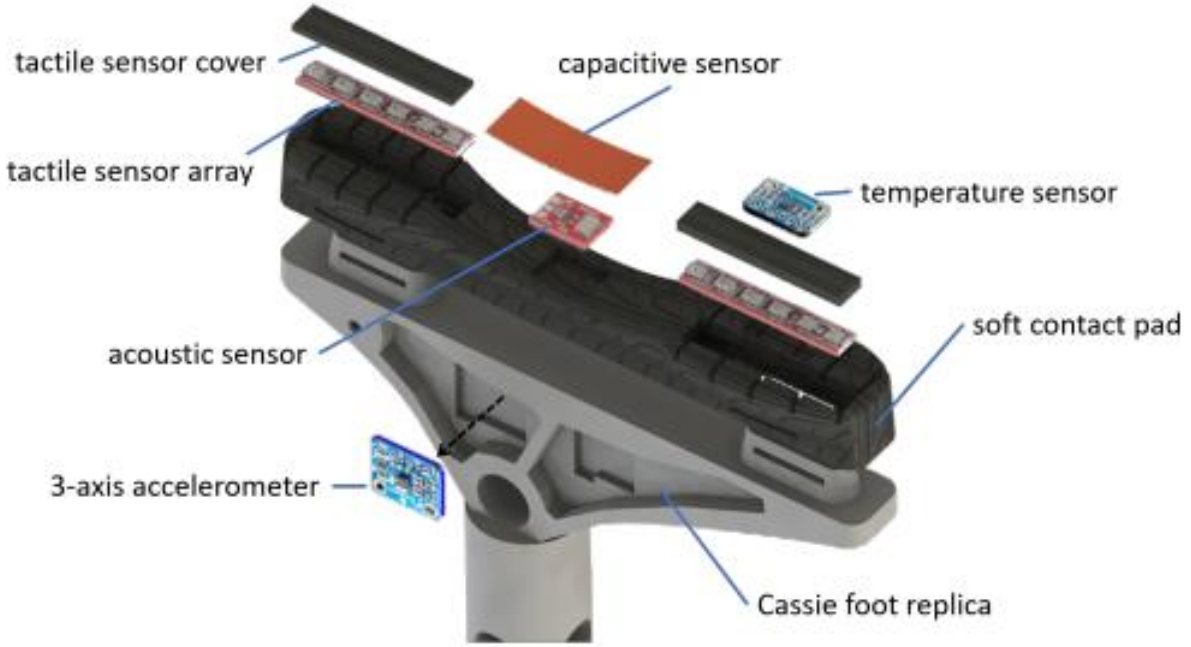


FlexiForce A201 FSR

[6] Tekscan, "How Does a Force Sensing Resistor (FSR) Work?," Tekscan, Jul. 03, 2019.

Foot Sensing Inspiration

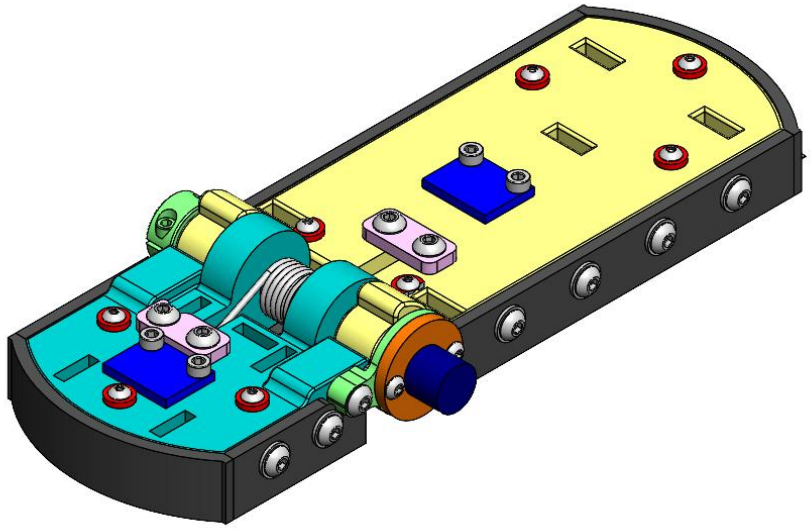
- Multi-modal sensing: tactile, inertial
- Inspired modular integration into existing biped



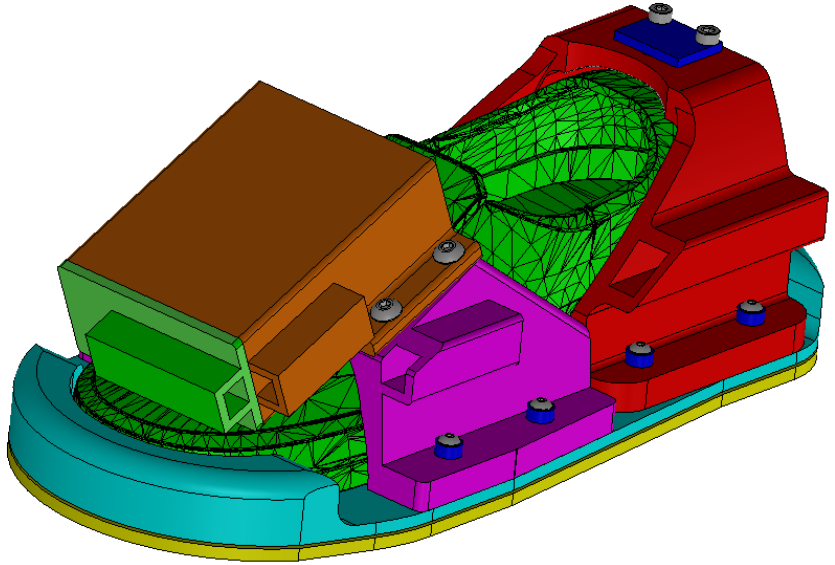
"Exploded view of the sensor-embedded Cassie foot design"[5]

[5] 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

Project Objectives

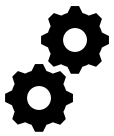


1) Custom humanoid foot sensing module

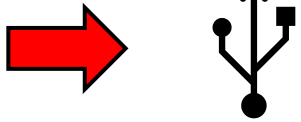


2) G1 humanoid foot sensing module

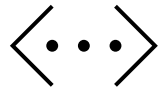
- Accurate, distributed force sensing
- Real-time, high-frequency output



CAD Modeling



PCB Design



Sensor Analysis

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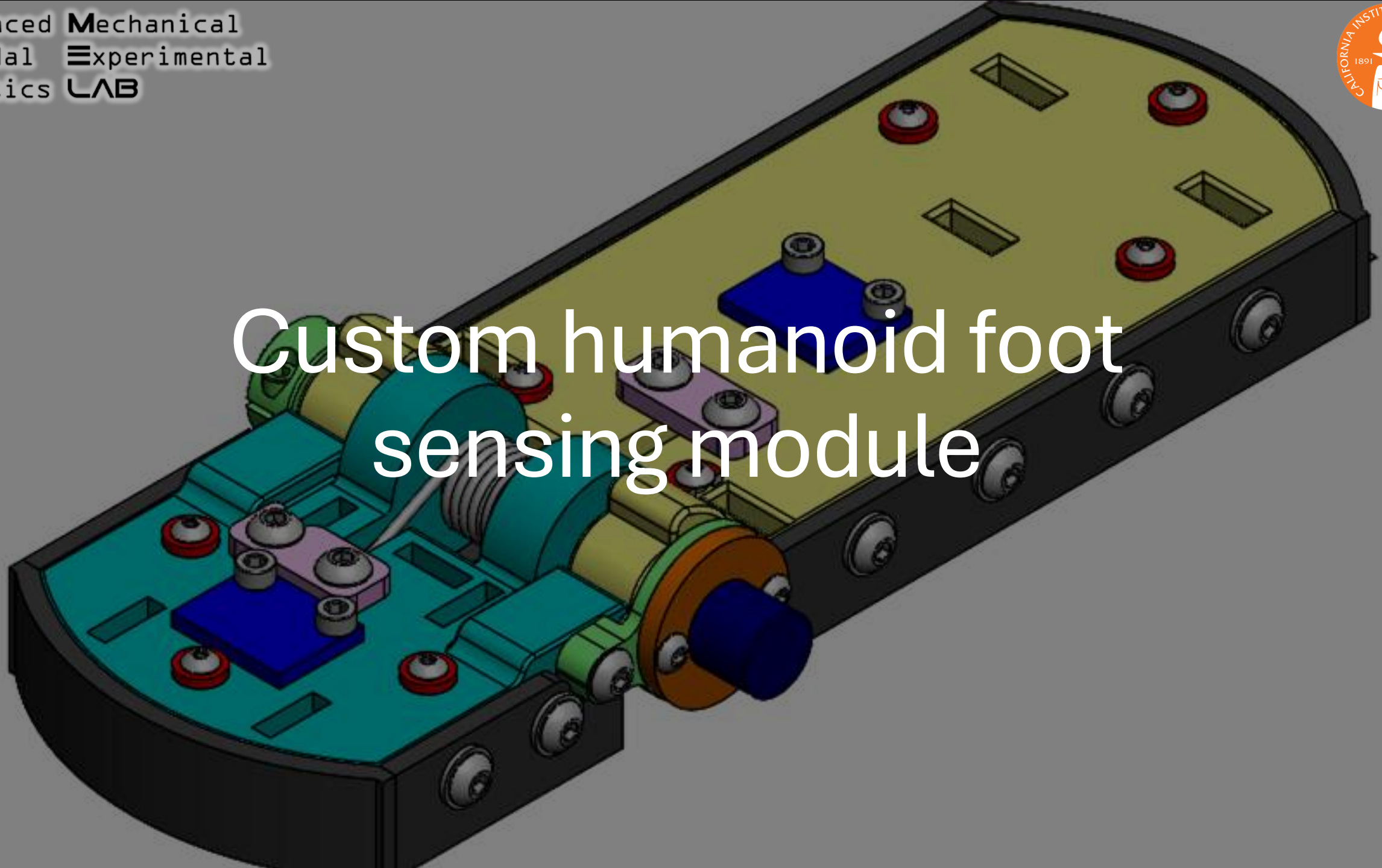
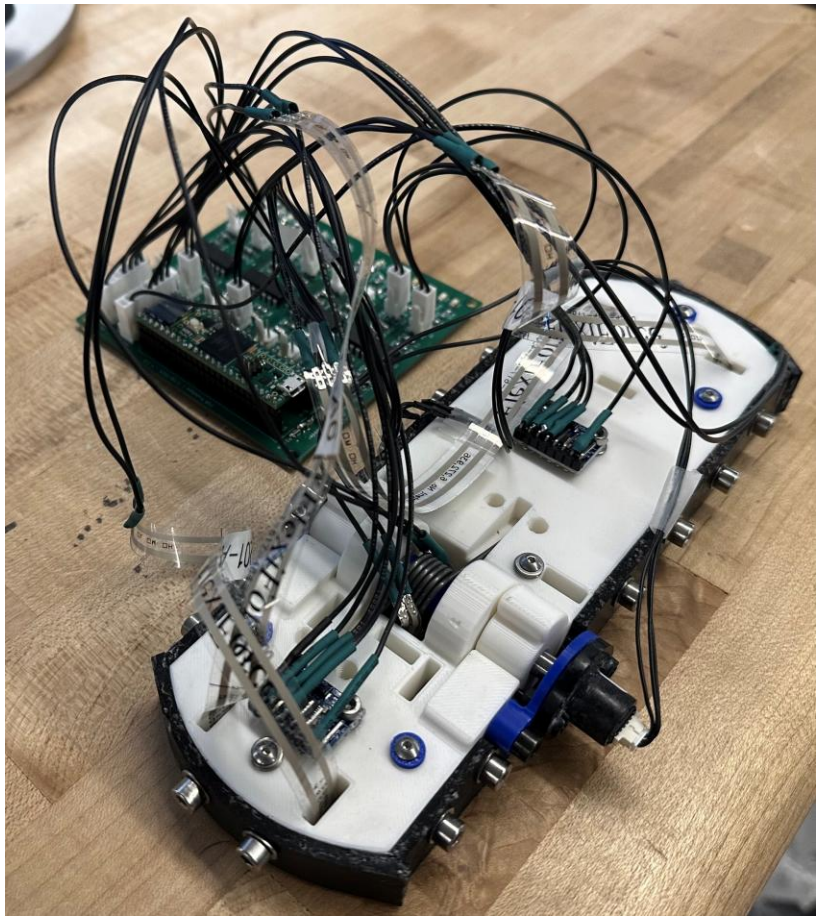


Custom humanoid foot sensing module

System Overview: Custom Humanoid Foot

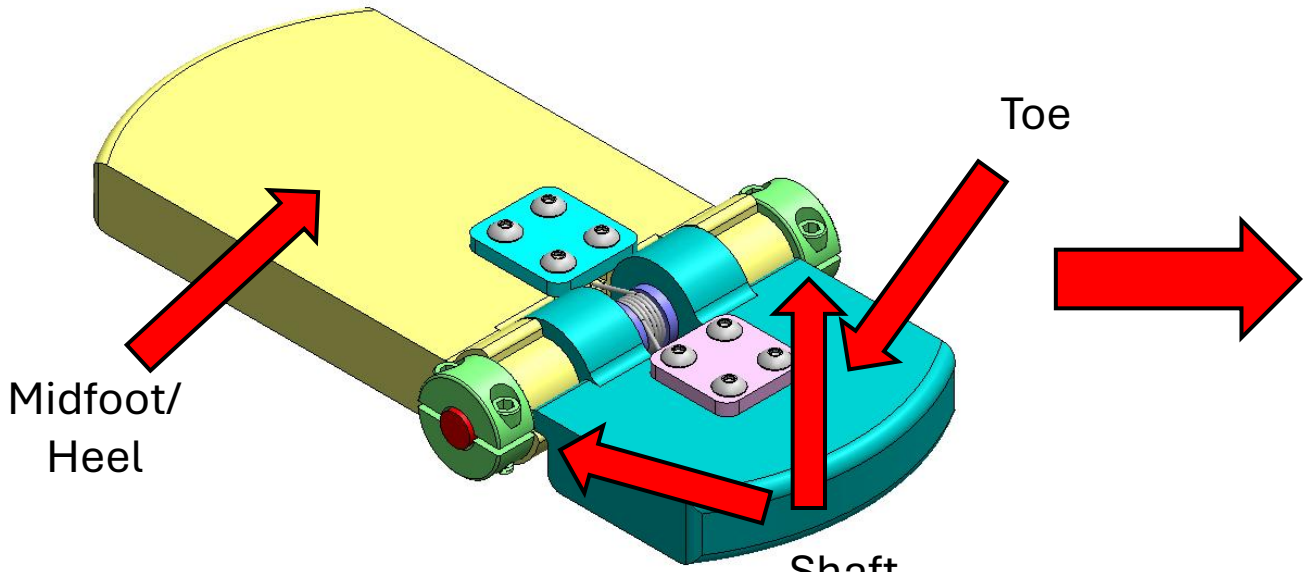
- Passive toe + midfoot segments
- Sensors onboard:
  - Force sensors at key load points
  - IMUs for segment orientations
  - Encoder for toe angle feedback
- Custom PCB + Teensy 4.1 microcontroller



Custom humanoid foot

Mechanical Design: Custom Humanoid Foot V1

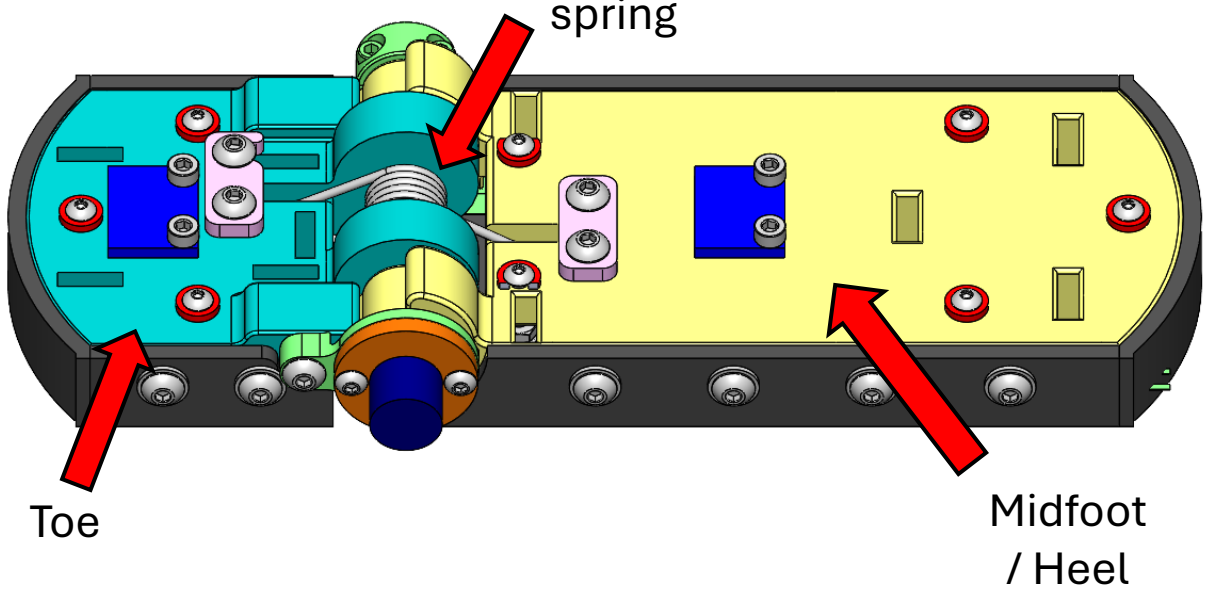
- Two segments: toe + midfoot / heel
- Torsional spring + steel shaft
- Validated hinge + stopping mechanism



