INTEGRATING FUNCTIONAL ELECTRICAL STIMULATION CONTROL AND IMU-BASED LIMB ANGLE ESTIMATION FOR DROP FOOT CORRECTION

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Motivation

Over 800,000 strokes are reported annually and a common side effect of stroke is drop foot, which causes a foot to drag or slap on the floor during walking (swing phase). The condition is due to the inability to control ankle muscles that produce dorsiflexion. It affects a patient's ability to balance and walk at a steady pace. The loss of control also increases the risk of fall from tripping [1].

Objectives

- Develop a wearable foot drop correction system
- Use inertial measurement units (IMUs) attached to the thigh, shank, and foot for predicting limb angles
- Apply Functional Electrical Stimulation (FES) using a commercial stimulator
- Obtain comprehensive information on limb postures

System Overview

The proposed solution takes care of the actuator and state estimation stages of a typical closed loop controller.

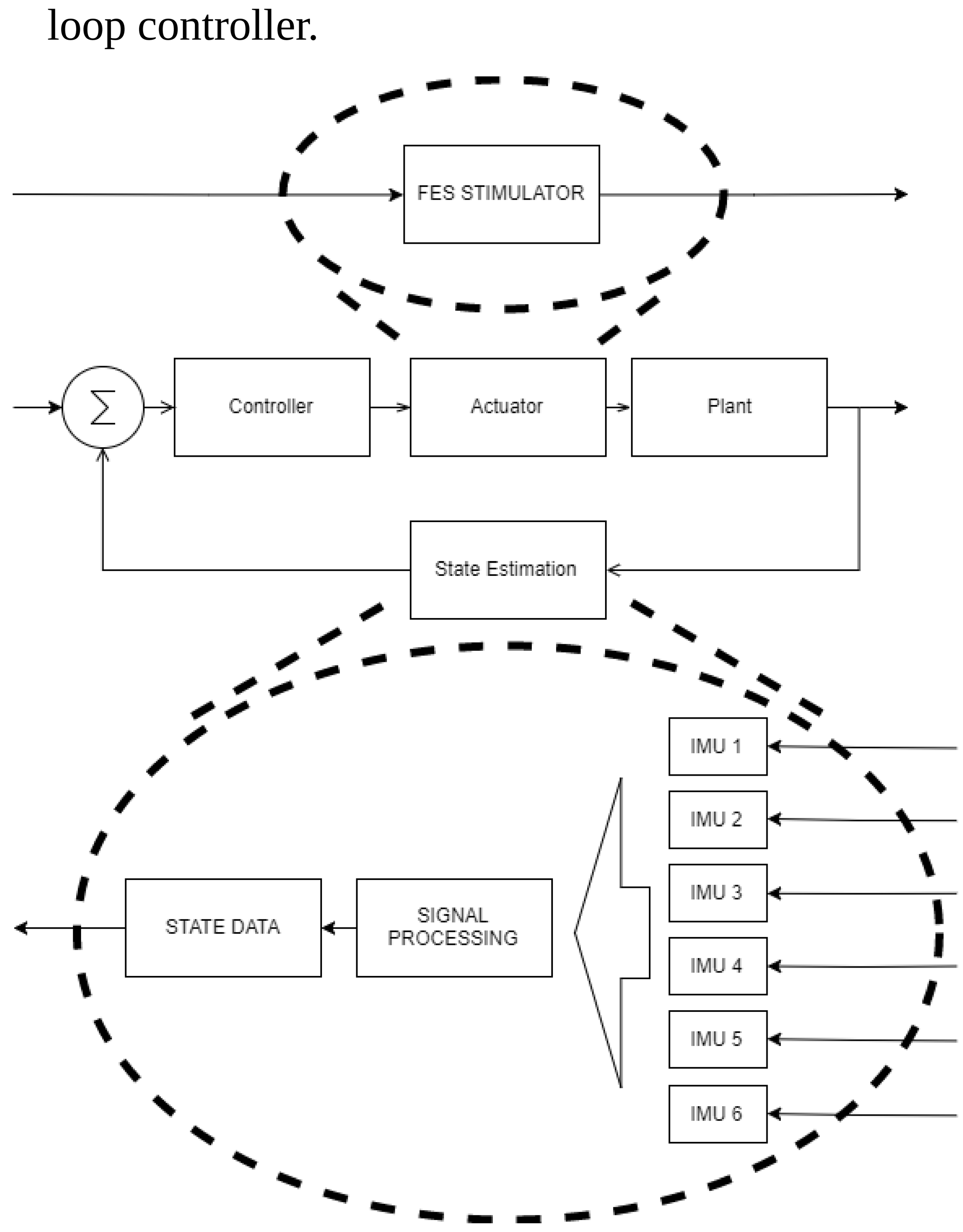

FIGURE 1: Stages of a typical closed loop controller that the system handles.

System Components

The major components in the system are:

- Raspberry Pi to run the control software
- Teensy 3.2 to handle IMU communication
- Cat5 cabling system for SPI signaling
- Invensense MPU9250 9-axis IMUs on a Sparkfun breakout board
- Rehastim V1 for 8 channels of FES stimulation
- Wireless network for communicating data to visualization software
- Attachment system

IMU Mux Design

A custom PCB was designed to fit on top of a Raspberry Pi that includes a Teensy 3.2 and indicator LED's. A 3D printed case was used to enclose all the components. A 2 Cell, 1 Ah, LiPo battery was used to power the Raspberry Pi and IMU Mux.

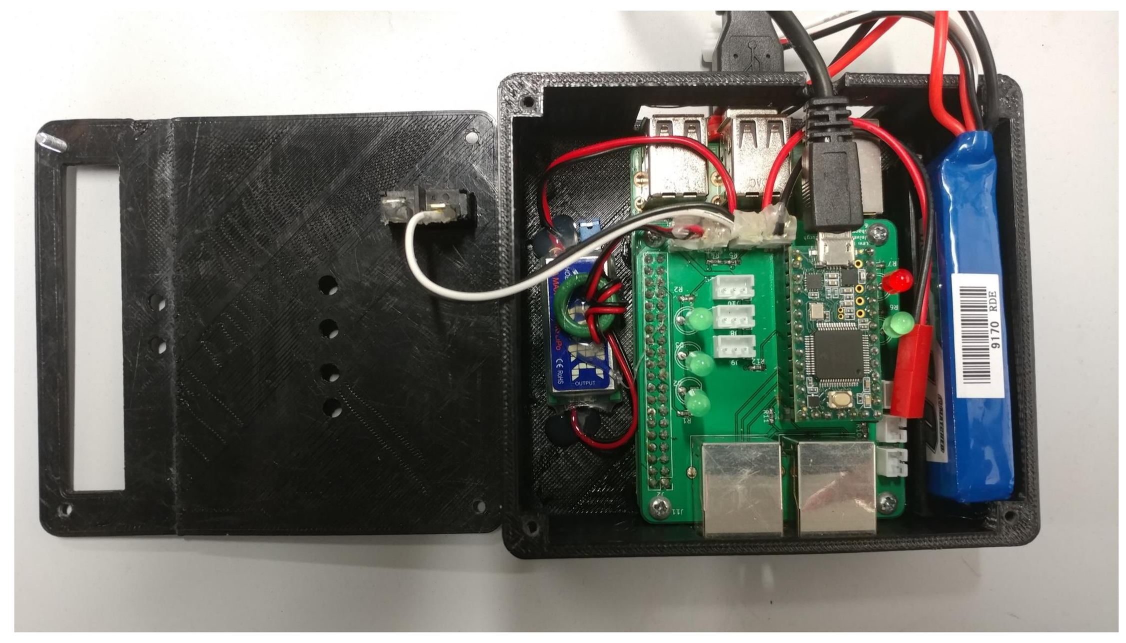

FIGURE 2: Raspberry Pi and IMU Mux inside the 3D Printed enclosure.

IMU Module Design

A custom PCB was designed to house the IMU and the selector switch. Cat5 cabling was used to make strands of IMUs up to 3 units long.

