WIRELESS INERTIAL MEASUREMENT SYSTEM PROVIDES ACCURATE DYNAMIC ANGLE CHANGE AND ANGULAR RATE DATA FOR BODY MOUNT APPLICATIONS

Christopher Harris, Sunny Mahajan, Paul Leslie, Carl Spani, Leo Spalteholz, William Hook, and Nigel Livingston

CanAssist, University of Victoria

INTRODUCTION

In furthering our mission of developing technologies to improve the quality of life for individuals with special needs, CanAssist has developed a wireless inertial measurement unit (IMU) system capable of human body motion capture and analysis. With this development, significant advances have been made in IMU calibration procedures. These unique calibration techniques involve using a pendulum to model the physics of a swinging human leg. Using this test hardware with curve fitting and optimization techniques, high precision gyroscope and accelerometer calibrations were found. A simple and effective run-time calibration of the magnetometers was also developed. The resulting data was suitable for gait and range-of-motion (ROM) analysis, as well as for non-walking gesture recognition applications.

IMU based systems offer many advantages over alternative technologies such as camera systems and pressure mats. Our IMU based system is portable, quick to set up and relatively easy to use. The 33m radius indoor wireless range means that it is possible to record data for as many as 50 strides of continuous walking in a straight line. With hardware features such as long battery life, and small light-weight sensors this system is a viable alternative to traditional monitoring and analysis methods for many applications, such as clinical gait analysis and in-home monitoring.

SYSTEM OVERVIEW

Our IMU system has 3 types of hardware components. The first is a sensor unit, the Wireless Inertial Sensor Package (WISP). The second and third components are a radio frequency base station, and personal computer. The system supports up to 15 WISP sensors that gather synchronous data and report these data back to a base station in real time. The base station links to the computer through a USB connection, allowing the processing software running on the computer to retrieve the sensor data.

The wireless link between the WISPs and the base station uses channels from the 915 MHz Industrial, Service, and Medical (ISM) radio band.

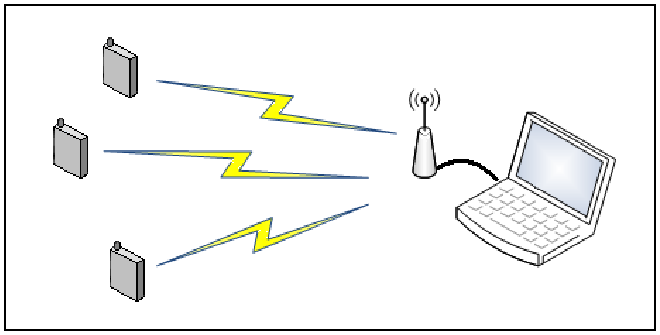

Figure 1: CanAssist IMU System Diagram

Our current system is capable of using as many as three of the 128 available channels in that band and up to 5 WISPs can time-share a single frequency channel. To support fully body motion capture, data from up to 15 WISPs (3 channels, 5 WISPs per channel) can be collected with a single system. Data are sampled 40 times for second and transmitted using Manchester encoding at 100kbps. Two samples are sent in each packet.

Data is received from the base station by connecting to a COM port. A software program, WispHost was created to connect to this COM port and process the incoming stream of data. Calibration parameters, fusion algorithms and co-ordinate transformations are applied to the sensor data processed by WispHost in real time. Optionally, WispHost can log the resulting data to files for later analysis.

IMU SENSOR DESIGN

The WISP includes 3 axis accelerometers, magnetometers and gyroscopes integrated with a radio transmitter and stored in a small 4.6 x 4.2 x 1.5 cm casing. As shown in Figure 2, the antenna extends about 0.6 cm beyond the WISP casing. The total sensor weight is 43 grams, including a 700mAh (17 hour run time) lithium-ion rechargeable battery. The three sensors used in the design of the WISP are the Aichi AMI601 magnetometer, the Kionix KXP74 accelerometer and the Invensense IDG-300 gyroscope. Because the IDG-300 is only a double axis gyroscope, a second chip is included in the WISP,

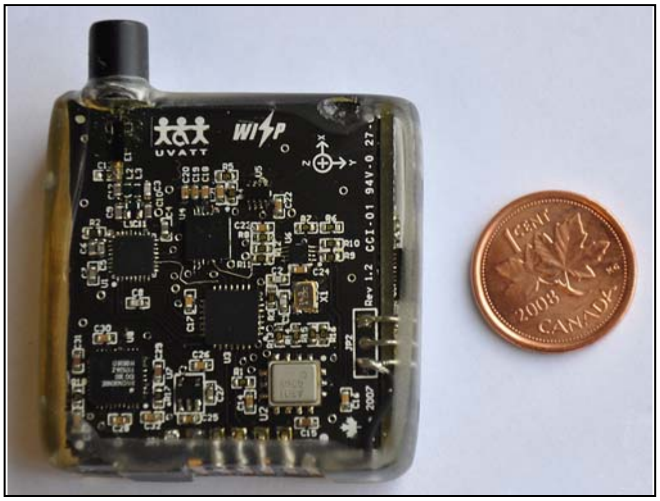

Figure 2: The WISP sensor (with a penny for scale)

mounted on a separate circuit board at a right angle to the primary board. All of these chips use Micro-Electro-Mechanical Systems (MEMS) technology.

