Designing a Miniature Gait Lab

Introduction

Problem

Human gait measurement systems are useful tools that measure gait to supplement a professional's observations. Human gait measurement facilities for research, diagnosis, and rehabilitation are inadequate in isolated regions of the world because existing measurement systems are either expensive, immobile, or ineffective.

Some devices exist that attempt to solve this problem, but they are restricted by high cost and limited success. Others are integrated into high-end prosthetic devices, and therefore cannot assist disadvantaged peoples. There is a lack of portable gait measurement devices, therefore people in need do not receive treatment. An unfortunate coincidence is that the people who need this the most are also the people who have the least access to treatment.

Background

Gait measurement is typically accomplished with infrared camera-based systems tracking markers which are placed on a subject. These systems can cost hundreds of thousands of dollars and are not easily moved from where they are set up. Some of the information they provide is the position and orientation of the subject's complete skeletal system, which can be used for further analysis.

Inertial-Magnetic Units (IMUs) can collect accelerometer, gyroscope, and magnetometer data. Filtering these data through the Madgwick filter provides orientation data. Using orientation data, acceleration due to gravity can be removed from accelerometer data. This accelerometer data can then be used to calculate position information of a given sensor, yielding two of the basic parameters needed for further gait analysis.

Solution

The solution being proposed by this project is a compact, portable, and inexpensive system that can measure lower limb segment position and orientation. With a mobile system, better treatments and outcomes become available to people who need them. The low cost of the system allows broader application and deeper understanding of human motion compared to existing methods, studies, and databases.

For an individual, the device can provide feedback and identify problems to quickly diagnose and treat any conditions that may be present. For groups that share a rare condition, the device can generate knowledge of their relatively obscure condition. Small enough to be mailed, the device can reach people and places previously inaccessible to the medical community.

Design Process

V.0

Specifications
Size: 40 mm x 45 mm | 1800 mm²
Mass: 9 grams + 16 gram battery
Max Sensors: 1 x IMUs
Sampling rate: 160 Hz
Data Storage: Bluetooth to PC

Cost/board: ~$75
Power: 3.6V|Li-Ion Battery
Microcontroller: 16-bit
Instructions: 16 MIPS

Figure 1. The V.0 Circuit

Problems
- Insufficient sampling rate
- Unreliable connection
- Costly Bluetooth radio
- Requires receiving computer
- Only one motion sensor

Solutions
Switch to microSD storage:
- Running on SPI, an SD card provides speed without connection problems.

Support additional sensors:
- Include connectors for additional IMUs
- More than 2 IMUs on a bus requires a switch to SPI

Remote IMU Dongle
- Size: 14.5 mm x 11.5 mm
- Mass: <1 g
- Function: Provide IMU connection
- Cost: ~$15
- Forward compatible

Figure 2. The IMU Dongle

Status
- Methods to attach to a person are still unexplored
- Small size is excellent for secure mounting
- Long cables cause noise, causing erroneous magnetometer resets

V.1

Specifications
Size: 40 mm x 60 mm | 2400 mm²
Mass: 11 grams + 16 gram battery
Max Sensors: 7 x IMU + 12 Analog to Digital Converters
Sampling rate: >300 Hz

Data Storage: microSD Card
Cost/board: ~$60
Power: 3.6V|Li-Ion Battery
Microcontroller: 16-bit
Instructions: 16 MIPS

Figure 3. The V.1 Circuit

Problems
- Magnetometer communicates, but experiences erroneous resets
- Voltage supply can damage components
- Sampling rate is still too slow
- Large, rectangular board
- Uncentered IMU

Solutions
- Identify cause of magnetometer resets
- Add a voltage regulator
- Separate IMU & microSD SPI buses
- Upgrade to 32-bit microcontroller
- Design smaller & square-shaped

V.2

Specifications
Size: 36 mm x 36 mm | 1296 mm²
Mass: 7 grams + 16 gram battery
Max Sensors: 7 x IMU
Sampling rate: ~300 Hz
Data Storage: microSD Card

Cost/board: ~$60
Power: 3.0V|Li-Ion Battery w/ Low-Noise Regulator
Microcontroller: 32-bit
Instructions: Up to 150 DMIPS

Figure 4. The V.2 Circuit

Current Status
- Firmware in-progress but functional
- Works with same dongle and connector as V.2
- Magnetometer issue solved by using coaxial cable
- Not running at full speed

Review of Problems

Power supply and physical package problems have been solved. However, the magnetometer signal line noise requires bulky, shielded cables. Compared to V.0 and V.1, the V.2 system works better and can collect data from 3 dongles, allowing knee and hip joint angle calculation.

Results

Pendulum Tests

Materials

A simple pendulum with a potentiometer measures the pendulum angle while the V.0 Circuit (Figure 1) measures 9-axis IMU data from the end of the pendulum arm as shown below in Figure 5.

