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SURF 2025 Interim Report #2

**Work Completed**

As part of the AMBER Lab’s new humanoid robot being spearheaded by Sergio Esteban and Adrian Ghansah, significant mechanical and electrical work has been completed for a custom foot sensing module inspired by LIDAR Lab’s modules [1-2]. The first major milestone was the full assembly and validation of the Passive Toe System V1. This prototype used McMaster-sourced components including sleeve bearings, shaft collars, and a 120° torsional spring to enable rotation of the toe segment relative to the midfoot (Figure 1). After press-fitting sleeve bearings, cutting the 0.25” diameter shaft to 2.95” in length, and manually pressing heat-set inserts, the assembled system demonstrated the desired behavior: the toe segment rotated smoothly under load and returned to baseline via the torsional spring, while a hard-stop mechanism maintained neutral positioning in-between steps (Figures 2-4). Although heat-set installation proved inconsistent and the spring underpowered, this proof-of-concept validated the mechanism as a viable solution for passive toe implementation.

The first PCB prototype was subsequently soldered, programmed, and tested to be fully functional (Figure 5). This board featured two Tekscan A201 FlexiForce force-sensitive resistors (111 N rated), each wired through Molex connectors into voltage divider circuits with 22 kΩ resistors to ground. Each FSR was also paired with a 220 Ω resistor in series with an SMD LED to indicate threshold force activation. This prototype successfully demonstrated serial readout through the Arduino IDE and visual feedback through the onboard LEDs (Figure 6).

Efforts shifted to breadboard testing of inverting and non-inverting op-amp configurations to improve the dynamic range and noise suppression of the FlexiForce FSRs. After initially attempting to construct an inverting op-amp, a simpler, non-inverting op-amp using the MCP6004 was utilized instead, controlled and powered by the Teensy 4.0 (Figures 7-8). The final configuration used a 68 kΩ / 10 kΩ voltage divider to set a 0.42 V reference (within the 0.25-0.75 V recommended range), a 22 kΩ feedback resistor for a gain of 3.2, and a 47 pF capacitor for stability. A total of four A201 sensors were calibrated to assess variability in output (Figure 9). All sensors exhibited linear trends, though slopes varied by up to ~30%, emphasizing the need for individual calibration (Figures 10-11). Additional testing confirmed that multiple sensors wired simultaneously to a single op-amp did not affect output behavior. In parallel, a larger A502 sensor (222 N rated) was introduced to increase coverage area over the foot. The A502 demonstrated a lower sensitivity than the A201s and maintained a linear relationship across its range (Figure 12).

Two supporting sensor systems were developed for enriched sensing: IMUs for the orientation of both toe and midfoot segments and encoders for measuring the passive toe angle. Teensy firmware was developed to read quaternion and angular velocity data from an MPU-6050 IMU (Figure 13). The MAE3 magnetic absolute encoder from US Digital was also integrated. A CAD assembly was completed, fixing the magnetic hub to the stationary shaft while the housing and base rotate with the toe segment (Figure 14). Final Teensy integration will provide angle feedback using the encoder’s PWM output.

Utilizing KiCAD, a full schematic and corresponding PCB were created, including 16 FSRs (each with a non-inverting op-amp), 16 status LEDs, 2 IMU connectors (for toe and midfoot), encoder port, all powered and controlled by a Teensy 4.1 (Figure 15). A custom footprint was created for the Teensy to connect the 48 side ports (Figure 16). The resulting PCB was created using four layers and approximately 40 vias to manage complex routing (Figure 17). The board measured 3.8” wide by 3.5” tall and was designed to mount on the humanoid’s leg rather than within the foot itself (Figures 18-19).

The Passive Toe System V2 was modeled to integrate the force sensors, IMUs, and encoder in a fully modular design (Figures 20-21). CAD mirrored the electrical advances, with spacers modeled for the A401 and A502 sensors, helical insert mounting for durability, and waterjet-cut, bolt-fastened rubber strips to protect and mount the sensors (Figures 22-26). Spacer dimensions, cutouts, and cable routes were all carefully planned to prevent interference. A total of 13 FSRs were included in the design, with slots for up to 16 on the PCB to accommodate future additions, like edge detection.

**Progress**

The project is on track, with key sensing, calibration, and mechanical integration milestones achieved. The Passive Toe System V1 validated the hinge mechanism and laid the groundwork for version 2. Mechanical redesigns, including a larger hinge diameter, a stronger torsional spring, and improved fittings for adhesive nuts and bolts, were incorporated into the CAD model. Integration of helical inserts replaced unreliable heat sets, and a modular design allows for rapid assembly and testing.