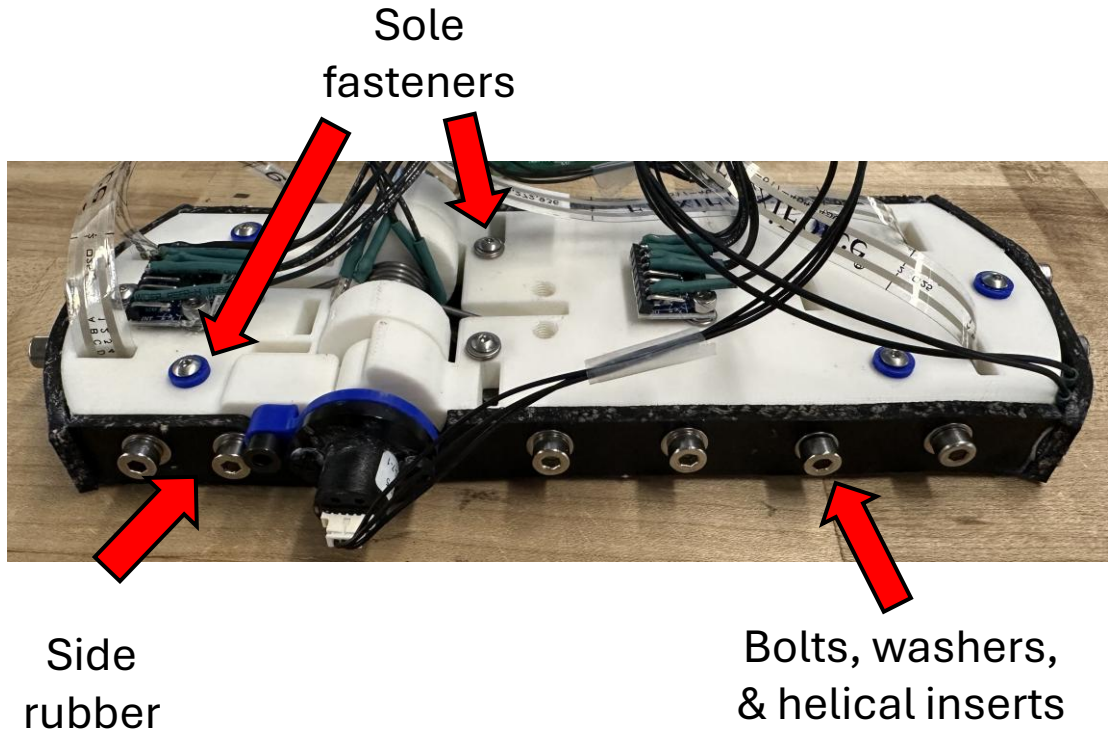
CAD Model

Prototype

Mechanical Design: Custom Humanoid Foot V2



CAD Model

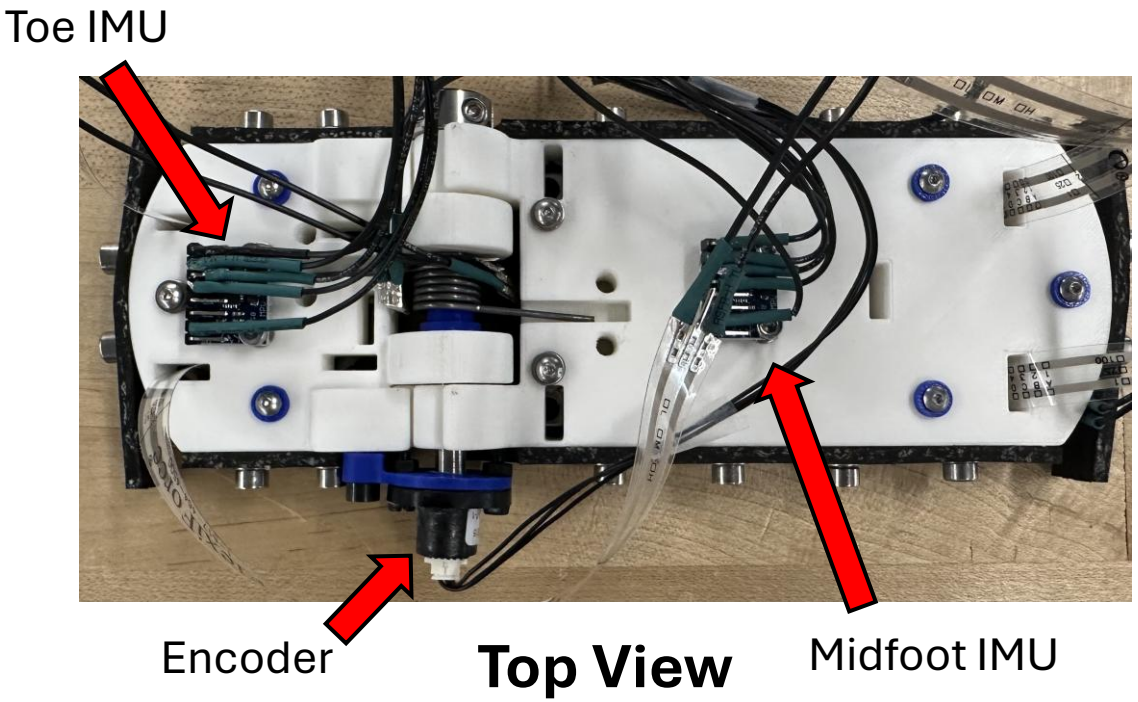


Prototype

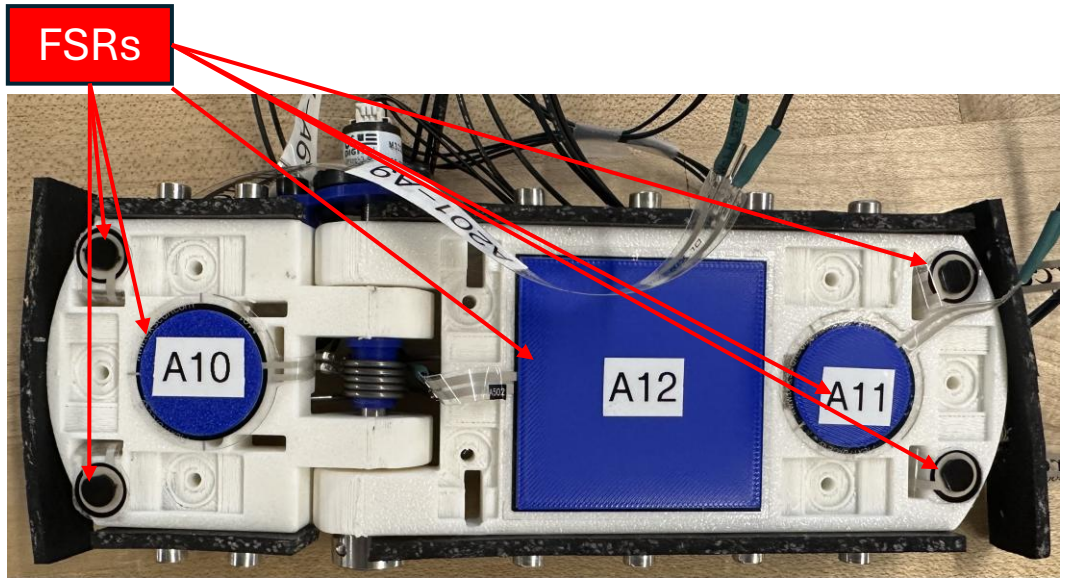
- Significantly more robust
- Integrated sensors + electronics
- PLA housing + rubber protective layer

Sensor Suite + Electronics

- 7x FSRs (force-sensitive resistors): force measurement
- 2x IMUs (inertial measurement units): accelerometer + gyroscope
- 1x Encoder: toe angle feedback
- Distributed sensor placement
- Integrated into modular platform

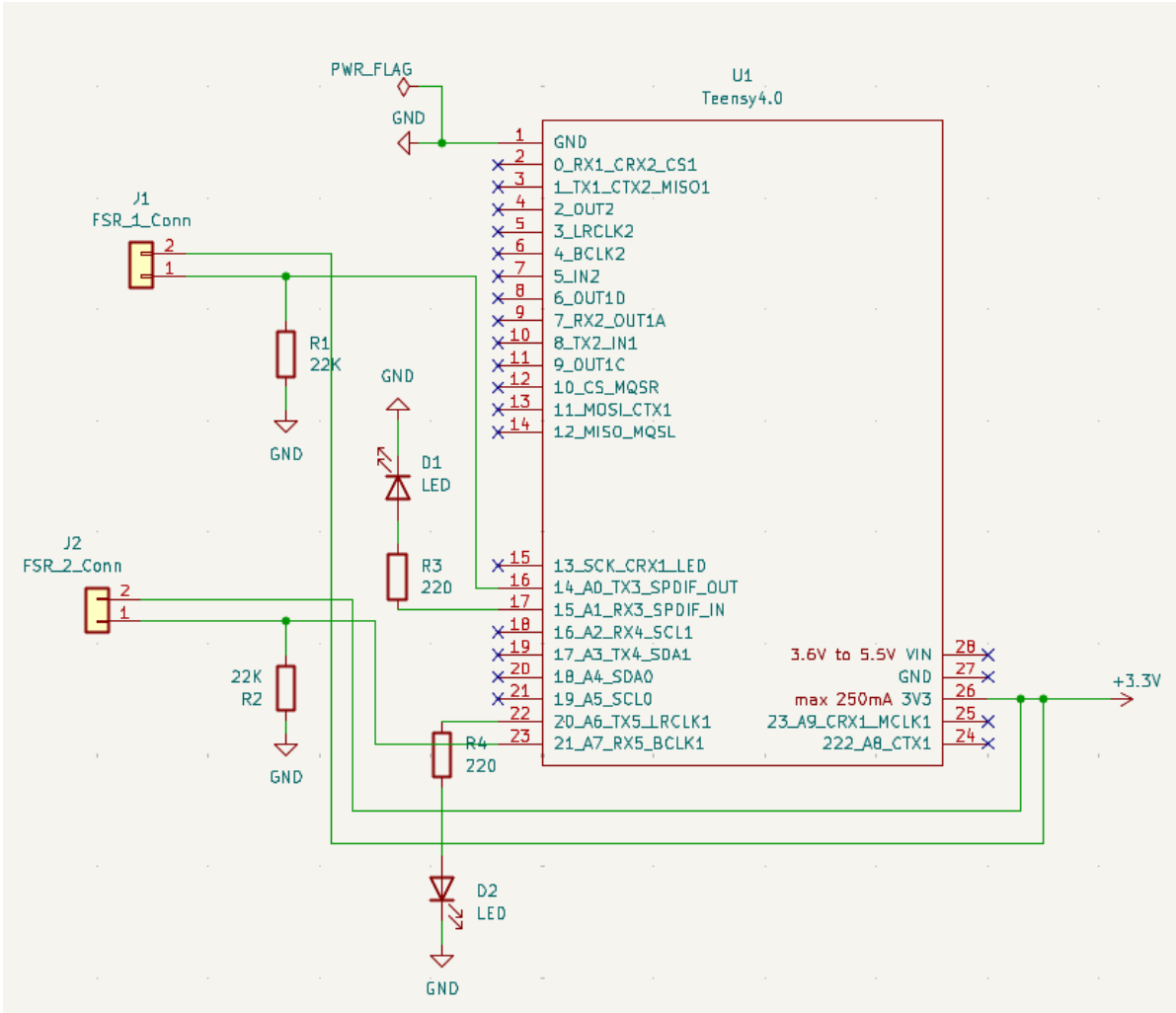


Top View



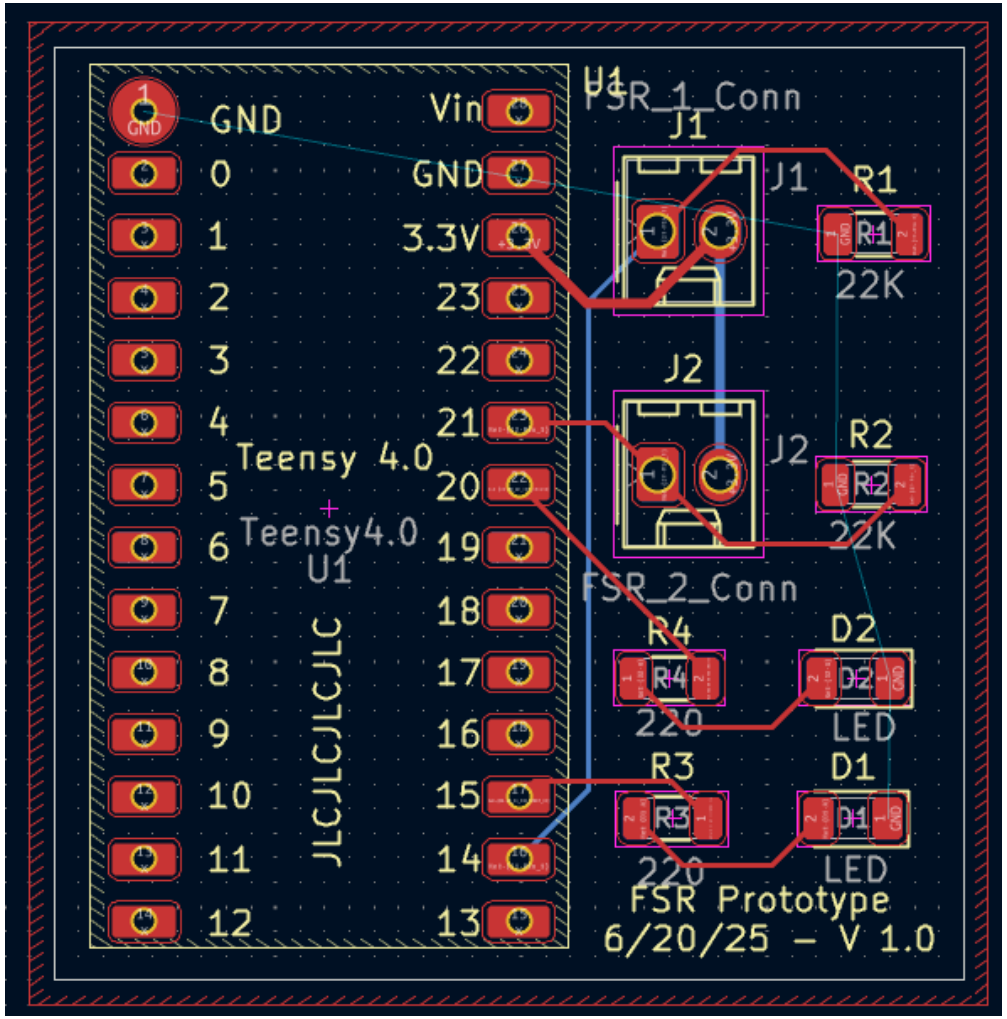
Bottom View (no rubber sole)