As shown in Figure 3, the Microchip PIC18LF2523 microcontroller is used to assemble the sensor data into a unified packet, which can be transmitted by the Nordic Semiconductor nRF905 transceiver. The WISP microcontroller samples the X, Y and Z axes of each sensor at a 40Hz sample rate. Two consecutive sets of samples are placed in each packet. All sensor data are transmitted as a 12 bit value, 0-4096, where the sensor zero output (bias) value is set in the vicinity of the midpoint. No calibration is applied to the data before transmission.

CALIBRATION THEORY

To calibrate the accelerometer and gyroscope in the WISP, a direct calibration procedure was developed. This was accomplished by creating a transformation matrix equation that produces accurate physical quantities in units of metres/second^2 and degrees/second respectively for each axis from the sensor readings, where all data use a common coordinate system. The magnetometer readings from the WISP were found to vary wildly from room to room (because of the effects of ferric materials[1]) so a one-time precision calibration was deemed not to be reliable. A simpler run-time calibration procedure was designed for the WISP magnetometer.

The WISP calibration system developed for the accelerometer and gyroscope both use the same fundamental approach. To transform data from raw sensor output into accurate physical quantities, two parameters must be found. The first is the bias or zero reading of each sensor. The second is the scaling factor of each axis as it relates to the output of each axis. This quantity can be represented as 3x3 matrix, and accounts for misalignment of the sensor axes with the reference axes, non-orthogonality of the sensor axes, and conversion of sensor data to physical units.

Accelerometer Calibration

The internal accelerometer X-Y-Z coordinate system was chosen as the common coordinate system for both the accelerometer and the gyroscope. This means no misalignment correction is required for the accelerometer. Furthermore, the manufacture's specifications show no significant X-Y orthogonality error. With these assumptions the four of the nine parameters in the 3x3 scaling factor matrix can be set to zero. The remaining five scaling factor variables and 3 bias variables produce a set of 8 calibration parameters for the 3 axes of the accelerometer.

The calibration parameters for the accelerometer were found by acquiring data from the accelerometer in 18 independent orientations. The data from these readings were processed using a Newton optimization algorithm[2] initialized with the factory specified bias and scale factors perfectly orthogonal axes.

Because the accelerometer is held static for data collection, the optimization algorithm 'expected' vector magnitude equals the theoretical vector magnitude of the acceleration of the earth's gravity, 9.81 m/s^2[3]. The optimization algorithm adjusts the 8 calibration parameters to minimize the error between the vector magnitude of the calculated physical data for all 18 orientations and the magnitude of the earth's gravitational acceleration.

Gyroscope Calibration

Calibration of the gyroscope offers several significant challenges not faced with the accelerometer. First, a misalignment correction must be found to account for possible variations in the directions of the accelerometer and gyroscope axes.

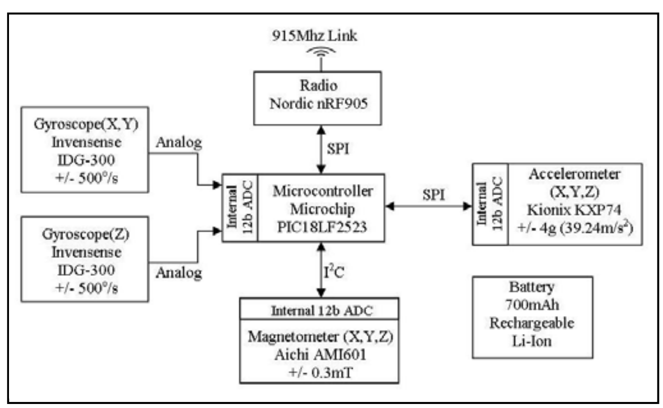

Figure 3: Block diagram of The WISP sensor

Secondly, there is no natural 'expected' constant to replace the earth's gravitation acceleration in the optimization objective function. Finally, the bias values of the gyroscope are known to fluctuate significantly.