The sensor system is functioning as expected. Calibrated force sensors operating in non-inverting op-amp circuits demonstrate consistent linearity and repeatability. Although individual sensors differ in slope, regression modeling allows each to be treated independently, maintaining precision. The IMU system also performed well in tests, providing real-time orientation feedback, and the encoder integration plan is well-supported mechanically and electrically. The schematic and PCB design progressed from early prototyping to a finalized design currently being manufactured. The Teensy 4.1 microcontroller provides sufficient channels for the full sensor suite. CAD development has resulted in a custom prototype foot for the humanoid.

**Challenges and Solutions**

Several key challenges arose during the prototyping process, resulting in design pivots and improvements. The initial plan to utilize inverting op-amps for FSR signal amplification was abandoned in favor of the non-inverting configuration due to the dual power supply requirement. Although the manufacturer recommends inverting circuits due to their superior noise suppression and zero-voltage offset, as explained in Tekscan’s integration guide [3], the non-inverting configuration proved reliable.

Precise sensor calibration presented another challenge. Steel and aluminum raw materials were acquired, weighed, and carefully stacked above sensors to measure corresponding voltage outputs. Accordingly, each FSR must be individually calibrated using a standardized load setup to ensure accuracy in the final integration.

Mechanical integration also brought unexpected difficulties. Heat-set inserts used in Passive Toe System V1 were inconsistent and unreliable, prompting a redesign using helical inserts. The geometry of the torsional spring’s sleeve was revised to radially constrain the torsional spring without interference. Additionally, incorporating the MAE3 encoder presented electrical challenges due to its 5 V requirement. Since the Teensy 4.1 operates at 3.3 V, the current plan is to provide an external power source in the final humanoid, such as a LiPo battery.

Finally, PCB complexity grew rapidly as the number of sensors and op-amps increased. In the first PCB prototype, no vias were needed on a two-layer board; the new design required 40 vias and the use of four layers to accommodate all routing while meeting JLCPCB constraints. Despite the complexity, the board remains manufacturable and mechanically mountable.

**Remaining Goals**

The remaining weeks will focus on final integration, testing, and analysis. Mechanically, the goal is to finish assembling the second passive toe system with integrated sensors. The finalized PCB will be fabricated, and upon arrival, all components will be mounted and soldered. The completed sensor module will be attached to the Unitree G1 humanoid robot’s foot, permitting real-time data collection by the FSRs, IMUs, and encoders (Figure 27). This data fusion will enable measurements of ground reaction forces, foot segment orientations, and passive toe angles during bipedal locomotion.

Experimental testing will focus on validating the sensor outputs during static and dynamic foot-ground interactions. The team plans to capture force data under various conditions, including flat stance, heel/toe roll, and load transitions, to evaluate system responsiveness and stability. Signal quality, latency, and data consistency across sensors will be quantified. Sensor drift and robustness will also be monitored under repeated loading. The final goal is to utilize the measured force and motion data to refine gait models based on real-world validation.

The original goals of the project remain intact, though they have expanded in scope and complexity. What began as a simple tactile-sensing prototype has evolved into a robust, multi-sensor, multi-modal foot sensing platform. The integration of MEMS barometer-based sensing [4] was abandoned in favor of more tractable FSR calibration [5] and toe angle feedback, but future extensions are possible. With final fabrication and validation approaching, the project is poised to deliver a complete sensing module for humanoid robotics across not only feet but also hands and other end effectors.

**Appendix**

A set of parts and parts of a toy

AI-generated content may be incorrect.

**Figure 1**. Top View of all Passive Toe System V1 Parts Before Assembly

|  |  |
| --- | --- |
| Top View of Passive Toe V1 | Bottom View of Passive Toe V1 |
|  | A metal hinge with screws  AI-generated content may be incorrect. |

**Figure 2**. Top and Bottom of Passive Toe System V1 with Inconsistent Heat-set Inserts

A close up of a keyboard

AI-generated content may be incorrect.

