Gait Monitoring with Wireless Sensors

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I. Motivation

Gait patterns, the measurable characteristics of an individual's walking movement, can provide insight into a variety of components of an individual's health status. Certain gait pathologies may be associated with specific medical conditions. Sudden changes in the way an individual walks can be indicative of the occurrence of an undetected but deleterious medical event, i.e. undetected stroke. A shift in gait pattern over time may come about as the result of muscular or neural decline that could increase the probability of a dangerous event, such as a fall, in the future. However, diagnosing conditions or predicting an increased fall risk from gait patterns requires the attention of a trained medical professional, which limits the settings in which gait analysis can be used.

Real-time fall risk detection coupled with off-line visualization of a patient's gait could expand the usefulness of gait analysis from a professional's office to an individual's day-to-day environment and beyond. Detection and visualization of gait patterns can be made a reality because different components of a gait pattern can be extracted from linear and angular acceleration data measured at specific points along a patient's legs. A system of wireless motes instrumented with Inertial Measurement Units (IMUs) could readily capture the relevant data and relay them to a backend server for processing in real time. Wireless sensor networks are particularly promising for accomplishing gait detection because the small nodes and lack of constraining wires minimizes the impact on the patient and allows for an honest gait assessment without the residual impact of cumbersome measurement devices.

II. Related Work

This project is based on research in gait assessment and measurement device calibration. The following work has shaped several of our project decisions.

Gait Assessment:

Gait analysis using wearable sensors is a well-studied approach to characterizing gait patters [1]. The goal of the gait analysis approaches is to analyze the various phases of the human gait to identify abnormalities. A normal walking gait is comprised of eight stages as shown in Figure 1.

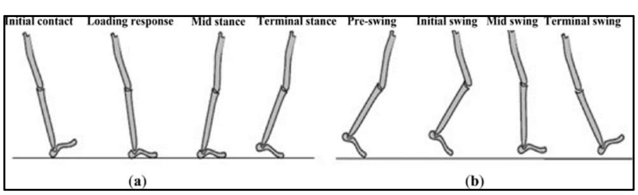

Figure 1- Phases of the stance (a) and swing (b) periods

Since the first study using wearable sensors in 1973, researchers have captured the data from these phases using a variety of transducers. Recently, multiple studies have used IMUs attached to a subject's thigh, calf, and foot to study gait kinematics. Gait kinematics investigates the movement of segments of the lower limbs while walking or running[2]. This is distinct from gait kinetics which analyzes the forces exerted on different joints while walking. The difficulty with kinetic analysis is the hardware required to capture accurate measurements. Previous studies have relied on specialized, instrumented footwear that measures the forces acting on a patient's foot. Gait kinematics, on the other hand, has moved towards less intrusive measurement techniques. For instance, [3] used small wireless sensor nodes to report information about the gait characteristics of test subjects.

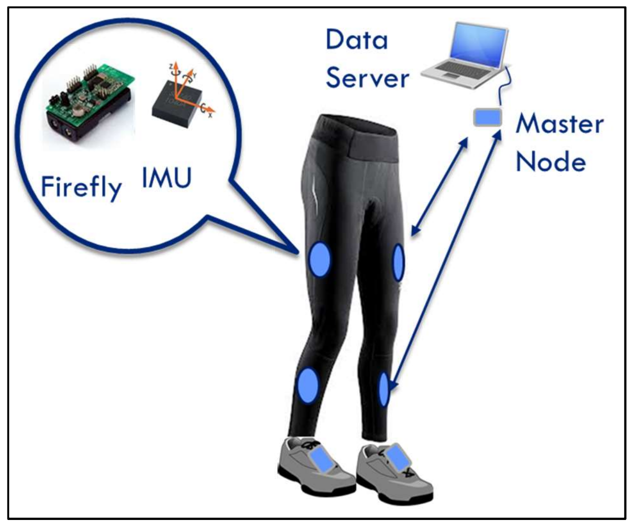

Figure 2- Overview of system design

III. Methodology

Our approach to gait monitoring is inspired by work in [4] and [3]. The system will rely on six IMU sensors and will require careful calibration and time synchronization to provide accurate results.