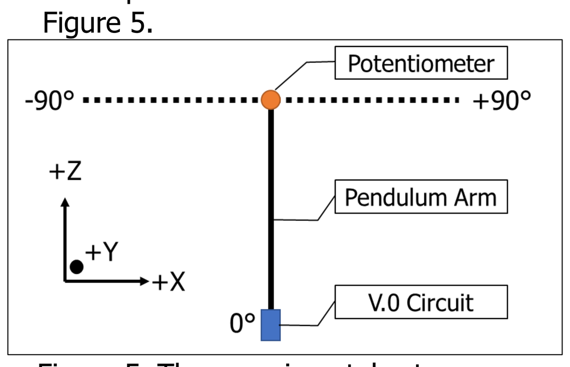

Figure 5. The experimental setup, showing the pendulum, potentiometer, and V.0 Circuit.

Method

1. Measure the pendulum angle and potentiometer voltage output at several angles.
2. Using measurements from step 1, create a linear model of Pendulum Angle vs. Voltage.
3. Attach, power on, and connect to V.0 Circuit.
4. Begin data logging of both the potentiometer and V.0 Circuit.
5. Lift pendulum arm to -35° and release.
6. Allow pendulum to swing freely until its motion stops.
7. Stop and save data logs.
8. Convert potentiometer voltage into pendulum angle offset so the resting position is 0°.
9. Apply the orientation filter to V.0 Circuit data to yield the orientation quaternion
10. Convert quaternion into Euler angles.
11. Offset Estimated Yaw so resting position is 0°.
12. Align Potentiometer and V.0 Circuit data using starting angle time, then decimate data to a uniform length.
13. Subtract V.0 Circuit data from Potentiometer data to give the error over the duration of the trial.
14. Calculate the RMS of the error during the pictured pendulum's motion to give the total RMS error value.

Result

The orientation accuracy of V.0 was tested by measuring the angle of a pendulum with a potentiometer and comparing that to the V.0 Circuit's estimation of orientation. The 9-axes of data collected are shown in the left side of Figure 6. The resulting orientation estimation and measured pendulum angle are shown together in the top right chart; the error is calculated below as the difference between the "Measured Angle" and the "Estimated Yaw" values. The total root-mean-square error over the time period was calculated as 0.94°, a resounding success for the V.0 design and the orientation estimation procedure.

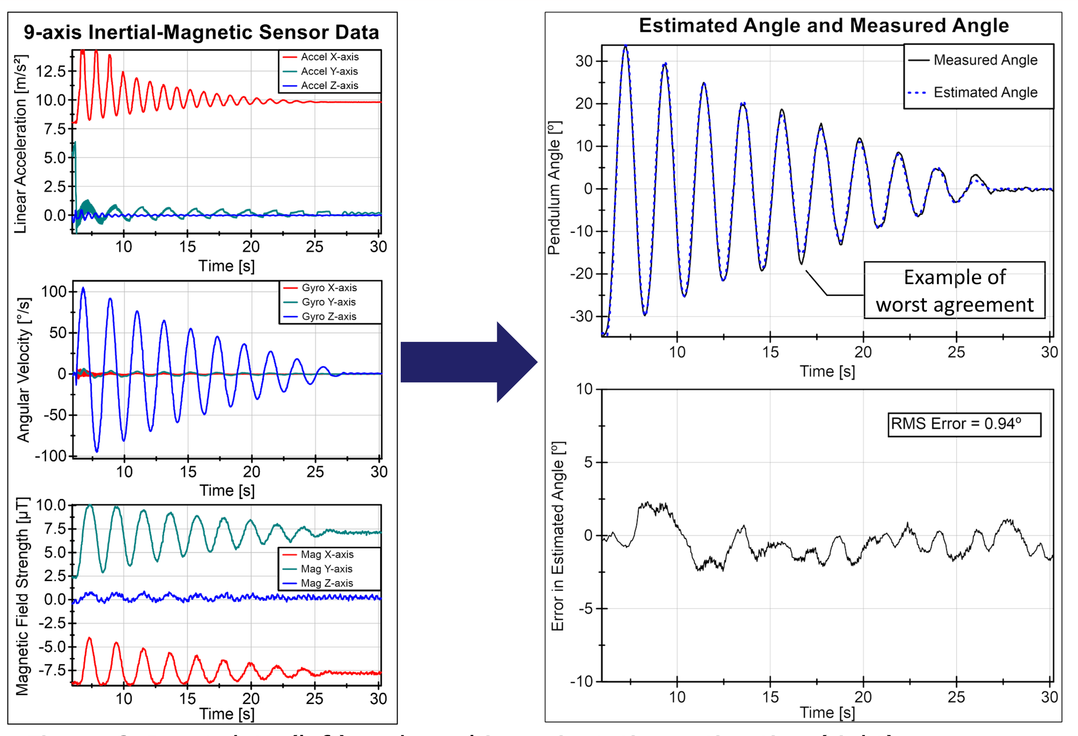

Figure 6. Input data (left) and resulting orientation estimation (right)

Walking Tests

Figure 7. Comparison of the miniature gait lab's predicted angle (red) to the actual angle as shown by a 2D image.

