SURF 2025 Proposal: Improving Humanoid Locomotion via Advanced Foot Sensing

Introduction/Background

This research project investigates the enhancement of bipedal robot locomotion by incorporating multi-contact foot behavior through the advancement of foot sensing capabilities. Current limitations in bipedal robotics, such as restricted agility and efficiency, stem from simplified models that often neglect the nuanced dynamics of human walking, which involve multi-contact interactions between the foot and the ground (e.g., heel-toe rolling). This research addresses these limitations by drawing inspiration from human locomotion and developing novel control strategies that enable more natural and dynamic walking behavior.

Building upon the research conducted by Professor Ames and his group in the AMBER Lab, which has established a strong foundation in developing control strategies for bipedal robots using reduced-order models and hybrid systems theory, this project will explore how integrating more advanced foot sensors can improve model accuracy and enable more dynamic, human-like gait transitions. Specifically, various sensors of interest will be investigated, the existing foot design will be modified to integrate these sensors, and their impact on locomotion performance will be validated. The successful implementation of these advancements will lead to significant improvements in the stability, efficiency, and robustness of bipedal robots, with potential applications in humanoid assistance, disaster relief, and space exploration.

Objectives

This project aims to improve humanoid locomotion by integrating advanced foot sensing, enabling more natural and efficient multi-contact walking. To achieve this, ground reaction forces, contact locations, and foot orientation among others will be measured using pressure sensors, inertial measurement units (IMUs), capacitive sensors, and various others under diverse walking conditions. The starting assumption is that the current humanoid robot has a rigid foot featuring toe and ankle mechanisms without sensing capabilities, limiting its ability to adapt to uneven terrain and dynamic motion. A successful outcome will involve designing and implementing a novel foot structure that seamlessly integrates these sensors; developing a data-driven model of multi-contact foot behavior utilizing sensor data collected from the robot; integrating sensor feedback into a control framework to adapt robot behavior in real-time based on observed interactions; and evaluating the enhanced robot's performance through metrics such as energy consumption, step length, and robustness to perturbations. Success will be determined by the effective integration and validation of the sensors, the accuracy of the foot behavior model, and demonstrated improvements in robotic locomotion.

Approach

To accomplish the project objectives, a structured, 10-week approach will be followed inspired by previous research in bipedal robotics, with key milestones outlined below:

1. Sensor Exploration (Weeks 1-2): Various sensors—pressure sensors, IMUs, capacitive sensors, and more—will be experimented with to understand their behavior and how to best integrate them into the foot. This hands-on exploration will inform the selection and analysis methods for each sensor type.

2. Mechanical Design (Weeks 3-4): The foot design will be modeled and modified in SolidWorks® to integrate the chosen sensors. This process will ensure the foot can support multi-contact interactions, enabling more advanced locomotion than flat-foot sensing.

3. Sensor Integration (Weeks 5-7): The selected sensors will be integrated into the foot structure, focusing on ensuring accurate measurements of foot-ground interactions, allowing for state-of-the-art motion including stair climbing and running.

4. Performance Validation (Weeks 8-9): The robot will undergo a series of tests to evaluate the effectiveness of the sensor-integrated foot. These tests will assess the foot's ability to adapt to different terrain conditions and its overall locomotion capabilities.

5. Evaluation and Adjustments (Week 10): In the final week, the foot's performance will be thoroughly assessed, and any necessary adjustments will be made to optimize its functionality, ensuring it is capable of humanoid and dynamic motion.

Sensor integration will be particularly challenging due to the diverse signal types from different sensors, requiring careful calibration and data fusion. To address this, insights will be leveraged from the LIDAR Lab and Professor Zhao's work on multi-modal contact sensing and terrain classification to optimize sensor selection and data processing strategies. Sergio Esteban, serving as the project mentor, will be consulted along with other AMBER Lab students to refine the integration process and troubleshoot issues collaboratively. The basic foot and humanoid robot will be inherited from the lab, but sensors, testing equipment, and facilities will be needed to measure the foot's effectiveness. For example, an Instron machine may be utilized to cyclically assess the sensor-equipped foot during validation testing. An Arduino or similar platform will be utilized for sensor integration and software like Simulink will be used for foot and sensor control. The role will involve collaboration with Adrian Ghansah, who is focused on the development of 3D humanoid robots. This project's completion will not depend on others, but the overall integration and validation of the robot will rely on progress from two students overseeing structural analysis and manufacturability.

Work Plan

Task	Start Date	End Date
Sensor Exploration	Week 1	Week 2
Mechanical Design	Week 3	Week 4
Sensor Integration	Week 5	Week 7
Performance Validation	Week 8	Week 9
Evaluation and Adjustments	Week 10	Week 10
Final Technical Paper & Presentation	To be determined	Week 10

References

[1] X. Guo *et al.*, “Soft Foot Sensor Design and Terrain Classification for Dynamic Legged Locomotion,” *IEEE International Conference on Soft Robotics (RoboSoft)*, pp. 550–557, May 2020, doi: https://doi.org/10.1109/robosoft48309.2020.9115990.

[2] T. Tyler, V. Malhotra, A. Montague, Z. Zhao, F. L. Hammond, 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.

[3] 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.

[4] 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.

Discussions with AMBER Lab PhD students Adrian Ghansah and Sergio Esteban emphasized that every biomechanical example of locomotion relies on foot sensing for stability and adaptability, but current systems operate with limited sensing capabilities. Their insights on ongoing efforts, including the development of a new bipedal robot with a dedicated toe mechanism, informed the direction of this project.