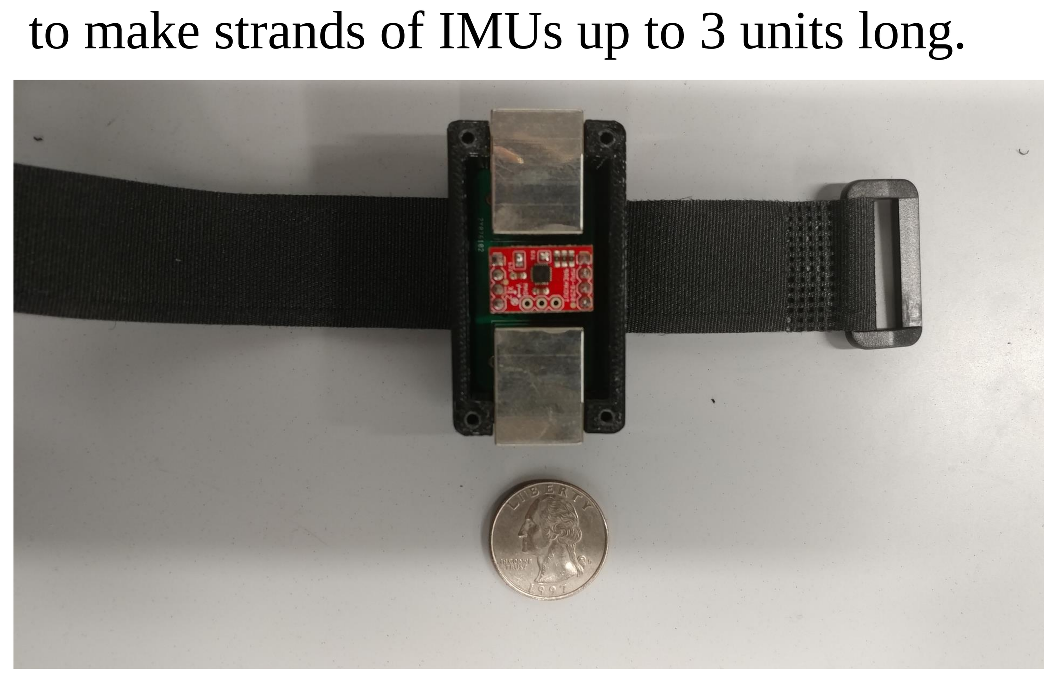

FIGURE 3: IMU Module in 3D printed enclosure with a Velcro strap.

Experimentation

The FES system was attached to an oscilloscope and python test scripts were used to command FES output.

The IMU Mux and Rehastim V1 were attached to the subject using a toolbelt. The IMU Modules were attached using the provided Velcro strap.

The IMU data was streamed from the IMU Mux to the Pi and then to a powerful ground station via WiFi. Six axis fusion was performed using a Python implementation of the Madgwick sensor fusion algorithm [2].