PCB V1 Circuit

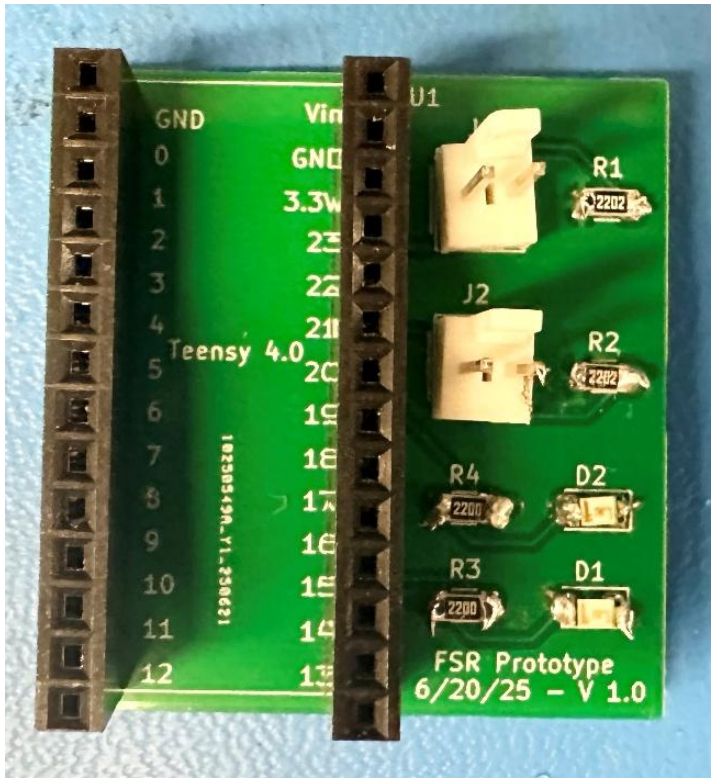


PCB V1 Design

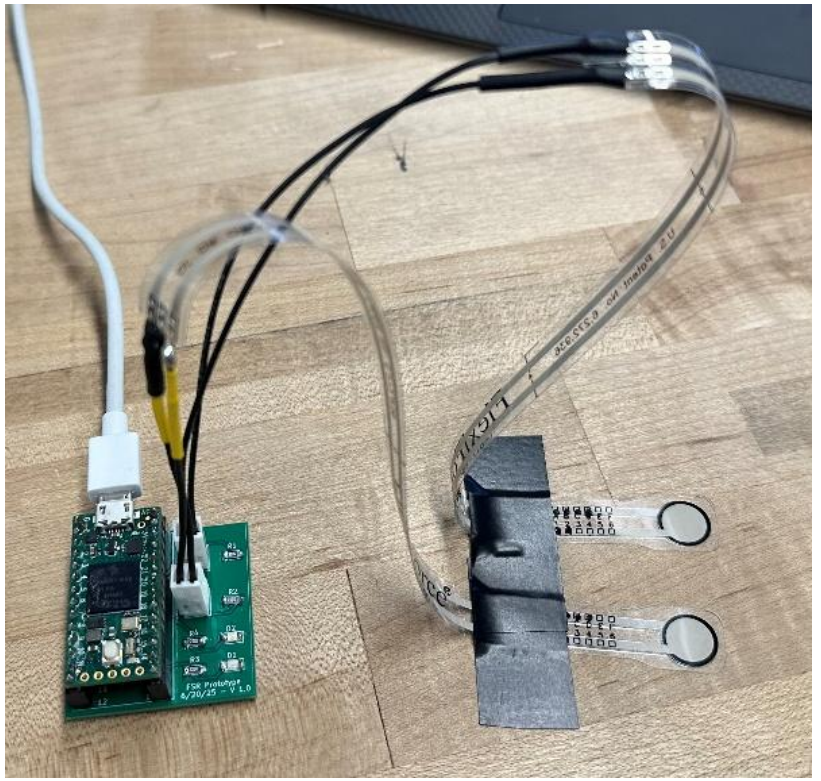
- 2-layer Teensy 4.0-controlled board
- Voltage divider signal conditioning
- 2 status LEDs
- Early proof of concept



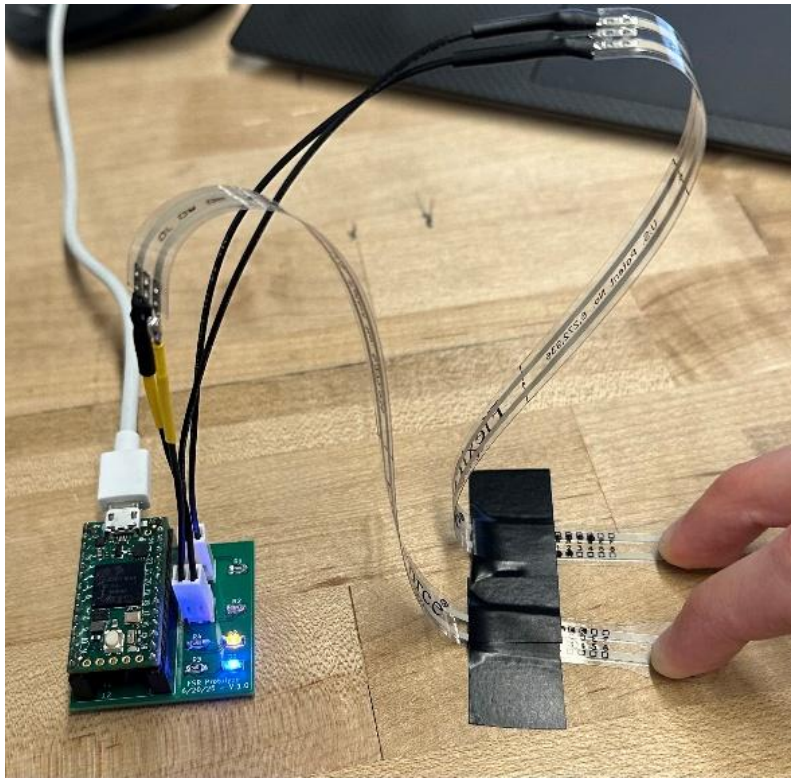
PCB V1 Functionality



Soldered PCB

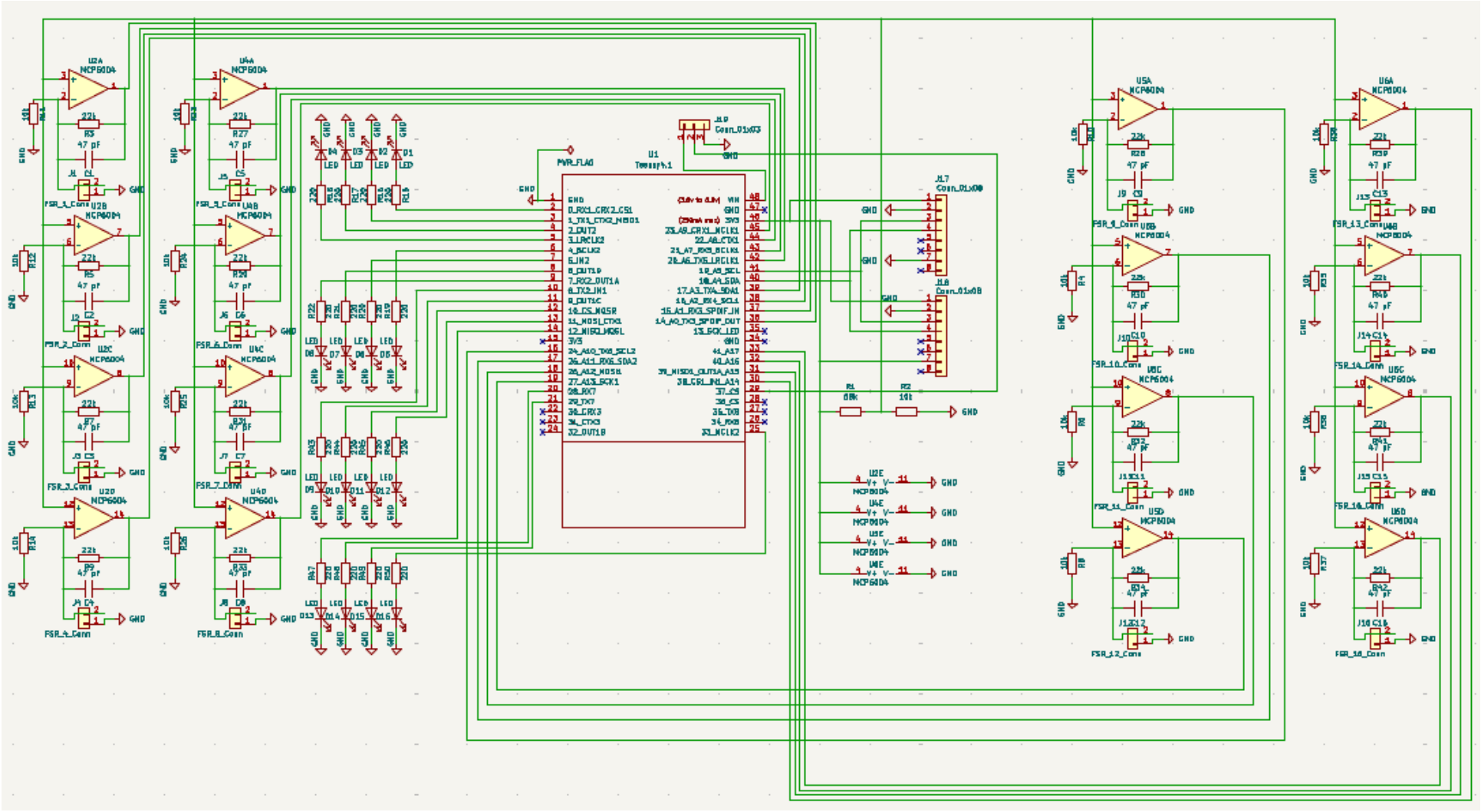


No forces detected: LEDs Off



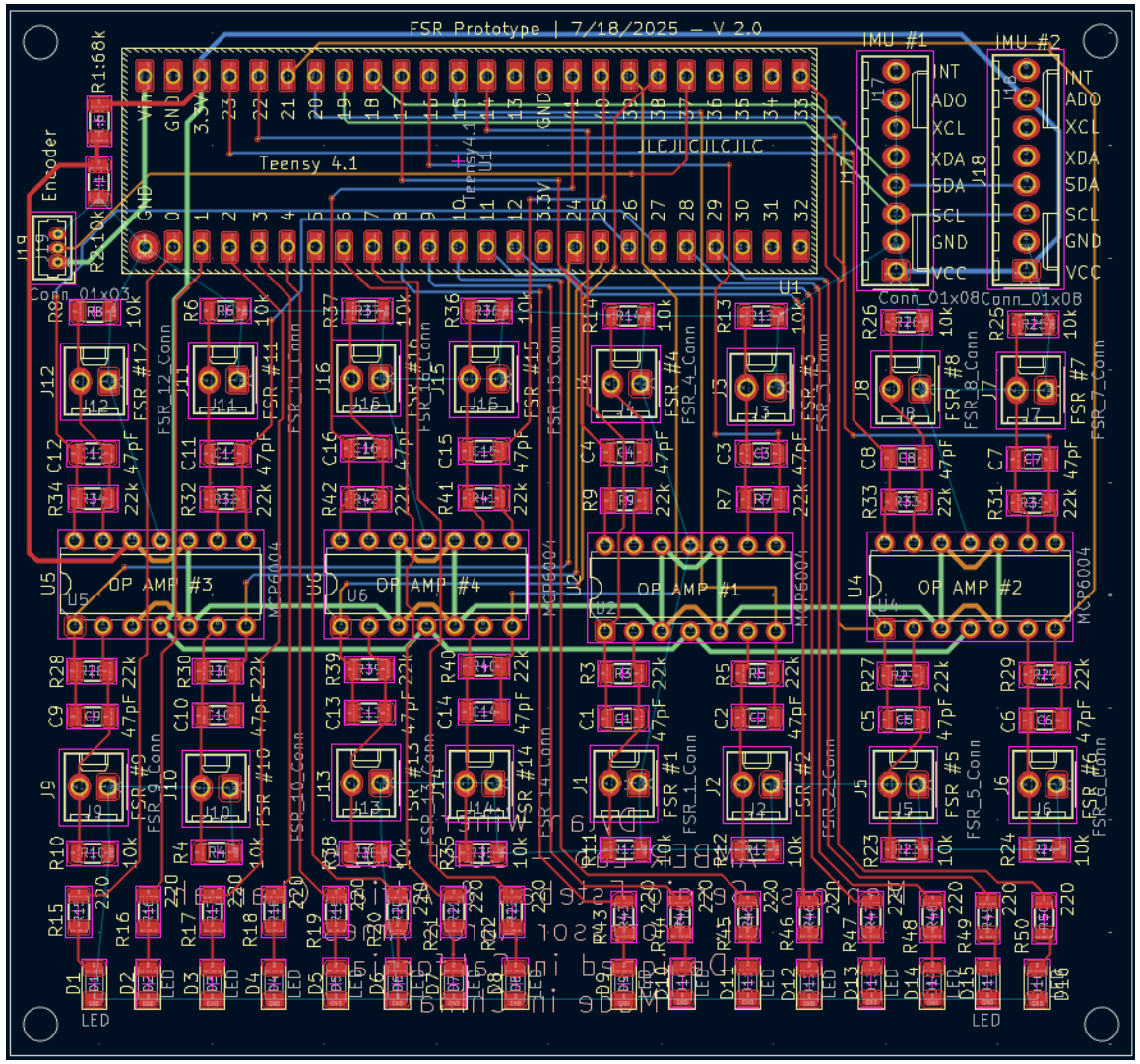
Forces detected: LEDs On

PCB V2 Circuit



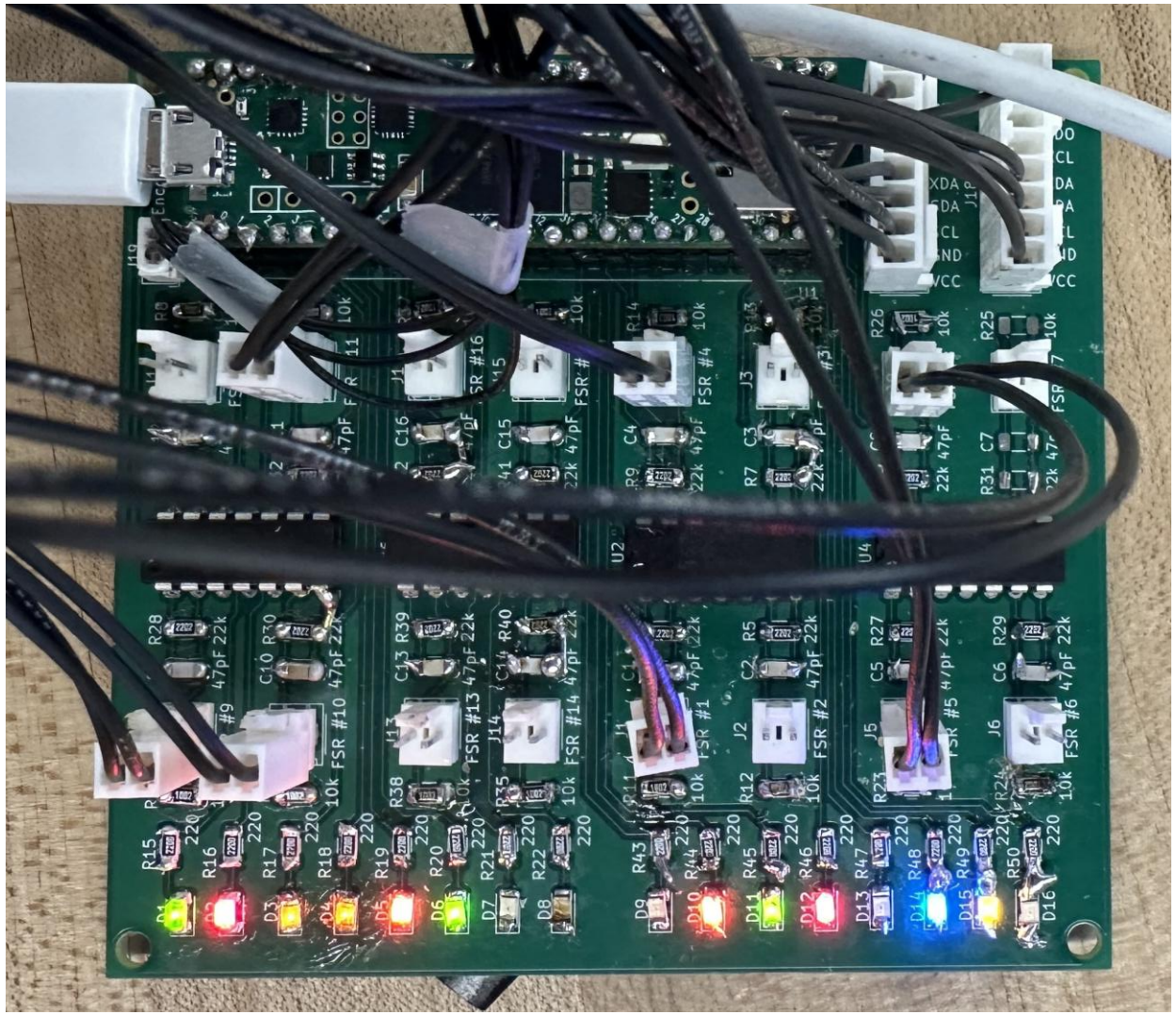
PCB V2 Design

- 4-layer Teensy 4.1-controlled board
- Op-amp channels for 16 FSRs
- 16 status LEDs
- IMU & encoder connectors
- Designed for custom humanoid
  - Would mount to ankle
  - Footprint: 93 x 100 mm