**Figure 3**. Side View of Passive Toe System V1 in Neutral State

|  |  |
| --- | --- |
| Side View of Passive Toe V1 | Isolateral View of Passive Toe V1 |
| A hand holding a white object  AI-generated content may be incorrect. | A hand holding a grey device  AI-generated content may be incorrect. |

**Figure 4**. Views of Functional Passive Toe System V1 in Extended State

|  |  |
| --- | --- |
| Front of Fully Soldered PCB V1 | Back of Fully Soldered PCB V1 |
|  |  |

**Figure 5**. Front and Back Views of Fully Soldered PCB with Connectors and SMD Components

|  |  |  |
| --- | --- | --- |
|  | FSR 1 Inactive | FSR 1 Active |
| FSR 2 Inactive |  |  |
| FSR 2 Active | A hand holding a computer chip  AI-generated content may be incorrect. |  |

**Figure 6**. Fully Functional PCB V1 with Two A201 FSRs Connected to Yellow and Blue SMD LEDs; FSR #1 Corresponds to Yellow, FSR #2 Corresponds to Blue

A circuit board with wires and a measuring stick

AI-generated content may be incorrect.

**Figure 7**. Prototype Inverting Op-Amp Circuit (non-functional)

A scale and a measuring device

AI-generated content may be incorrect.

**Figure 8**. Prototype Non-Inverting Op-Amp Circuit with Scale for Calibration

A metal cylinder on a table

AI-generated content may be incorrect.

**Figure 9**. Side View during A201 Calibration Demonstrating Weight Concentration on the A201 Puck

A group of wires connected to a device

AI-generated content may be incorrect.

**Figure 10**. Non-Inverting Op-Amp Circuit with Four A201 FSRs for Calibration

A graph of a graph with colored lines

AI-generated content may be incorrect.

**Figure 11**. Linear Fit Models between Voltage Output and Force Input for the Four A201 FSRs

A graph of different colored lines

AI-generated content may be incorrect.

**Figure 12**. Linear Fit Models for the Four A201 FSRs and Additional A502 with Shallower Slope

A circuit board with wires and a usb port

AI-generated content may be incorrect.

**Figure 13**. Prototype MPU-6050 IMU Circuit in Calibration State

|  |  |
| --- | --- |
| Encoder at Neutral Angle | Encoder at Full Extension |
| A model of a machine  AI-generated content may be incorrect. |  |

**Figure 14**. CAD Model of Integrated MAE3 Encoder in Passive Toe System V2

A computer screen shot of a circuit board

AI-generated content may be incorrect.

**Figure 15**. Schematic of Foot Sensing Module Including FSRs, LEDs, IMUs, and Teensy 4.1

A screen shot of a computer screen

AI-generated content may be incorrect.

**Figure 16**. Custom Footprint for the Teensy 4.1 to Connect all 48 Side Ports

A circuit board with many wires

AI-generated content may be incorrect.

**Figure 17**. PCB Schematic of Foot Sensing Module for tactile, orientation, and position sensing

A green circuit board with many small lights

AI-generated content may be incorrect.

**Figure 18**. 3D Rendering of Front of PCB with Surface Mounted Devices

A green circuit board with white text

AI-generated content may be incorrect.

**Figure 19**. 3D Rendering of Back of PCB with Through Holes, Traces, and Label Visible

|  |  |
| --- | --- |
| Isometric Left View | Isometric Right View |
| A model of a machine  AI-generated content may be incorrect. | A model of a toy  AI-generated content may be incorrect. |

**Figure 20**. Isometric Views of Passive Toe System V2

A yellow and blue machine

AI-generated content may be incorrect.

**Figure 21**. Top View of Passive Toe System V2 Highlighting IMUs, Toe and Midfoot Segments, and Bolt Fasteners

A black rectangular object with colorful objects

AI-generated content may be incorrect.

**Figure 22**. Bottom View of Passive Toe System V2 Highlighting Rubber

A cartoon of a machine

AI-generated content may be incorrect.

**Figure 23**. Side View of System in Extended Orientation

A colorful machine with a door

AI-generated content may be incorrect.

**Figure 24**. Bottom View of System without Bottom Rubber Layer

A colorful machine with bolts and nuts

AI-generated content may be incorrect.

**Figure 25**. Isometric View of System with Hidden Rubber and Housing Segments

A colorful rectangular object with a red stripe

AI-generated content may be incorrect.

**Figure 26**. Cross-Section View of Spring, Housing, and Encoder Mechanism

|  |  |
| --- | --- |
| Unitree G1 Feet and Shins | Unitree G1 Feet and Calves |
|  |  |

**Figure 27**. Views of Unitree G1 from Knees to Feet

**References**

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[3] “FlexiForce Integration Guides | Tekscan,” Tekscan.com, 2016. https://www.tekscan.com/resources/datasheets-guides/flexiforce-integration-guides (accessed Jul. 24, 2025).

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