To account for the bias fluctuation, the gyroscope bias calibration parameters were obtained at the beginning of each run by leaving the wisp at rest for a few seconds at the beginning of each test. This practice continues during field operation of the wisp.

The misalignment, orthogonality and unit conversions were all combined into a single 3x3 calibration matrix. Since the biases are derived from static data at the start of each run, they can be considered known, and the calibration equation reduces to a linear equation that can be solved by a least square fit method[4].

To generate a set of known precision 'expected' data with which to compare gyroscope data, a pendulum test set was used. A precision angular encoder was installed to detect the pendulum angle. Angle data collected from the encoder were differentiated to provide known angular velocities. Data from the encoder were synchronized with the WISP gyroscope data by aligning the peak values in the resulting outputs. During the calibration process, data were collected for 18 independent orientations to ensure accuracy on all axes.

Figure 4 shows the rotating axis WISP gyroscope readings for a sample pendulum run. Plotted alongside are the corresponding angular encoder values. Calibration parameters are generated by scaling the gyroscope curve to match the time derivative of the encoder data (this derivation resolves the phase shift between the two curves).

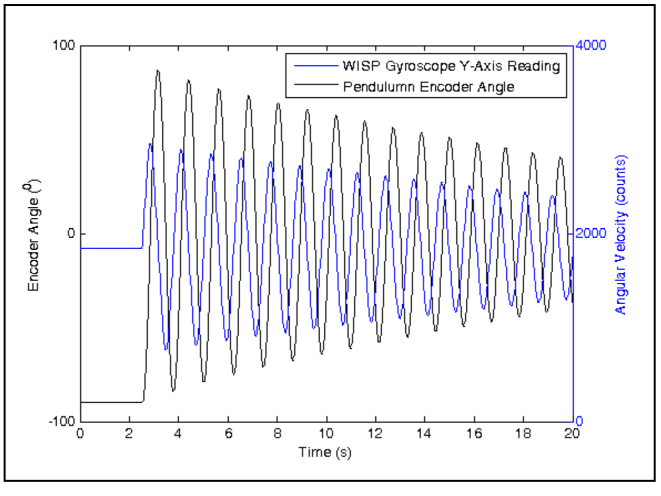

Figure 4: Sample Encoder and Wisp Gyroscope Pendulum Data

The pendulum test set offers several significant advantages in gyroscope calibration. Pendulum motion allows the gyroscope to pass through a wide range of peak angular velocities in a single experiment. Also pendulum motion replicates the type of motion produced by many limb motions. Finally, a pendulum system moves the wisp through a wide range of angular rates, making it a better choice than a conventional constant speed motor.

Magnetometer 'Run Time' Calibration

Magnetic interference is so prevalent in most buildings that a precise magnetometer calibration would not be valid even in an adjacent room without the use of artificial magnetic fields[5]. For this reason, a quick run time calibration of the magnetometer was chosen rather than a one-time precision calibration. As such the misalignment and orthogonality correction factors are not computed for the magnetometer. The run time calibration involves rotating the WISP so that each axis aligns with the local magnetic north and magnetic south to the best precision possible.

Software tracks the magnetometer reading during calibration and stores the maximum and minimum values attained on each axis. At the end of calibration a bias and scale factor value is computed from this data. Scale factors are normalized such that the vector magnitude of calibrated magnetometer data is 1.0 and positive values indicate magnetic north.

CALIBRATION HARDWARE

Pendulum Test System

The pendulum test system used to calibrate the WISP accelerometer and magnetometer is shown in Figure 5. The WISP is placed within a two axis gimbal which is rotated by the aluminum shaft. The gimbal can be adjusted and locked in each of the 18 independent orientations to support full 3 dimensional calibration. To ensure the only linear acceleration experienced by the WISP is that caused by gravity, the WISP is mounted in line with the rotating shaft of the pendulum.

The bob of the pendulum is a spherical weight affixed to the end of the rod that runs through the shaft. At the start of each test, the pendulum is allowed to rest in a vertical position, then raised to a horizontal position and held again at rest, and then dropped. The resulting motion is monitored by both the WISP and an angular encoder mounted to the shaft. This encoder measures the angle of bob with respect to the vertical at a frequency of 200 Hz. For verification tests, the WISP is mounted to the bob.