PCB V2 Soldering + Wiring

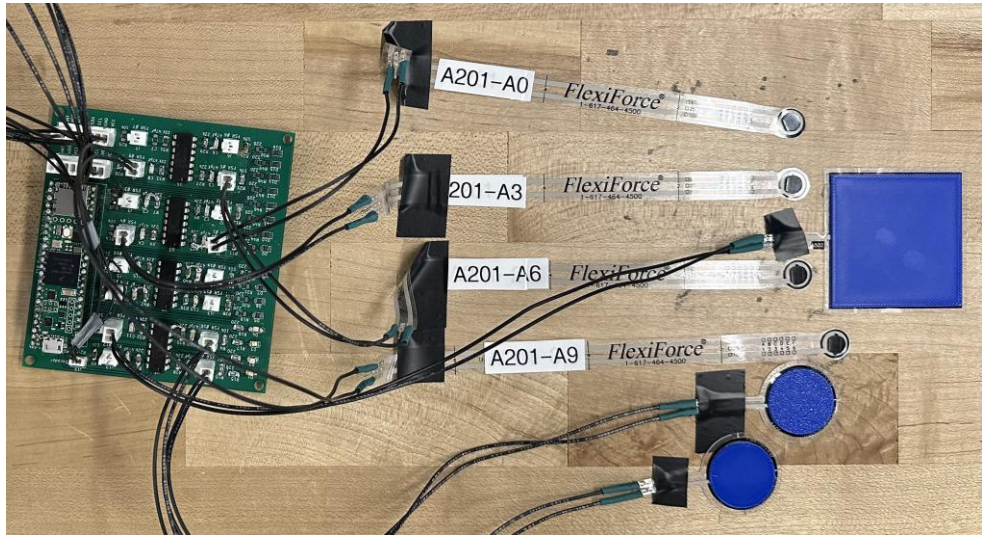
- SMD resistors, capacitors, and LEDs
- 4x MCP6004 for non-inverting op amp circuits
- 16x 2-pin connectors for FSRs
- 2x 24-pin connectors for Teensy 4.1
- 2x 8-pin connectors for IMUs
- 1x 3-pin connector for encoder



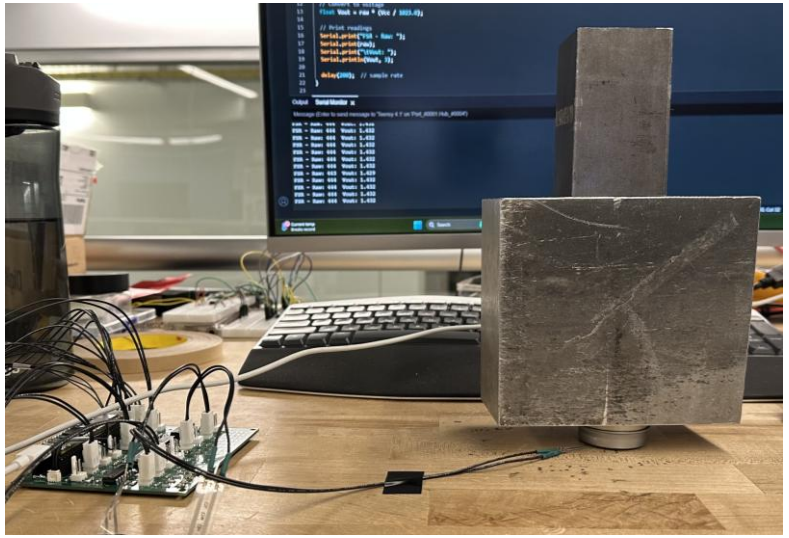
All LEDs On during Testing

Calibration & Testing Methods

- Measured weights with scale
  - Ensured full weight on sensors
- Recorded corresponding sensor voltage outputs



7x FSRs Ready for Calibration

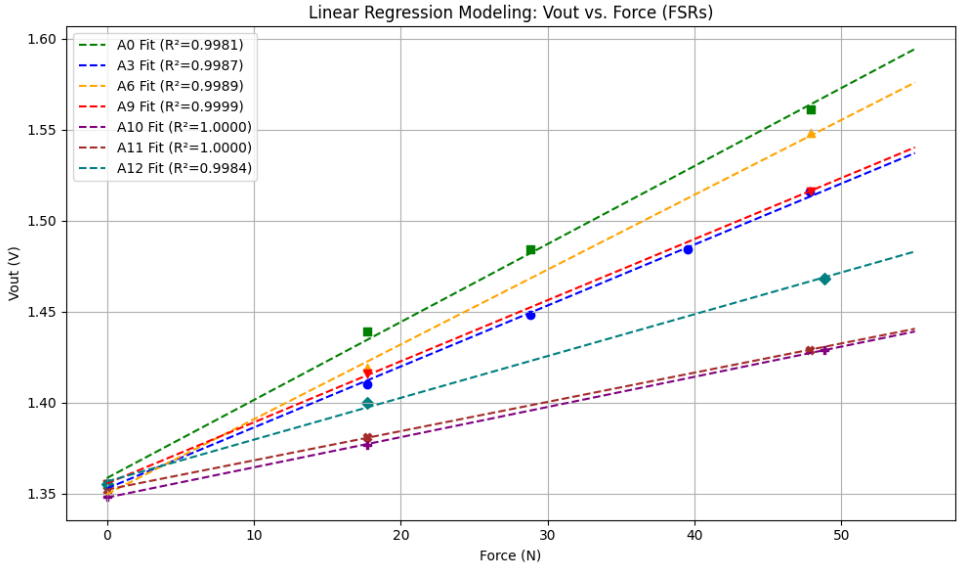


Calibrating individual FSR

Gap b/w weight & table

Linear Regression Modeling

- Linearly fit voltage vs. force
- Threshold tuning for LEDs
  - Ensure activate only when force applied
- Validated first on breadboard then PCB
- Result: map voltage to forces



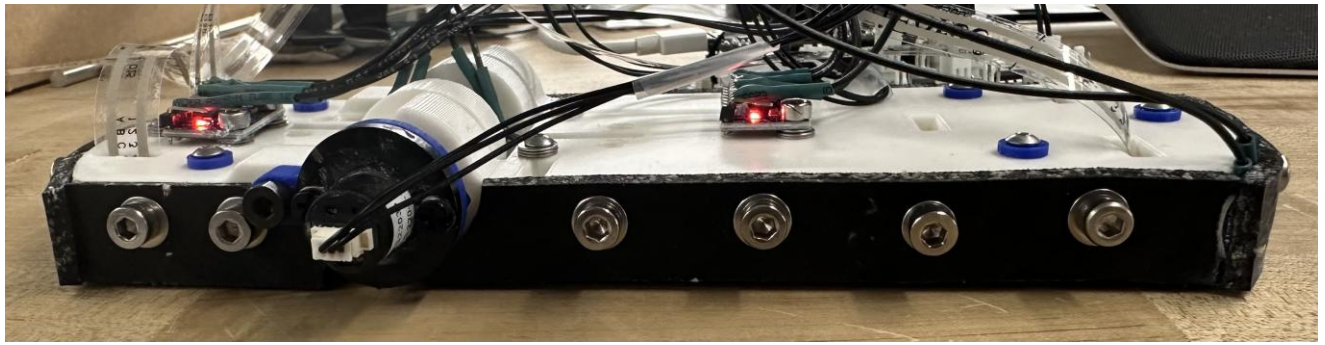
Linear Fit Calibration Plotting

$$
\begin{aligned}
\text{A0:} &\quad \text{Force} \approx 233.257 \times V_{\text{out}} - 316.886 \quad (R^2 = 0.9981) \\
\text{A3:} &\quad \text{Force} \approx 298.334 \times V_{\text{out}} - 403.587 \quad (R^2 = 0.9987) \\
\text{A6:} &\quad \text{Force} \approx 243.102 \times V_{\text{out}} - 328.109 \quad (R^2 = 0.9989) \\
\text{A9:} &\quad \text{Force} \approx 297.801 \times V_{\text{out}} - 403.681 \quad (R^2 = 0.9999) \\
\text{A10:} &\quad \text{Force} \approx 602.777 \times V_{\text{out}} - 812.439 \quad (R^2 = 1.0000) \\
\text{A11:} &\quad \text{Force} \approx 622.299 \times V_{\text{out}} - 841.463 \quad (R^2 = 1.0000) \\
\text{A12:} &\quad \text{Force} \approx 435.190 \times V_{\text{out}} - 590.396 \quad (R^2 = 0.9984)
\end{aligned}
$$

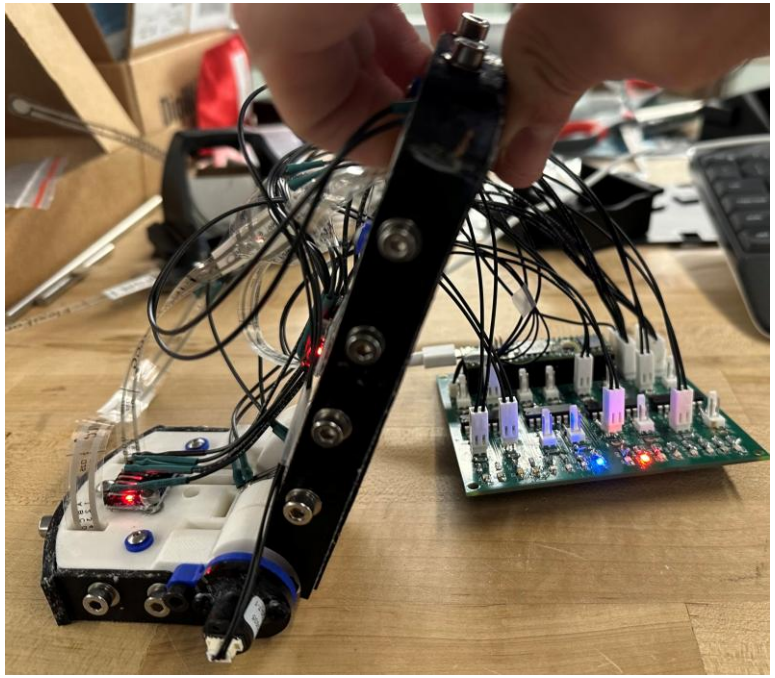
Linear Fit Relationships

Encoder Integration

- US Digital MAE3 magnetic absolute encoder
- PWM signal read by Teensy
- Mapped to toe angle degrees
- Neutral position calibration
- Integrated into foot sensing PCB
  - Above 60° rotation → 2 LEDs On



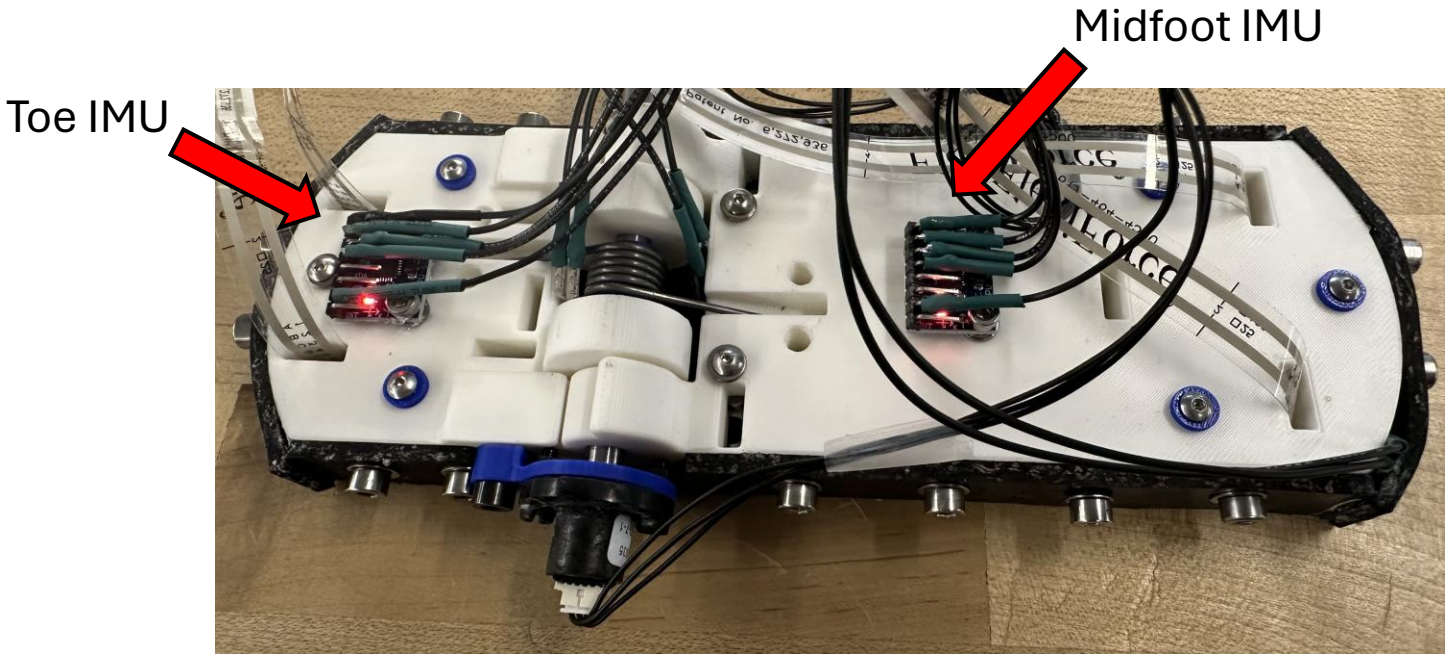
Neutral state: 0°

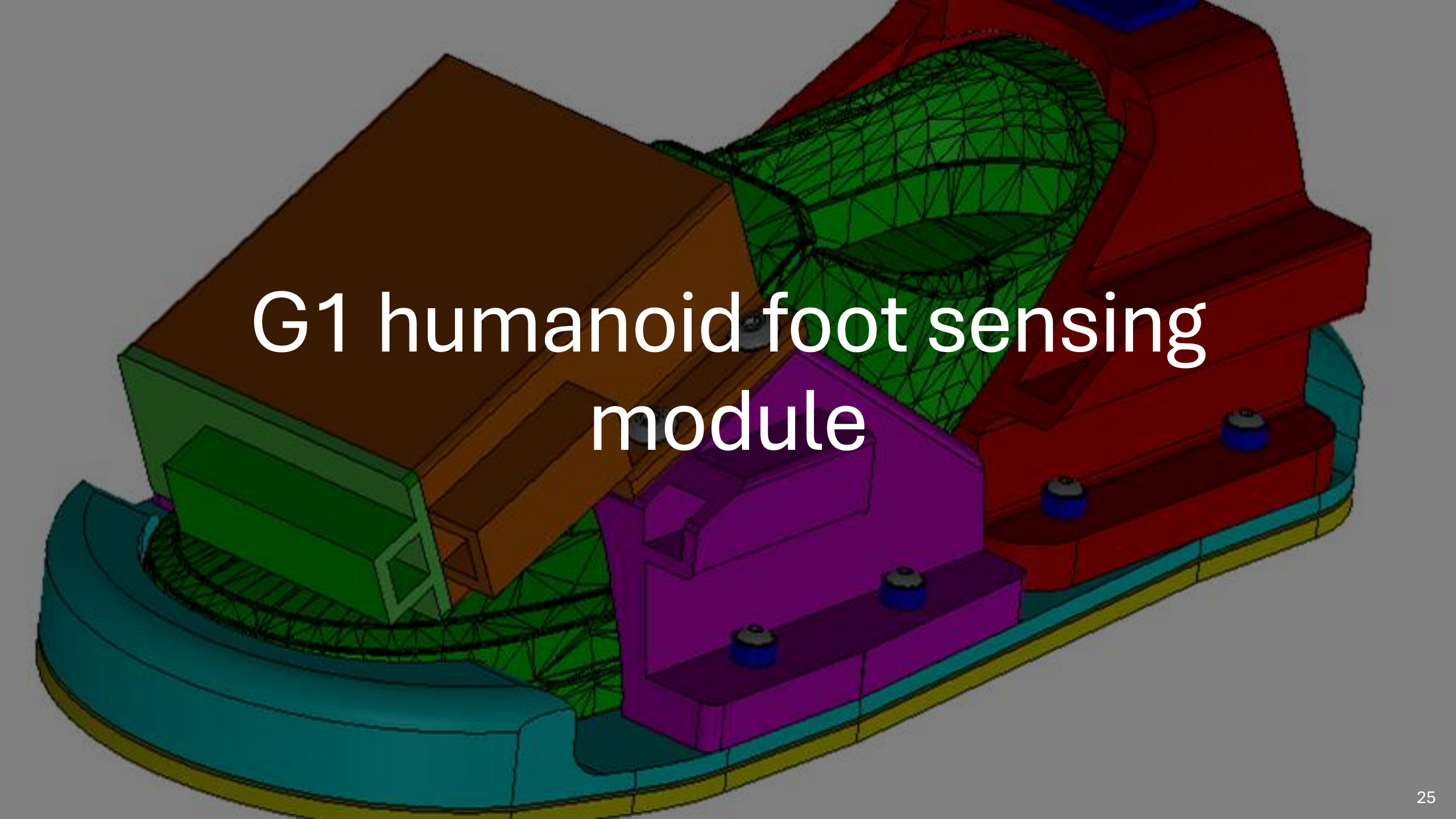


Extended state: 65.8°

IMU Integration

- MPU-6050 for orientation
- Toe + midfoot IMUs supported
- I^2C communication with Teensy
- Quaternion measurement (orientation)
- Gyroscope measurements
  - Angular velocity about X, Y, and Z axes