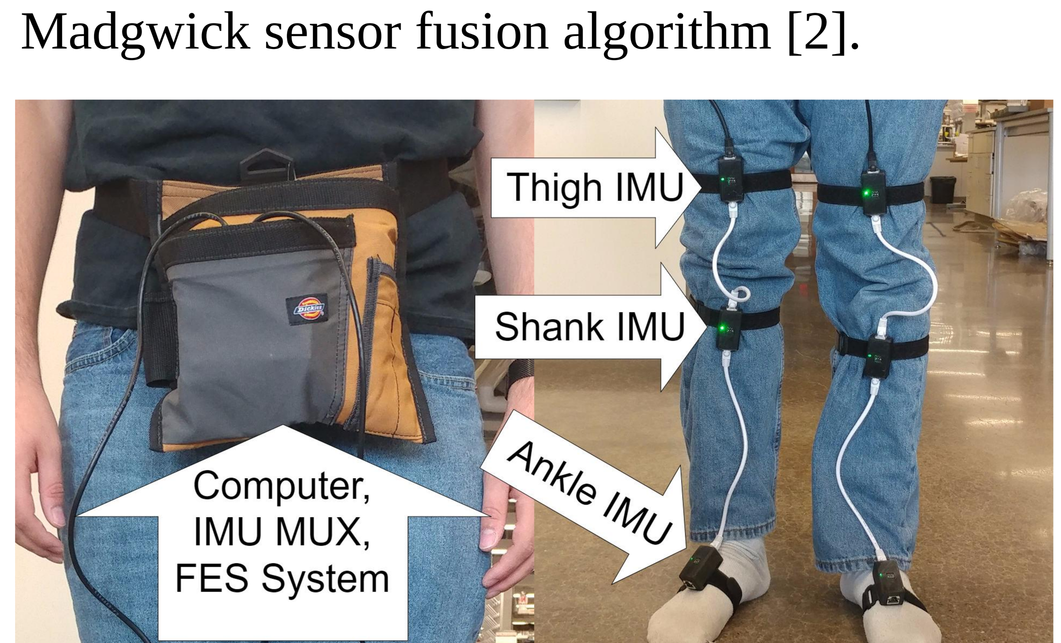

FIGURE 4: Control computer, IMU Mux, FES unit, and IMUs attached to a subject.

Results

The oscilloscope revealed that overshoot, reflection, and crosstalk on the SPI lines were within acceptable levels.

Oscilloscope measurements also revealed that the Raspberry Pi was able to command FES stimulation.

The limb angles accuracy was verified using a skeletal model on the host computer while a subject walked around wearing the system. It was found that gimbal lock caused slight discontinuities at certain angles.

The limb angles were also recorded and plotted over time. This revealed that the angle estimations were mostly continuous and repeatable.

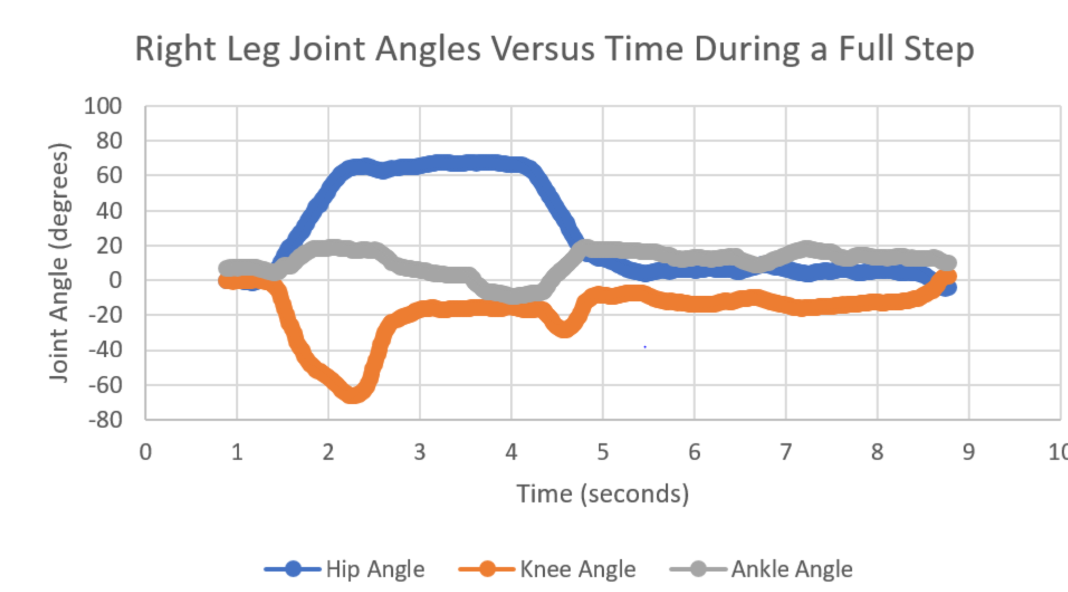

FIGURE 5: Angle estimations for one leg.

Discussion and Conclusions

- IMUs can produce data required for accurate limb angle estimation
- The multi-channel stimulator could be mounted to a human subject while remaining reasonably comfortable
- Further work needs to be done to improve the efficiency of the algorithms so they can be run in real time on the Raspberry Pi
- Ergonomics of IMU Modules need to be improved to limit slippage and improve comfort
- While the ability to apply FES was demonstrated, an algorithm that commands the stimulator based on joint angles needs to be developed
- The IMU angles need to be further benchmarked against an Optitrack system or similar to ensure accuracy
- A limb angle estimation system that takes the physical structure of human limbs into account would improve angle estimation

References

1. O'Dell et al. *Phys Med Rehabil Clin N Am* **6**(7), 587-601, 2015.
2. Madgwick. *Report x-io and University of Bristol*, **25**, 2010.

Acknowledgements

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