System Overview

Figure 2 shows the high-level system design of our project. It includes six Firefly nodes [5] each with an IMU sensor attached. At least the four IMUs attached to a subject's thighs and calves will be the SparkFun 9DoF Razor IMU because of the plethora of software available for calibrating and visualizing the data it produced [6]. The two IMUs attached to the feet will be either SparkFun Razors or Yost Labs 3-Space Embedded Sensors [7]. The 3-Space sensors will provide more accurate data than the Sparkfun models, which is important because measurements at the foot provide key insight into a subject's balance. However, learning to work with two IMUs and intelligently merging the data they provide is a significant challenge. Therefore we will begin development using the Sparkfun IMUs and integrate the 3-Space Sensors if we find accurate gait measuring to be infeasible without them.

The IMU data will be passed to the Firefly over I2C and the slave nodes will transmit their data via the nanork PCF TDMA [8] protocols to the data server. The TDMA MAC layer will minimize packet conflicts in the system and provide an inherent, high degree of time synchronization- two key requirements for our system. The data server will rely on ROS, the open source Robot Operating System platform, to provide libraries that will simplify the process of analyzing IMU data and producing intuitive user interfaces to the gait data. The master node will be responsible for relaying all data acquired from the slave nodes to the data server accompanied by time stamps of when the packets were sent and when they were received.

Calibration Plan

To accurately track a subject's movement, the position of the IMUs must be known at the start of the data collection. We will use two cameras to calibrate the locations of all IMUs mounted on a subject's legs. The calibration result contains the offset including translation and orientation of each IMU in the associated cameras' coordinate system. At a high level, our calibration method will require a subject to move through a series of positions, and the cameras will track the movement of the IMUs and calibrate the IMU output based on absolute measurements made by the cameras. In detail, the calibration will proceed as follows.

For each IMU, we define several variables to describe its calibration and motion:

- $\mathrm{M_i}$: The ith IMU's initial offset (when powered up) relative to the camera's coordinate (unknown)
- $\mathrm{P_i^t}$: The ith IMU's motion including translation and orientation in its local coordinate (origin defined when the IMU powered up) at time t

For the camera system, we define the projection matrices for each camera and the extrinsic parameters of the second camera relative to the first camera:

- C_1, C_2: The projection matrix of camera 1 and 2 (requires calibration)
- T_{12} : The transformation from camera 1's coordinate to camera 2's coordination (requires calibration)

The calibration method requires good time synchronization among cameras and IMUs. At time t, we use two cameras to capture the visible IMUs mounted on human's legs. Then we can manually extract each visible IMU's 2D position on the images of two cameras:

- $\mathrm{I_{1i}^t}$: The 2D position of visible IMU's 2D position on the first camera's image
- $\mathrm{I_{2i}^t}$: The 2D position of visible IMU's 2D position on the second camera's image

For each IMU, we get a series of IMU measurements and camera measurements:

- $\{\mathrm{P_i^t}\}_{t\in\{1,2,\ldots,n\}}$: IMU measurements
- $\{\mathrm{I_{1i}^t}\}_{t\in Vis1}$: 1st camera measurements
- $\{\mathrm{I_{2i}^t}\}_{t\in Vis2}$: 2nd camera measurements

Then we can build a linear system to solve the unknown M_i of ith IMU:

$$\begin{cases} C_1 M_i P_i^{t\in Vis1} = I_{1i}^{t\in Vis} \\ C_2 T_{12}^{-1} M_i P_i^{t\in Vis2} = I_{2i}^{t\in Vis2} \end{cases}$$