G1 humanoid foot sensing module

Objectives: G1 Foot Module

- Seamlessly clamp onto G1 foot structure
  - No adhesives, bolts, etc. directly on G1
- Measure ground reaction forces / moments and foot orientation

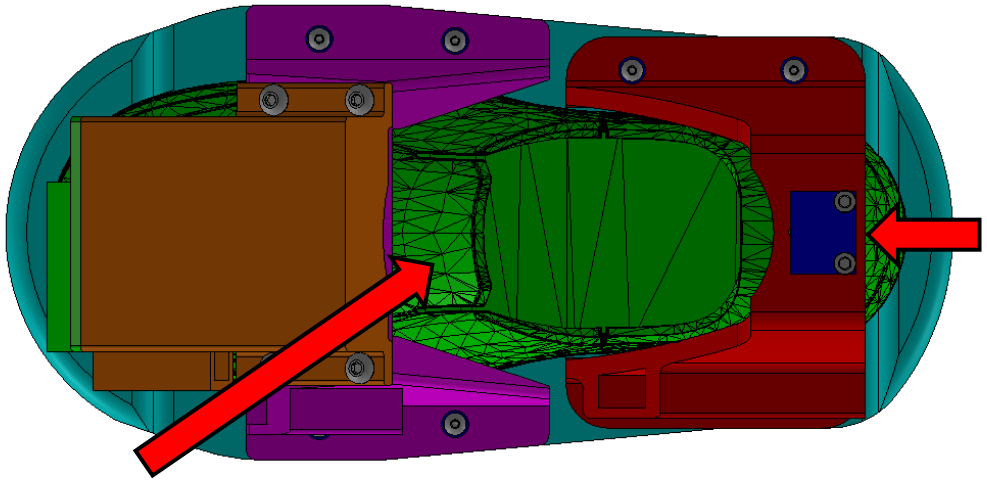
G1 Humanoid Foot

System Overview: G1 Foot Module

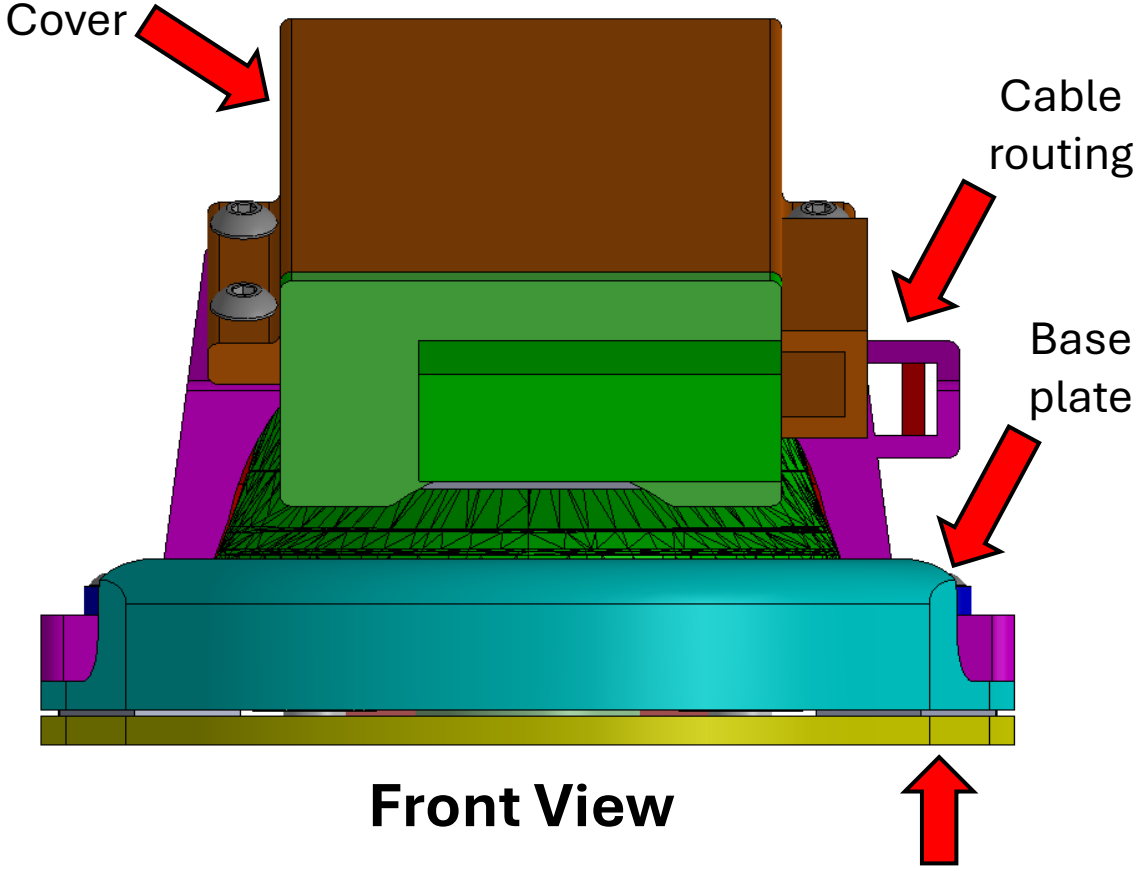
- 3 attachment parts:
  - Base plate, heel clamp, midfoot clamp
- Sensors onboard:
  - Force sensors
  - IMU for G1 foot orientation
- Custom PCB + Teensy 4.1 microcontroller

Complete G1 Foot Module

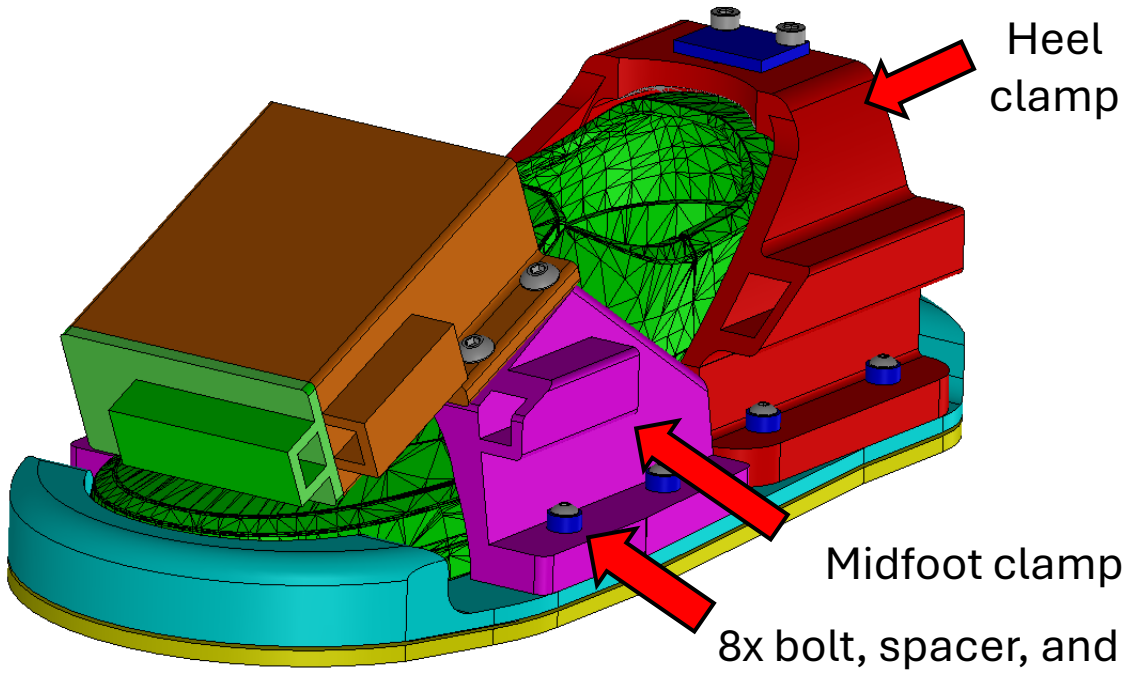
Mechanical Design: G1 Foot Module



Top View

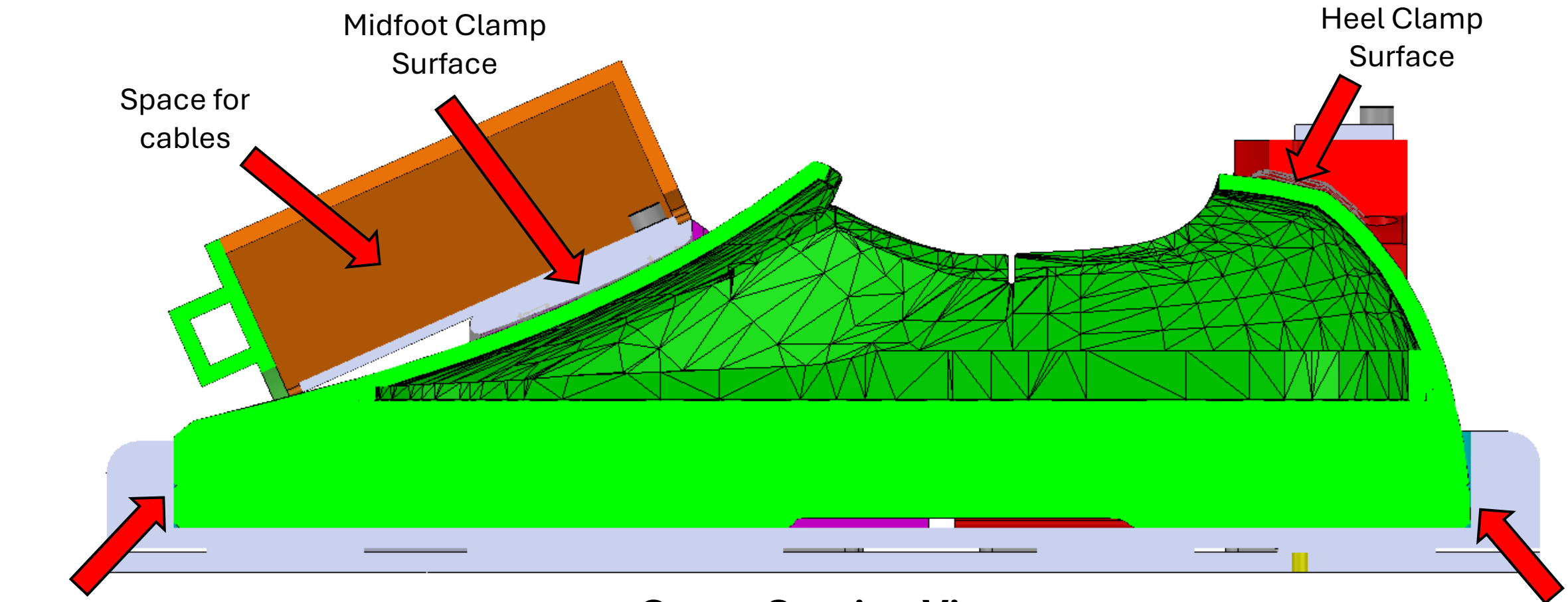


Front View



Isometric View

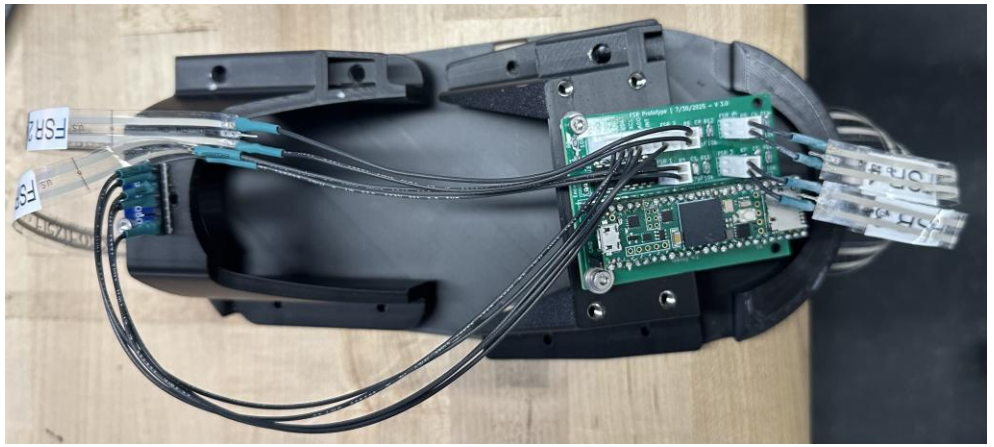
Mechanical Design: G1 Foot Module



Cross-Section View

Sensor Suite + Electronics

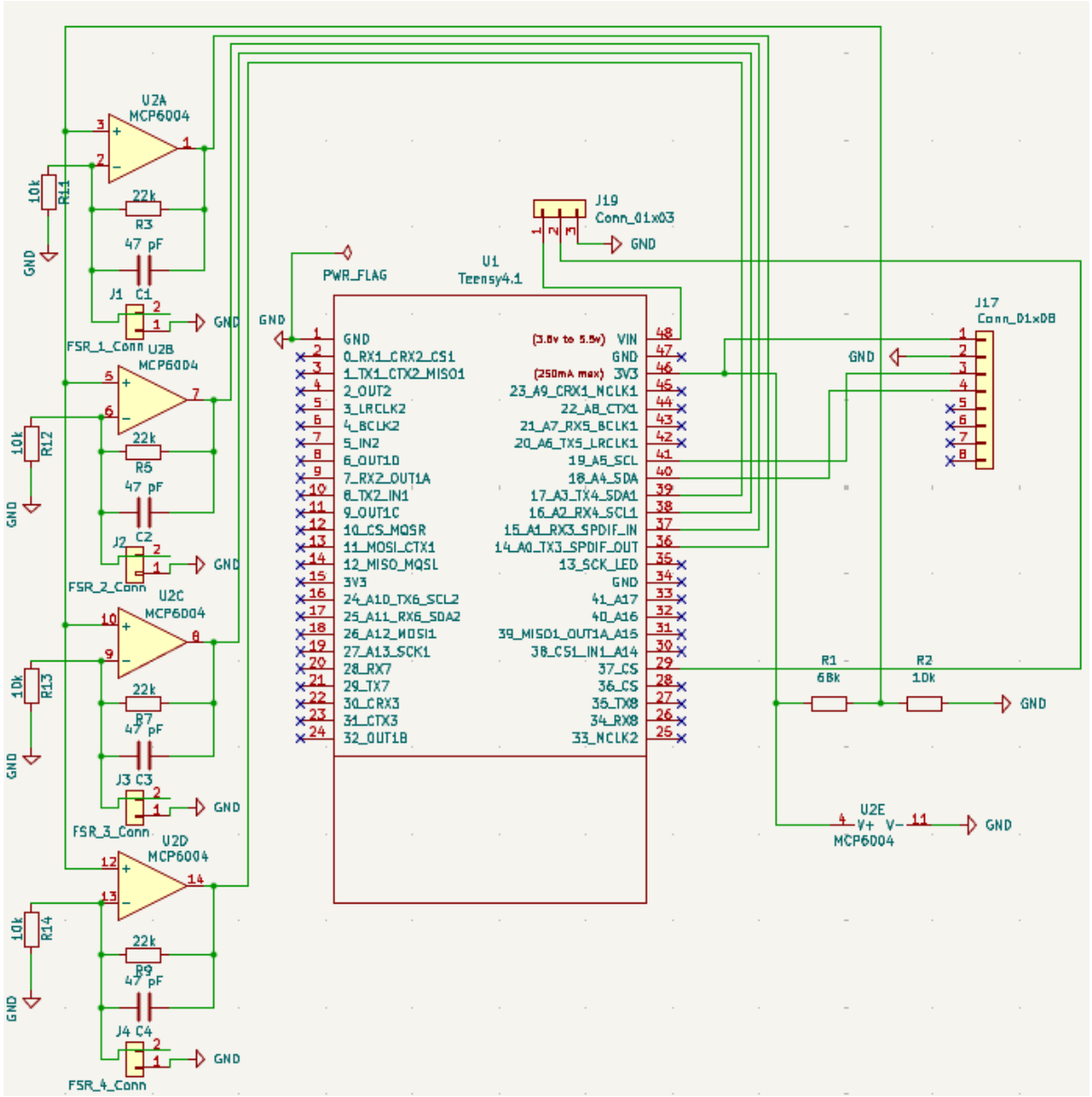
- 4x FSRs: corner force measurement
- 1x IMU: orientation of segment
- 2-layer PCB with Teensy 4.1
- Integrated onto existing G1 foot