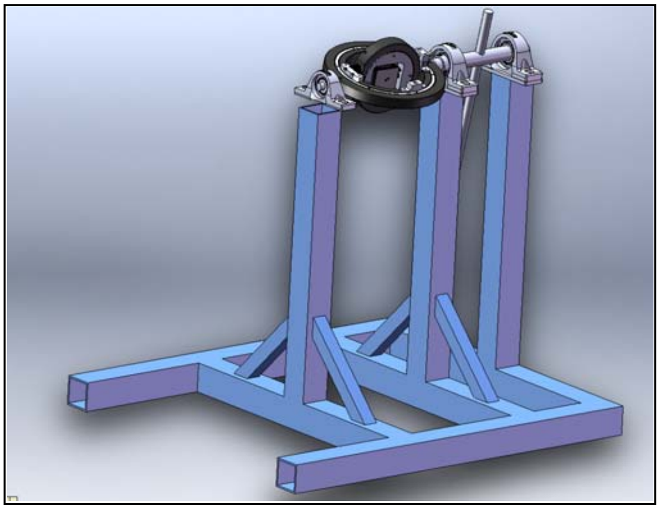

Figure 5: The WISP Calibration Pendulum

Motorized Gimbal System

A motorized gimbal system was used to establish a high precision set of magnetometer calibration data for comparison against values generated by the run time calibration. This system is comprised of a plastic three axis gimbal where one of the axes is controlled by a motor. An angular encoder is used to monitor the rotation of the motorized axis. This system was specifically designed for magnetometer calibration, so the motor and other metal components were placed as far as possible away from the WISP mounting. Accurate magnetometer calibration parameters were generated by curve fitting a biased sinusoid function to data points sampled from the entire rotation.

CALIBRATION RESULTS

The above calibration procedures were performed on 4 different WISPs. After the calibration parameters were applied, the average and standard deviations of the resulting errors between calibrated data and the expected data were gathered for each sensor. Those data are shown in the table below. The abbreviations acc, mag, and gyro are used for accelerometer, magnetometer and gyroscope, respectively.

The magnetometer error values in Table 1 were generated by comparing two sets of calibrated data generated from the same set of raw data. One set was generated using the calibration data from the precision motorized gimbal, and the other used run-time calibration data. The difference between each axis of the two corresponding points was used to create an error vector. The data shown in the table represents the mean and standard deviation of the magnitude of that error vector.

Table 1: WISP Calibration Results

	WISP 3	***WISP 4***	***WISP 5***	***WISP 6***
Acc. Mean error (m/s^2)	0.013	0.016	0.011	0.010
Acc. error std. dev. (m/s^2)	0.013	0.016	0.011	0.011
Gyro Mean error ($^0/s$)	1.97	2.82	1.92	1.43
Gyro error std. dev. ($^0/s$)	0.52	0.80	0.54	0.56
Mag. Mean error	0.0345	0.0218	0.0097	0.0165
Mag. error std. dev.	0.0070	0.0034	0.0028	0.0042

SUMMARY AND FUTURE STUDY

The IMU calibration techniques outlined in this paper have been shown to produce accurate results, usable in a wide variety of applications. We have successfully applied the resulting calibration data to perform gait and ROM analysis and real time motion capture. Research is continuing in several other applications such as fall prediction and gesture recognition.

The small size, long battery life and wireless design of the WISP sensor makes it an attractive tool for clinical testing, and research. These same features enable the device to be used as a human-machine interface that can be tailored to users with very limited mobility and/or strength.

ACKNOWLEDGEMENTS

The authors of this paper would like to thank: Mike Woods for the WISP photography and the entire CanAssist team for their help and support.

REFERENCES

[1] W. Dong, K. Y. Lim, Y. K. Goh, K. D. Nguyen, I. M. Chen, S. H. Yeo, B. L. Duh, "A Low-cost Motion Tracker and Its Error Analysis", IEEE International Conference on Robotics and Automation, Pasadena, CA, USA, May 19-23, 2008

[2] I. Skog, P. Händel, "Calibration of a MEMS inertial measurement unit", Proceedings of the XVII Imeko World Congress, Rio de Janeiro, Brazil, 2006.

[3] D. Jurman, M. Jankovec, R. Kamnik, M. Topi˘c, "Calibration and data fusion solution for the miniature attitude and heading reference system", Sensors and Actuators A, vol. 138, no. 2pp. 411-420, 2007.

[4] D. Campolo, M. Fabris, G. Cavallo, D. Accoto, F. Keller, E. Guglielmelli, "A Novel Procedure for In-field Calibration of Sourceless Inertial/Magnetic Orientation Tracking Wearable Devices", the first IEEE / RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics (BIOROB), Pisa, Italy, February 20-22, 2006.

[5] D. Roetenberg, P. J. Slycke, and P. H. Veltink, "Ambulatory Position and Orientation Tracking Fusing Magnetic and Inertial Sensing," IEEE Transactions on Biomedical Engineering, vol. 54, no. 5, pp. 883-890, May 2007.