Static Test

A static test of the V.2 circuit was used to demonstrate the ability to measure joint angle. In this test, the V.2 circuit was attached to the thigh and shin using athletic tape as shown in Figure 7. The orientation of the thigh and shin was calculated, then the total angular difference of the knee was calculated for a single moment in time. The result is shown in Figure 7, where the system measured an angular difference of 154° that closely matches the actual angle shown in the image. This static test shows that the angular difference calculation works as long as the limb segment orientation values are precise.

Dynamic Test

A dynamic (walking) test of the V.2 circuit was used to demonstrate the ability to measure human motion. In this test, the V.2 circuit was attached to the hip, thigh, and shin using athletic tape as in Figure 7. The orientation of the limb segments was calculated, then the total angular difference from the hip to the thigh and from the thigh to the shin was calculated. The resulting data for one gait cycle, starting at heel strike, are shown in Figure 8.

In these results, the shape of the curves over one gait cycle is correct, but the range of values is far lower than expected for knee and hip joint angles. This likely a result of the measured acceleration including both gravity and the motion of gait, so further work is needed to eliminate the consequential error.

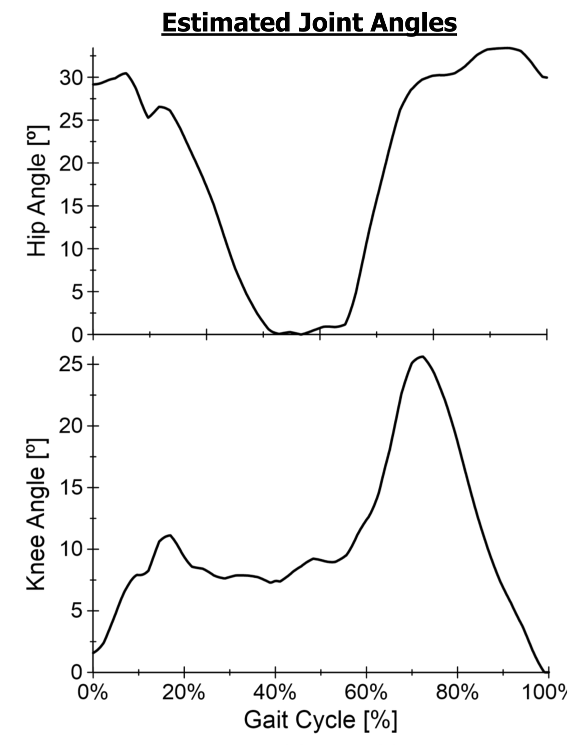

Figure 8. Estimated hip and knee joint angles over an arbitrary gait cycle.

What's Next?

Circuit Improvements
- The orientation filter and other data processing tasks will be adapted to run entirely on the system rather than on a computer after data collection.
- The firmware components controlling data capture and storage will be optimized to maximize data sampling rates and maintain constant rates.
- A compact cable and connector system will be needed to reduce signal noise in order to consistently acquire magnetometer data. Figure 9 shows current progress on this issue.

Figure 9. The different cable assemblies used for the remote dongle. Cable A fails at lengths greater than 20 cm; Cable B consists of twisted pairs but also fails at longer lengths. Cable C, which carries high-frequency signals through coaxial cable, functions at longer lengths. Like Cable C, HDMI cable could offer the same shielding in a smaller package and at a lower cost.

Measurements
- Testing the system by measuring gait and comparing results to a fully-featured motion capture system will prove its potential and provide a robust accuracy comparison.
- A larger dataset will be needed in the future to fully understand the nature of IMU-based motion capture. A study applying the system to a group of human subjects will create this dataset.

Optimizing Data Handling
- The orientation filter utilizes an adjustable parameter, β, which can be dynamically adjusted to maximize accuracy depending on the nature of the system's motion. Future work will focus on developing a novel algorithm to adjust this parameter to optimize it for human motion. This is a potential solution to the issues encountered during the dynamic test.
- Digital filters applied to the raw data can be applied to help correct sensor noise and drift before it is run through orientation and position estimation filters. Some filters are integrated into the sensors, but other filtering must be done on the motherboard processor.

Conclusion

During pendulum tests, the V.0 circuit has high performance with an orientation error of <1° when compared to the control; position estimation for these trials is showing promise. Firmware for the newly constructed V.2 circuit is in progress, so it will change to solve current problems. Additional data that captures high-speed motion are needed to further understand the nature of IMU-based motion capture. Walking tests show that the system is capable of measuring limb segment orientation, however, comparison to a motion capture system is needed to optimize the system for high-speed motion to eliminate the large errors in the dynamic test.

All photos/images/graphs/charts are by and/or depict the Finalist.

Bibliography

Madgwick, S. O. H., Harrison, A. J. L. & Vaidyanathan, R. "Estimation of IMU and MARG orientation using a gradient descent algorithm." Zurich, s.n. 2012.

A complete bibliography is in the Finalist's binder.