Top View

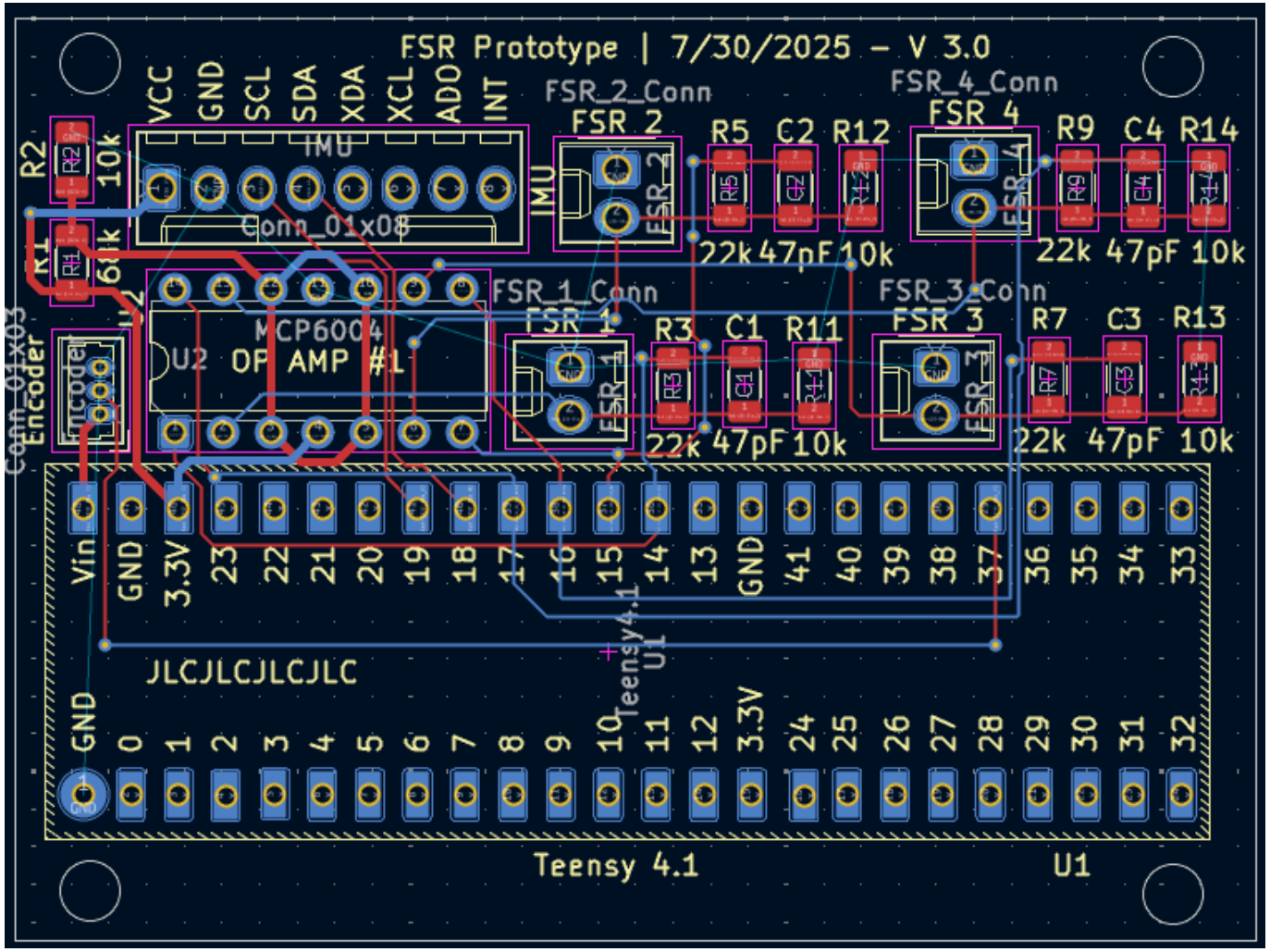
Bottom View (just FSRs)

PCB V3 Circuit



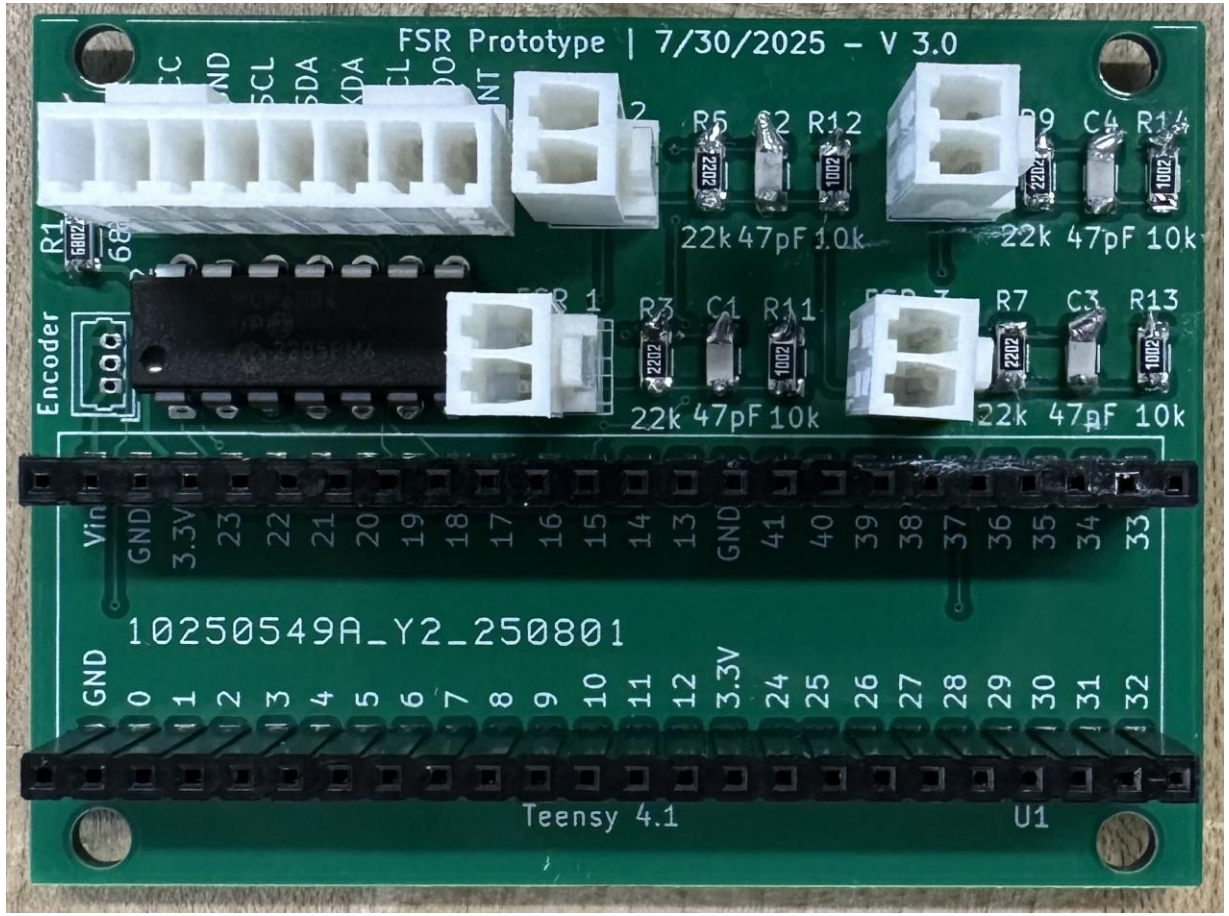
PCB V3 Design

- 2-layer Teensy 4.1-controlled board
- 4 op-amp channels for FSRs
- IMU connector
- Designed for integration onto G1
  - Smaller footprint: 49 x 66 mm



PCB V3 Soldering

- SMD resistors and capacitors
- 1x MCP6004 for non-inverting op amp
- 4x 2-pin connectors for FSRs
- 2x 24-pin connectors for Teensy 4.1
- 1x 8-pin connector for IMUs



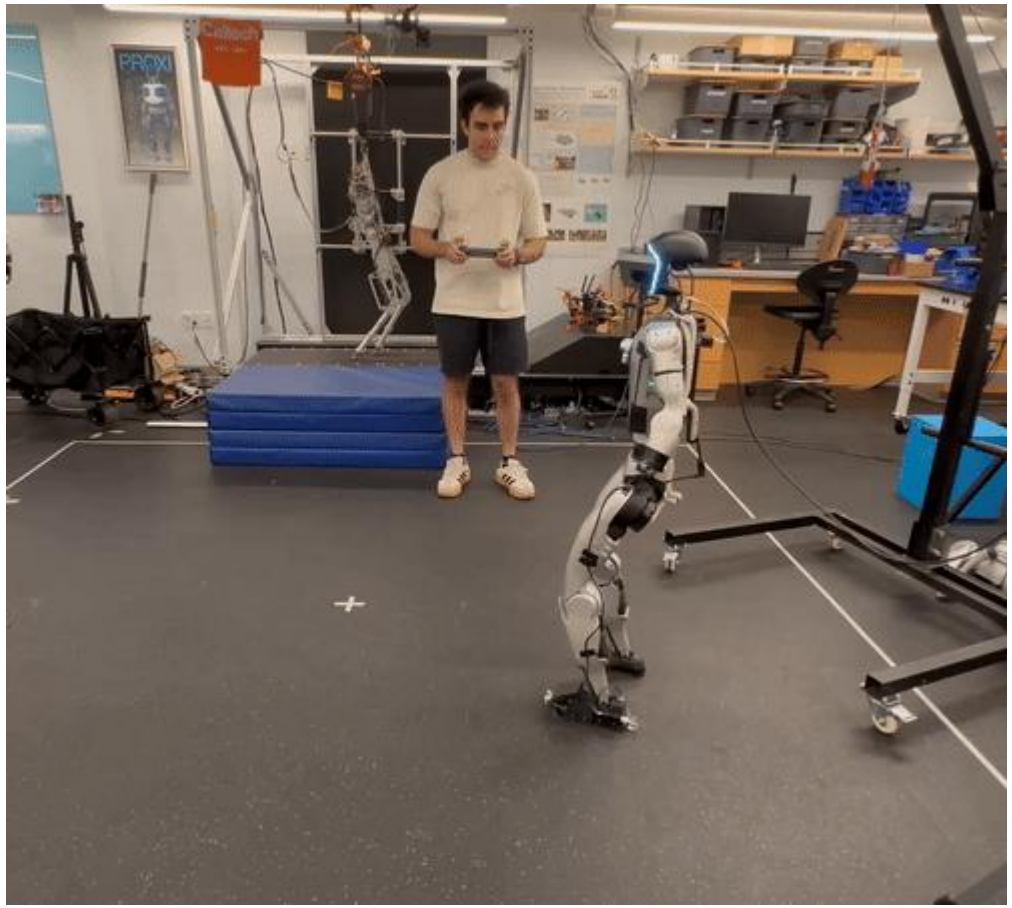
All LEDs On during Testing

Testing Process: G1 Foot Module

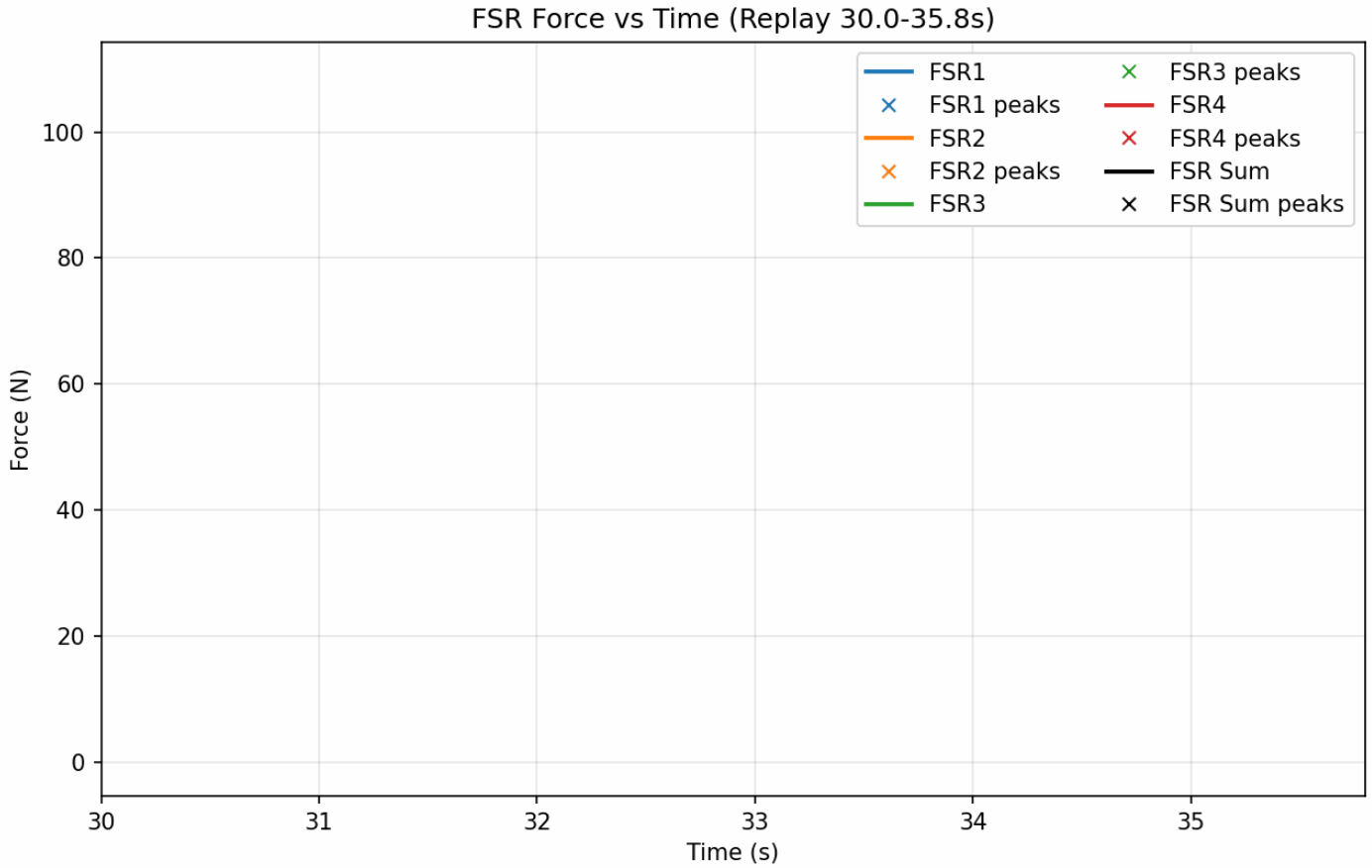
- Attached module to G1
  - Left foot only
- Recorded 2 minutes of walking data
  - Force from FSRs
  - Orientation from IMU
  - 1000 Hz frequency
- Parsed CSV file after test to plot & analyze