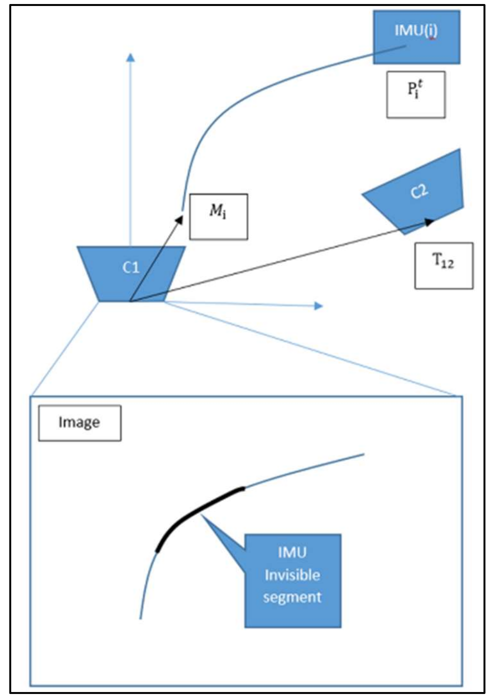

Figure 3- IMU Calibration

Once all IMUs' offsets $\{\mathrm{M_i}\}$ are calculated, we can visualize them in a coordinate at time t:

$$\mathrm{Q_i^t} = M_i P_i^t$$

Figure 3 demonstrates the calibration of an $\mathrm{IMU_i}$ with initial position $\mathrm{M_i}$ and instantaneous motion $\mathrm{P_i^t}$ in the projection matrices of the cameras, C_1 and C_2.

IV. Goals

Our goals for the project can be divided into several categories based on the different challenges associated with transporting raw data collected wirelessly into an informative user interface.

Data Communication

- Accurately detect packet loss
- Achieve time synchronization within tens of milliseconds between the nodes and the master
- Efficiently query the slave nodes to simplify data logging and minimize packet loss

IMU Management

- Calibrate the IMUs to enable leg movement tracking
- Implement noise filters to improve data quality
- Build a sensor enclosure and develop repeatable method for securing IMU to subject

Gait Analysis

- Measure gait speed, stride length and leg swing time
- Create data visualizations of the gait measurements listed above
- Trigger real-time warning of significant changes in gait pattern
- Meet our extra credit goals of:
    - Measuring knee extension
    - Visualizing subject motion

VI. Milestones and Task Division

The table below describes the deliverables our team will need to produce to accomplish the goals listed above.

Date	Deliverables
March 21st	1. Attach IMU to Firefly and prototype enclosure 2. Transfer IMU data from slave to master to PC 3. Calibrate one IMU for orientation capture
April 4th	1. Visualize data from single sensor on PC 2. Synchronize master and slave clocks 3. Intermediate demo (described below)
April 18th	1. Gather data from all slave nodes 2. Measure packet loss 3. Complete multiple IMU calibration
May 4th	1. Extract gait measurements from sensor data 2. Finalize visualization of all gait data 3. Final demo (described below)

Intermediate Demo

We will demonstrate data transfer from generation to analysis for a single sensor node. The first step of the demo will demonstrate single node IMU calibration with the Sparkfun Razor and single node time synchronization. The second step is IMU data transfer from the sender to the master. The transfer, calibration and synchronization will be demonstrated by printing the messages sent and received by the master which will include the results of these three phases. Finally, the data collected by the master will be graphed to demonstrate our user interface and basic data processing capabilities.

Final Demo

The final demo will show all six slave nodes returning data to the master and the processing of all the data. Specifically, we will demonstrate our method for multiple IMU calibration and system wide time synchronization. The emphasis of this demo will be the gait measurement analysis using data from all size sensor nodes. A willing subject will be equipped with fireflies and IMUs, and his/her movements while walking will be tracked. We will show visualizations of gait speed, stride length and swing time measurements captured during the demonstration. The real-time gait warning will also be demonstrated by asking the subject to drastically change his/her gait pattern. Finally, we will hopefully demonstrate our extra-credit goals by also showing subject motion in three dimensions on the user interface and measuring knee extension.

Task Division

The following table illustrates the segments of the project each member is responsible for completing.

Emily: • Communication between nodes • IMU to Firefly communication • Gait pattern analysis
Alex: • Multiple IMU calibration • IMU data processing • Data visualization in ROS
Iljoo: • Communication between master node and PC • Gait pattern analysis • Data visualization & logging

References

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