Attached G1 Foot Module

Testing Video:
G1 Foot Module



G1 Foot Module Testing



Force Plot

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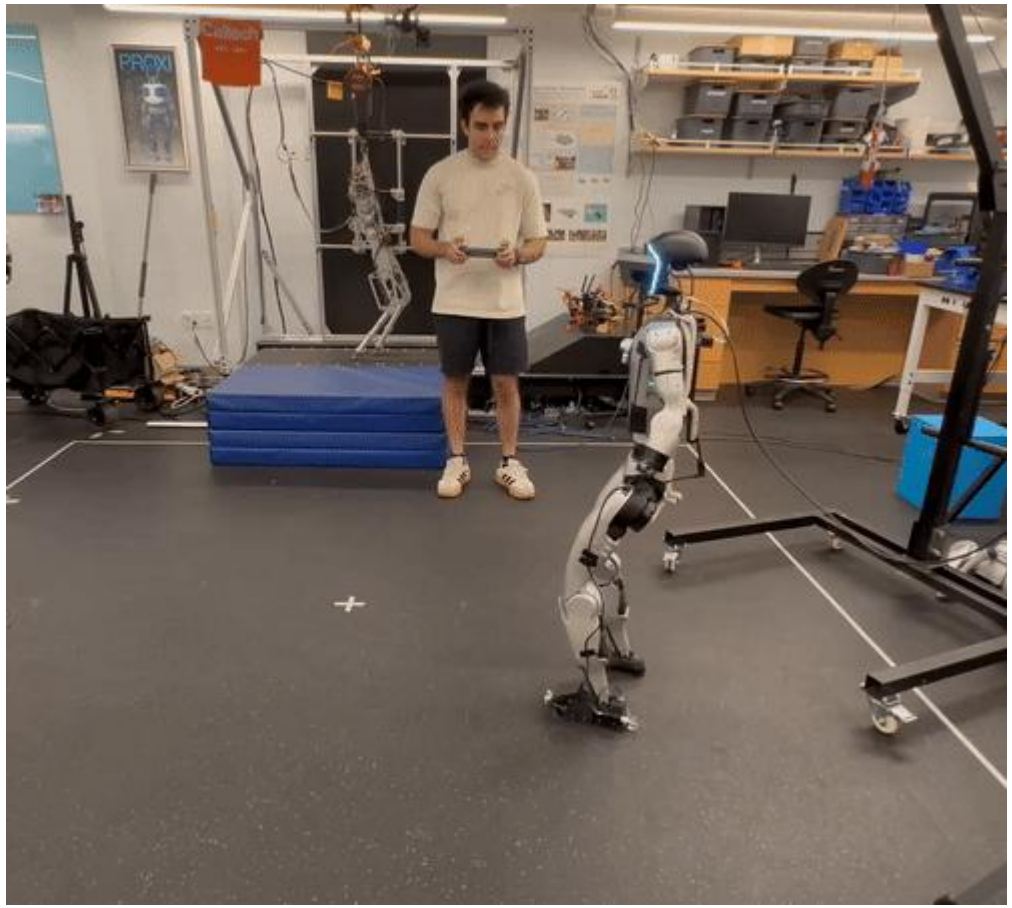
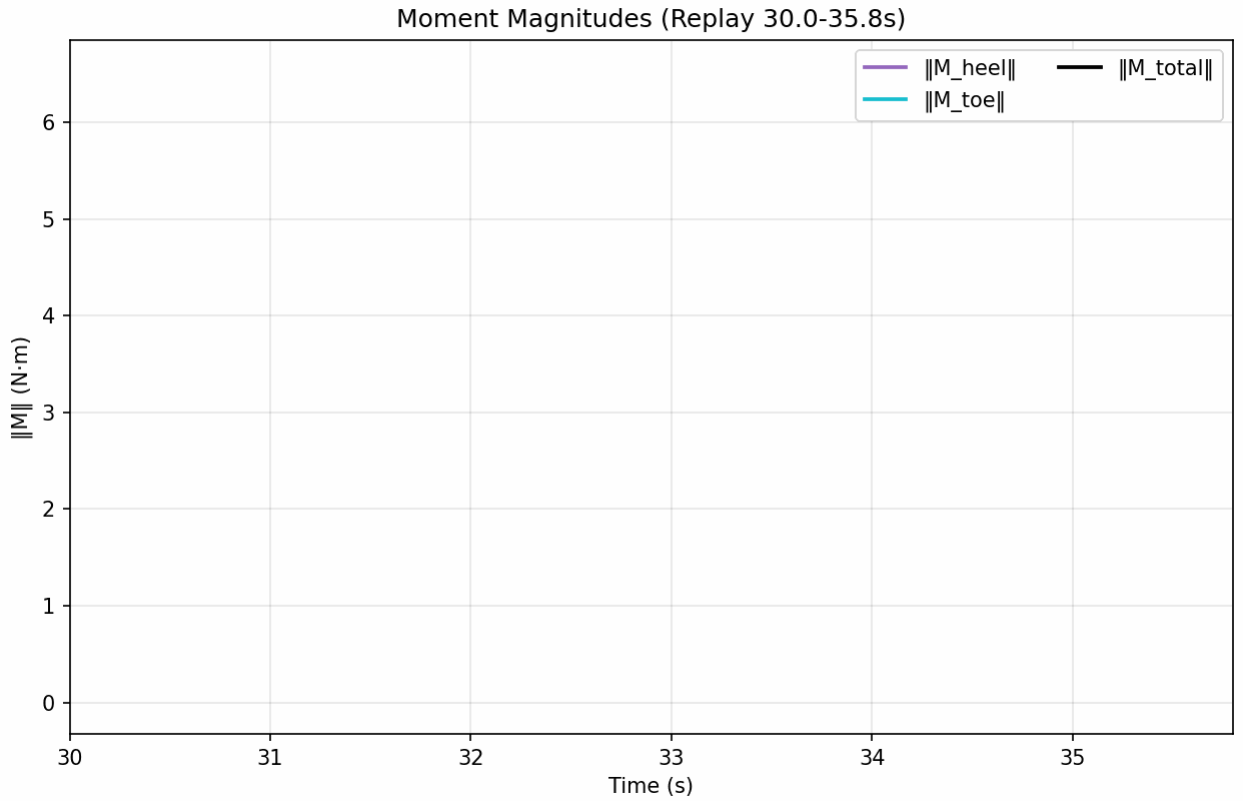
Testing Video:
G1 Foot Module

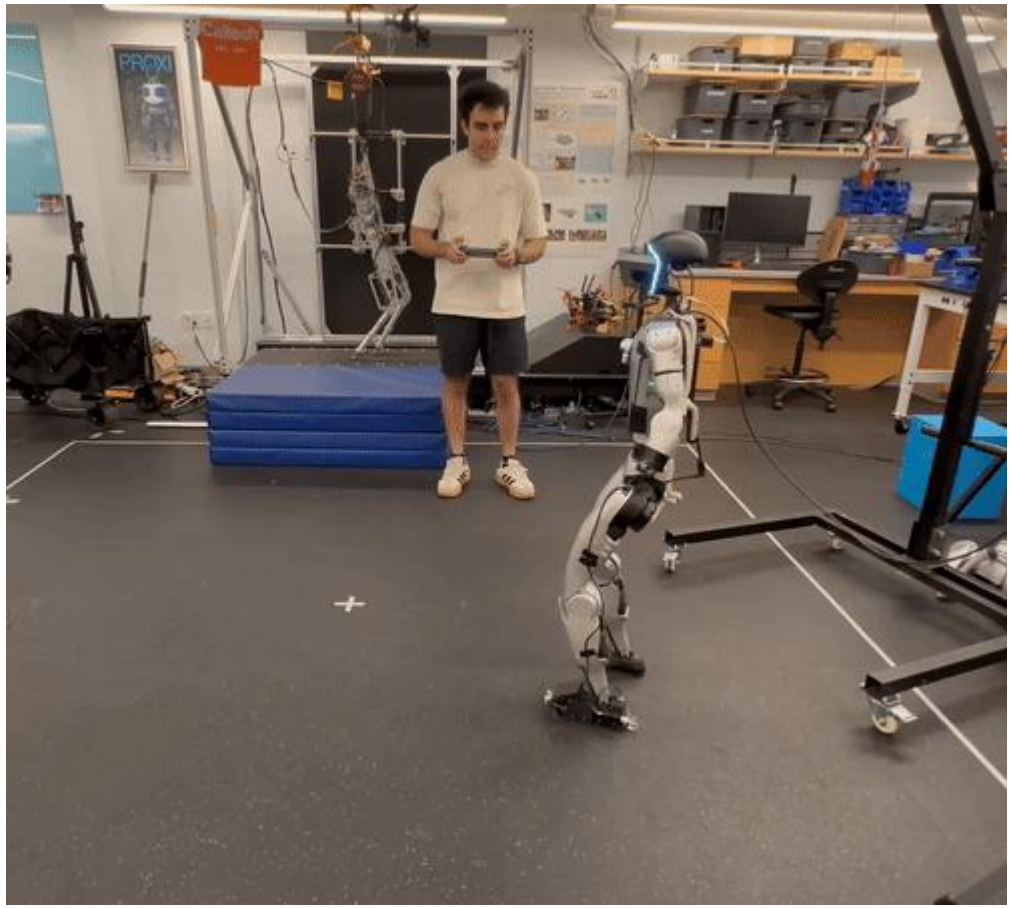


G1 Foot Module Testing

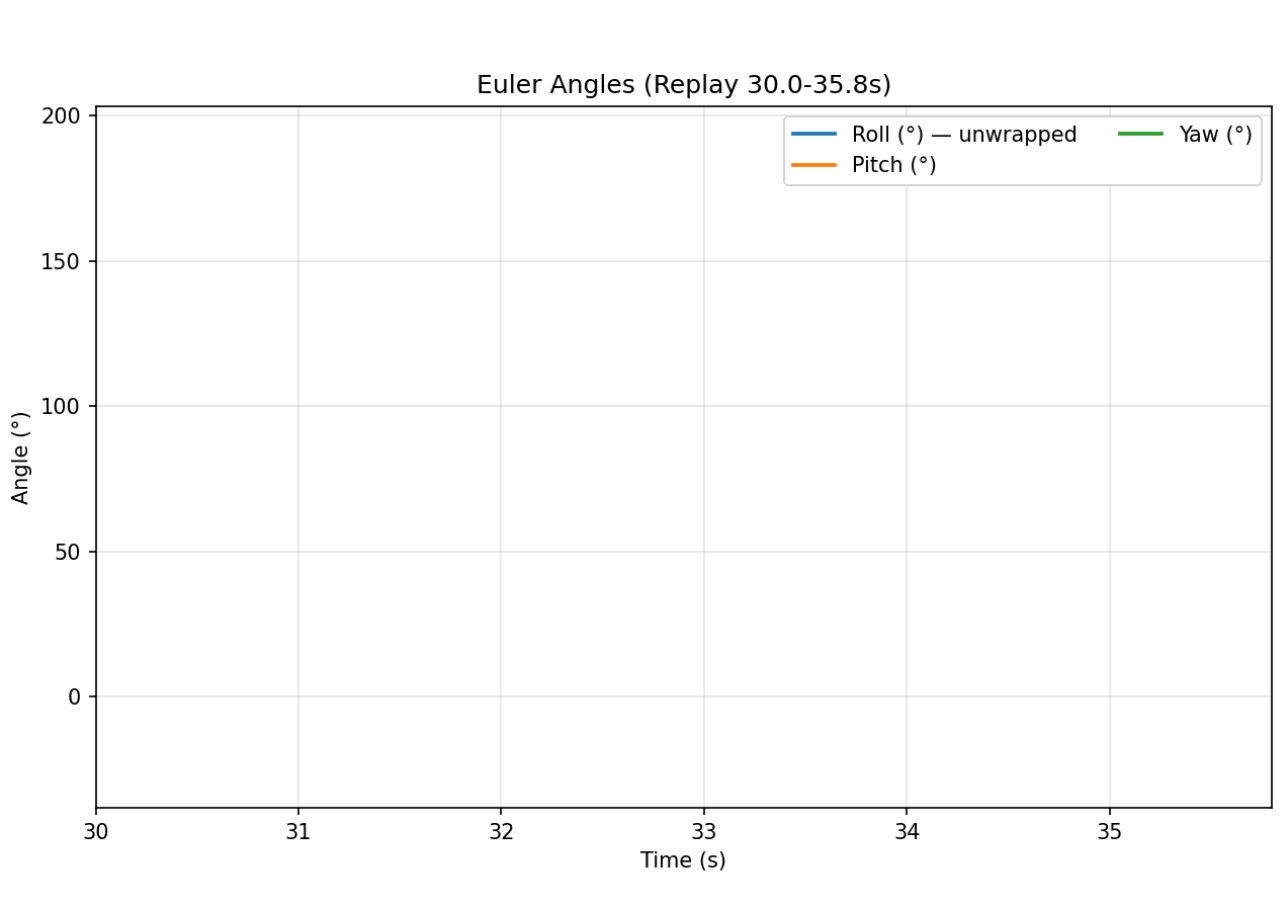


Moment Magnitude Plot

Testing Video:
G1 Foot Module



G1 Foot Module Testing



Euler Angles Plot

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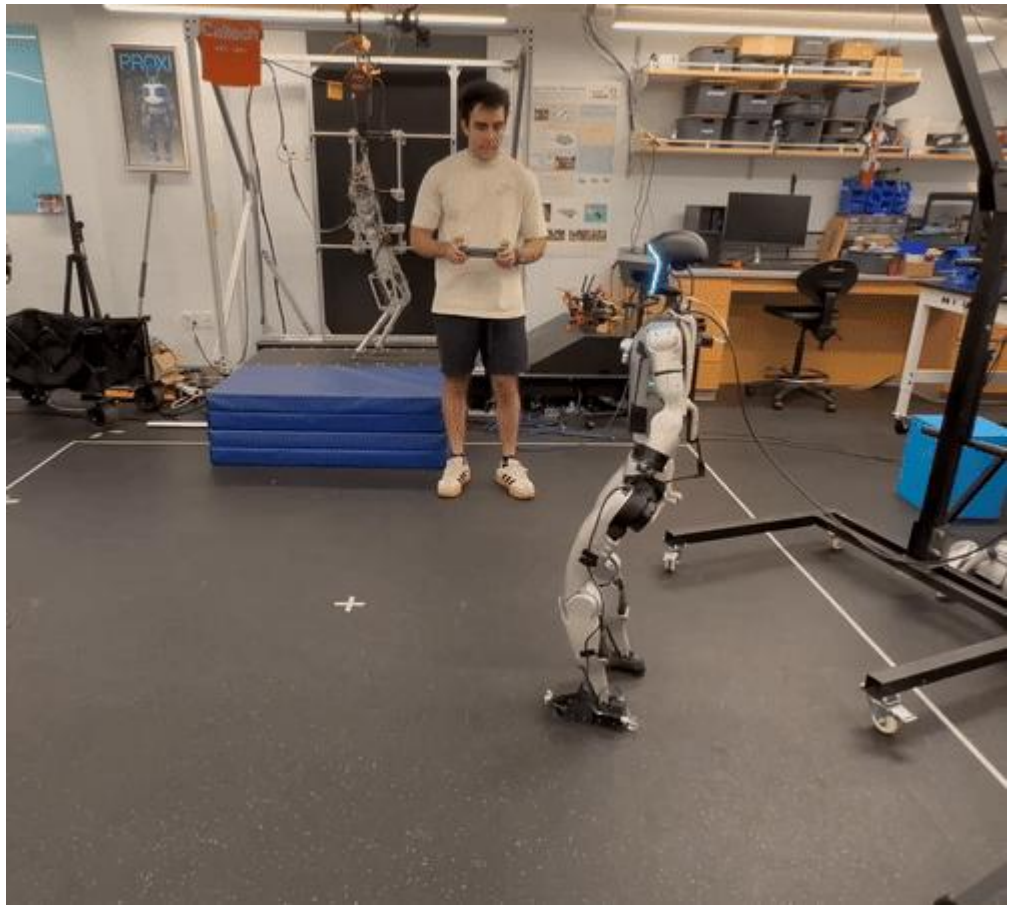
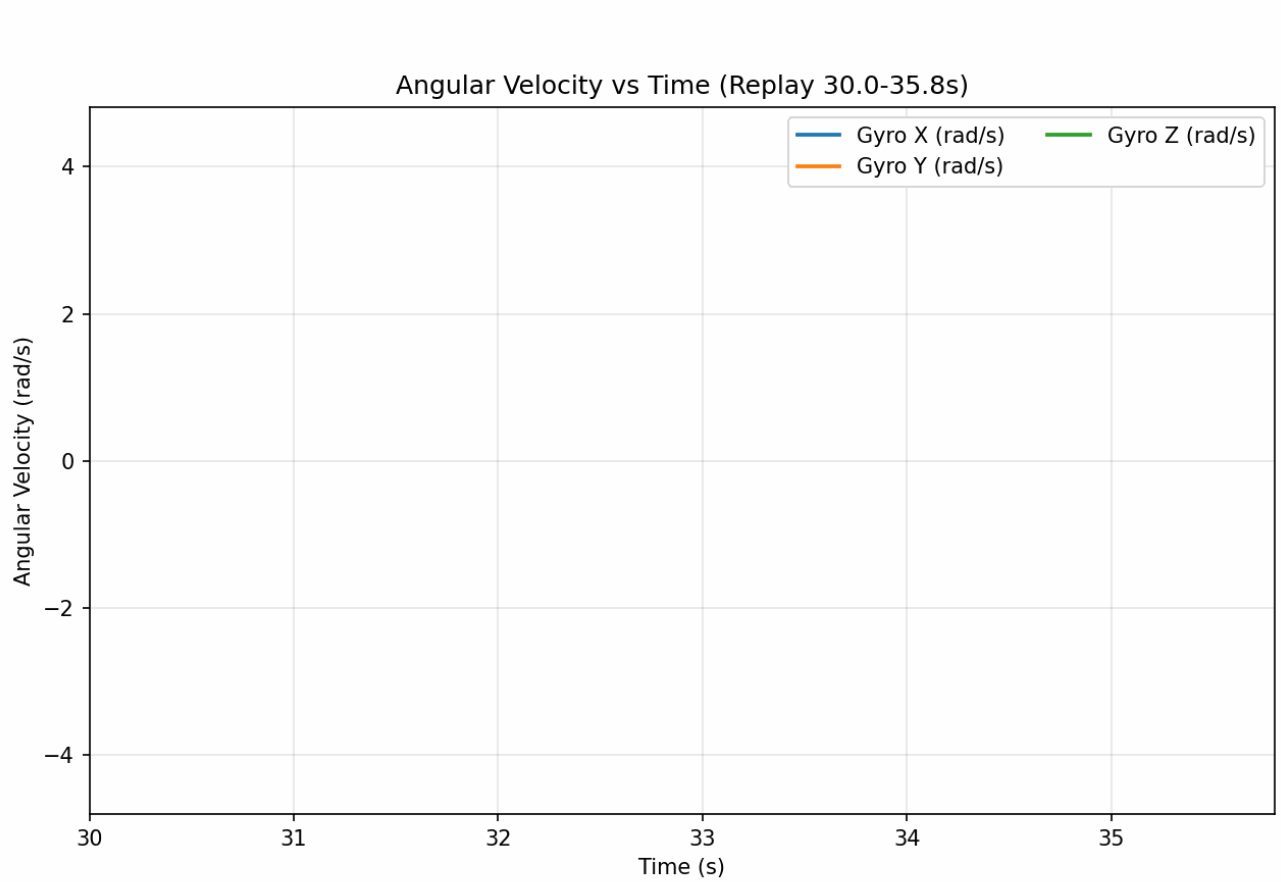
Testing Video:
G1 Foot Module



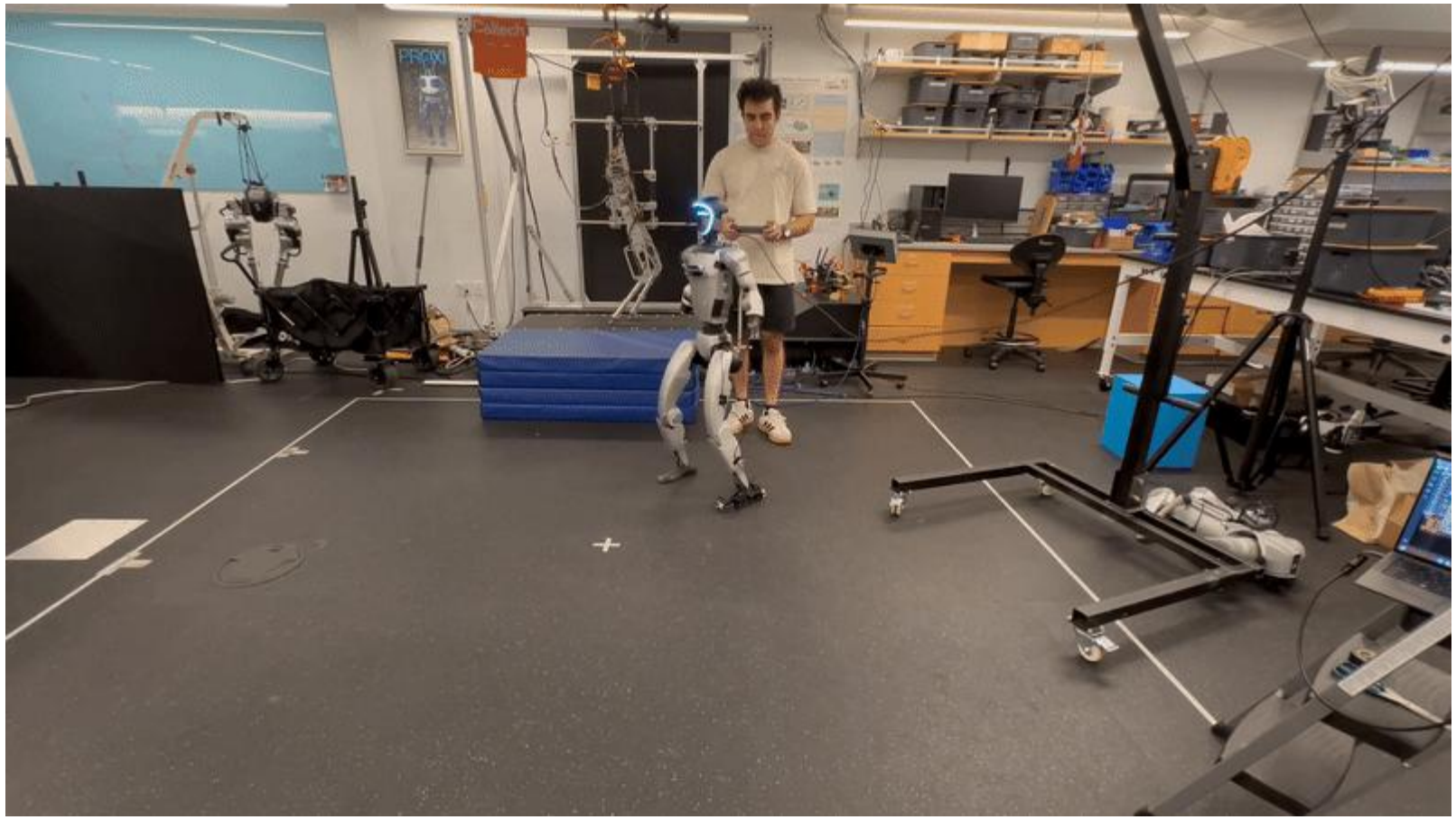
G1 Foot Module Testing



Angular Velocity Plot

Conclusion

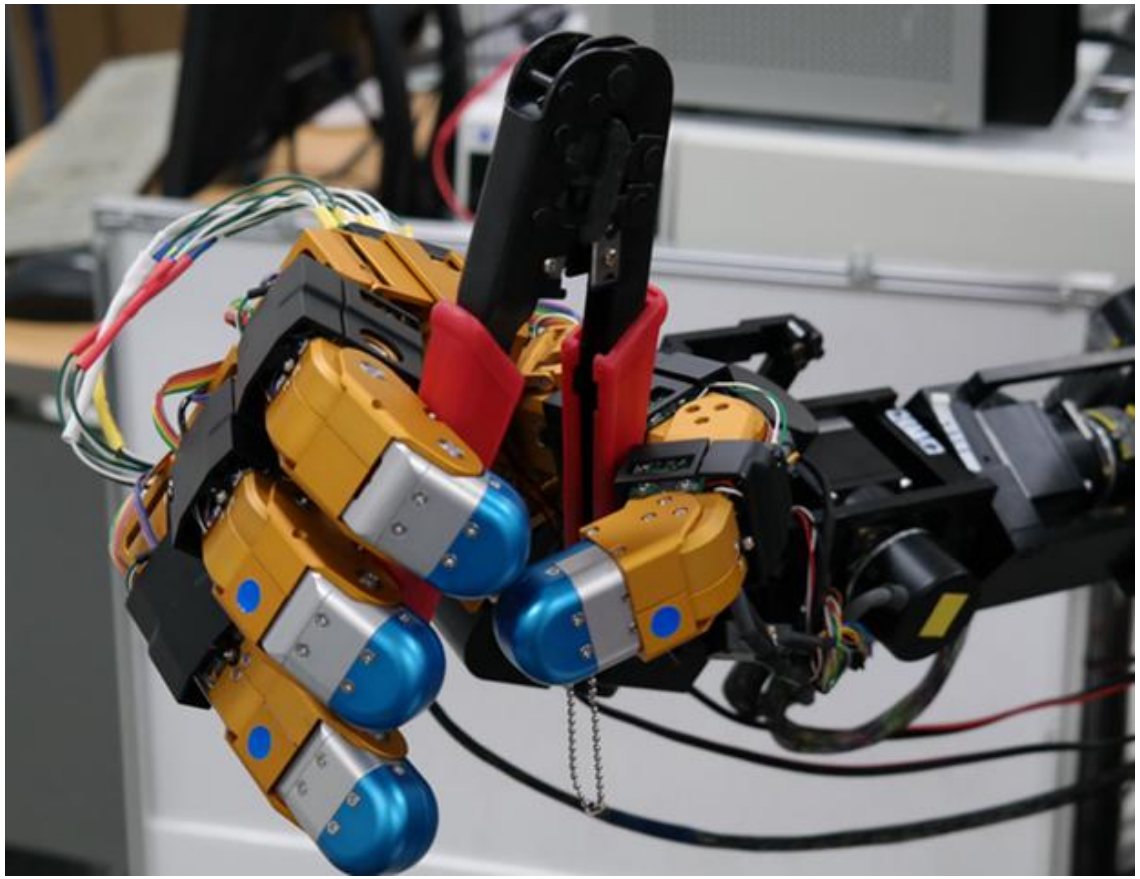
- Modular, replaceable sensing platforms
- Distributed force + motion sensing
- Passive toe improves gait realism
- Calibrated sensors demonstrated accuracy
- Scalable to other end effectors (other feet, hands)



More G1 Foot Module Testing

Future Work

- Short-term
  - Integrating module to both G1 feet
  - Additional dynamic walking validation tests
  - Sensor drift + durability analysis
  - Add barometric edge sensors
- Long-term
  - Integrating findings into the custom humanoid's foot design
  - Expand to hands & other limbs



Robotic Hand Manipulation[6]

[7] "Robotic Hands, Grasping and Manipulation - IEEE Robotics and Automation Society - IEEE Robotics and Automation Society," www.ieee-ras.org.

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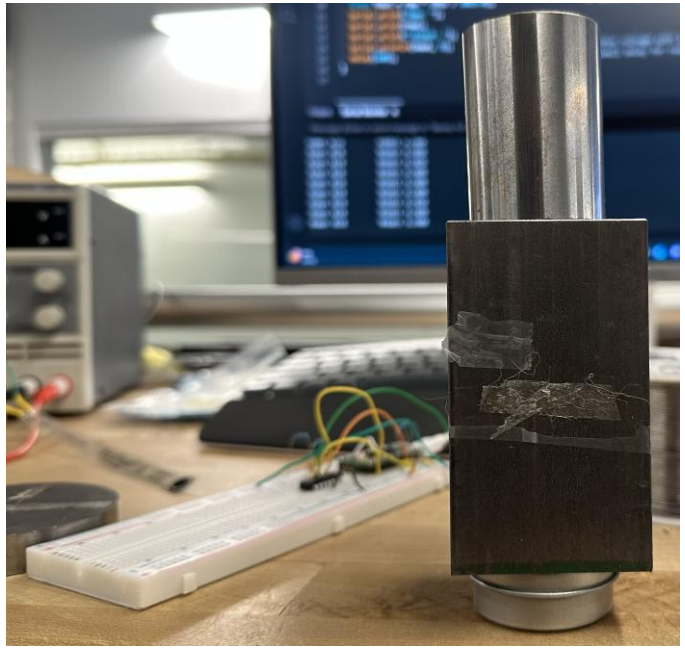
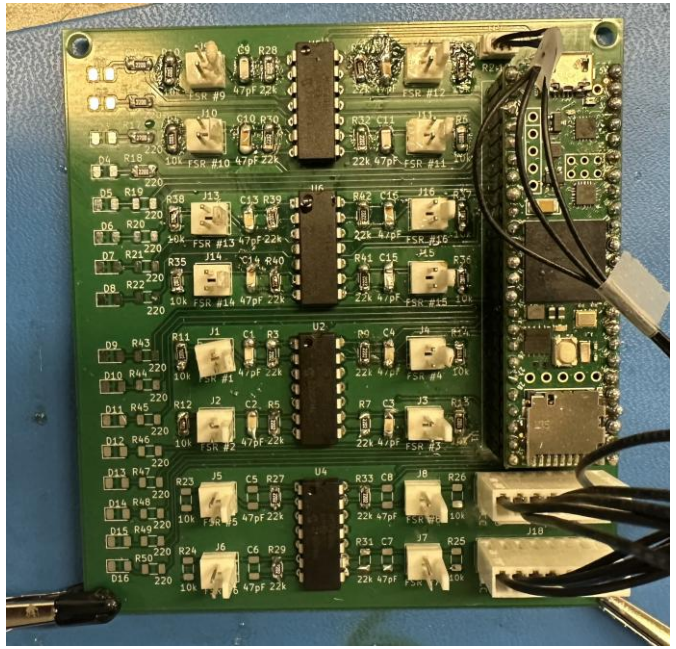
Key Takeaways

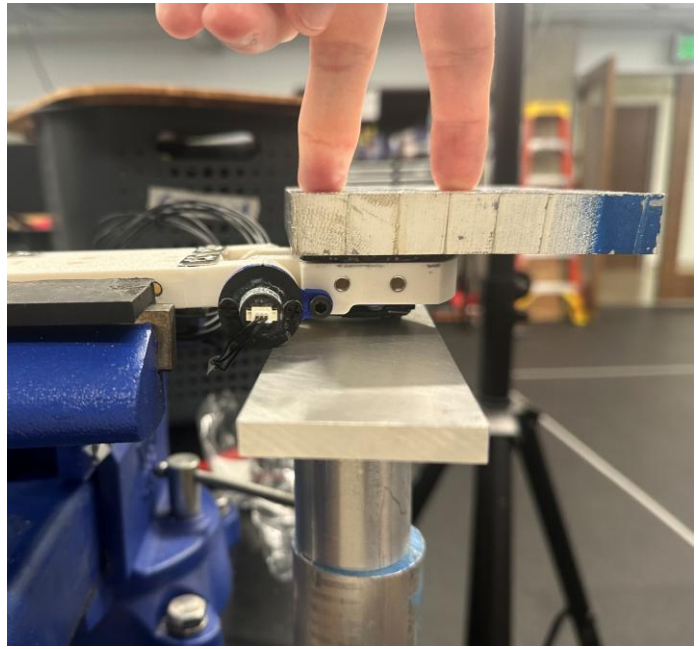
Technical Skills	Research Skills
Mechanical prototyping & CAD iteration	Literature review & prior work analysis
Sensor integration (FSR, IMU, encoder)	Prototyping → testing → design iteration
PCB design (KiCAD), soldering/wiring	Data validation & troubleshooting
Calibration & signal processing	Interdisciplinary collaboration
Embedded programming (Teensy, I^2C, PWM)	Technical documentation & presentation



Calibrating FSR on Breadboard



Soldering PCB V2



Gluing Nuts to Rubber

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- Professor Ames and the AMBER Lab for supporting my work
- My mentors Sergio Esteban, and Adrian Ghansah for guiding me through every stage of the project
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Q&A