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An Automated Calibration Tool for High Performance Wireless Inertial Measurement in Professional Sports

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Abstract—**Traditional motion capture techniques, for instance, those employing optical technology, have long been used in the area of rehabilitation, sports medicine and performance analysis, where accurately capturing bio-mechanical data is of crucial importance. However their size, cost, complexity and lack of portability mean that their use is often impractical. Low cost MEMS inertial sensors when combined and assembled into a Wireless Inertial Measurement Unit (WIMU) present a possible solution for low cost and highly portable motion capture. However due to the large variability inherent to MEMS sensors, such a system would need extensive characterization to calibrate each sensor and ensure good quality data capture. A completely calibrated WIMU system would allow for motion capture in a wider range of real-world, non-laboratory based applications. Calibration can be a complex task, particularly for newer, multi-sensing range capable inertial sensors. As such we present an automated system for quickly and easily calibrating inertial sensors in a packaged WIMU, demonstrating some of the improvements in accuracy attainable.**

I. INTRODUCTION

MEMS based Inertial Sensors such as Accelerometers and Gyroscopes offer significant reductions in cost and size over traditionally manufactured mechanical and optical variants. However, these benefits come at the cost of accuracy in sensing. Parts are sold by their ideal performance, however, due to the large scale manufacture of these devices there is often significant differences between one device and the next. Manufacturers' data sheets quote expected performances along with tolerances for 0 offset, sensitivity, sensing range limits, linearity, cross-sensitivity etc. based on large scale random testing of devices. Additional errors can be introduced during further device manufacture, assembly and packaging steps. Although these errors would often be considered small and present no issue for simple applications such as detecting screen orientation or determining if a device is turning clockwise or anti-clockwise – such as is commonly used in consumer electronics devices – they can lead to significant errors when used in applications where accuracy is critical. Inertial Measurement Units (IMUs) built with these sensors for applications such as navigation or motion tracking can give large errors over time in reported versus actual location as a result of the accumulation of these small errors; this is called "drift". In these applications it is not good enough to rely on the manufacturers' generic datasheet, each device needs to be individually tested and characterized in its final packaged form.

As part of ongoing research into using Wireless Inertial Measurement Units (WIMUs) for sports motion capture a system, capable of automatically and rapidly calibrating a packaged WIMU has been designed, built and experimentally validated. The system consists of a purpose built turntable (Fig. 1) and custom software running on a connected PC. Data is collected from the WIMU via a USB connected wireless base-station. The complete system is automated such that the PC issues commands to the turntable via serial cable, receives raw inertial data from the attached WIMU via the connected base station before subsequently checking and logging the data. Known values of rotation rate and acceleration for each motion command issued are then compared to the response of the inertial sensors. The system then generates a response curve and automatically calculates useful calibration values such as: 0 offset, sensitivity, sensing range limits and linearity. The results are displayed to the user for reference and saved to file.

Prior to developing this tool a laborious semi-manual process was used which required several hours per sensor axis to complete. However, employing the new approach, this time has been dramatically reduced to approximately 5-10 minutes between placing the WIMU on the turntable and getting calibrated values for the sensor axis under investigation while allowing far more data points to be investigated. Use of this calibration system can greatly improve the accuracy of a WIMU system, allowing its use in the capture of accurate, high performance motion data for applications such as professional-level sports. These calibrated WIMU are being used in ongoing research to monitor motion[1] and assess the performance of athletes[2,3].

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II. METHODS

To calibrate a WIMU, a known stimulus is applied and the sensor responses are measured. In the case of an accelerometer, this would be an accurately known acceleration; in the case of a gyroscope, this would be an accurately known rate of rotation. These stimuli can be generated using a motorized turntable. In the case of a gyroscope, it is placed at the center of rotation to reduce the effects of centrifugal force, whereas in the case of an accelerometer it is placed at a known distance from the center of rotation (r) using centrifugal force to impart an acceleration (a_c) towards the center of rotation proportional to the angular velocity in radians (ω), according to the well known equation for radial acceleration, $a_c = \omega r^2$. For a more complete understanding of device performance the response across a wide range of rotation rates is investigated.

By issuing a series of constant rotation rate or “slew” commands to the motor we can control the stimuli that the WIMU under investigation is subjected to. Once a new slew command is issued, the motor will accelerate or decelerate to the desired rotation rate. Once it has reached this and transients have died down we can record the sensor responses. By recording several hundred values at each rotation rate and calculating the average we can reduce the effects of ADC quantization, noise and any remaining transients in the motion of the stepper motor. In some situations the values for noise, transients etc. might be large compared to the sensor's response. The variability in the data recorded at each step, such as standard deviation, should also be calculated to give a measure of confidence in the results for that step. The calculated values of response versus stimuli can be linearized and a graph created, allowing other values of use such as 0 offset, sensitivity, sensing range limits & linearity to be identified for each sensor. Once calibration has been performed for each sensing axis of a WIMU the calculated values can be used to convert the raw IMU data into more meaningful accelerations and rotation rates.

III. EXPERIMENTAL EQUIPMENT

Several separate pieces of equipment are used in the experimental setup, these are explained below.

A. *Calibration Turntable*

A calibration turntable has been designed and built for the purposes of this work. This consists of a highly accurate HR-4700 industrial stepper motor, a NSC-1S intelligent programmable motor controller and suitable power supply from Newmark Systems [4]. The remaining mechanical components (mounting plate, moveable stage, base plate, protective cover) attach to the motor and controller to hold items to be tested and protect the user, and were made in-house. The mounting plate on top of the motor holds a moveable stage with mounting holes on its adjustable upper surface. These mounting holes allow for packaged WIMUs and various WIMU holding tools to be securely attached using nuts and bolts. The entire system rests on a solid base plate with adjustable leveling screw legs and a built in spirit level to help ensure horizontal orientation of the calibration turntable during testing. The rotating part of the turntable is covered with a heavy-duty, shatter-resistant, clear cover to protect users from injury. The motor controller connects to the motor and PC using standard DB9 “Serial” data cables. Commands can be issued to, and data read, from the motor controller via a terminal program. The motor controller has internal storage allowing for several thousand commands to be stored and easily accessed

B. *WIMU System*

The Wireless Inertial Measurement Unit (WIMU) used in this work is based on the modular Tyndall 25mm mote platform [5]. It consists of 3 layers: a lithium ion battery power layer, version 3 of the IMU layer and a combined 2.4GHz transceiver/microprocessor layer. The IMU layer contains a 3-axis Accelerometer, 3-axes of dual output Gyroscope and a 3-axis Magnetometer the specifications of which can be seen in table 1 below. These are assembled into custom ABS plastic enclosures.

TABLE I. IMU VERSION 3 SPECIFICATION

Sensor Type	**Sensor Specifications**	
	Component Name	***Nominal Range***
Accelerometer	ADXL345	±2/4/8/16g*
Gyroscopes	IDG-650 & ISZ-650	±440°/s & ±2000°/s
Magnetometer	HMC5844	±0.7/1/1.5/2/3.2/3.8/4.5/6.5G*

* Range is Electronically Selectable

IV. SOFTWARE & CODE

For this work several different pieces of code were written in different languages. The WIMU and base station run TinyOS code [6], the motor controller uses MicroLYNX code [7] and the PC GUI data gathering and analysis system runs in Labview[8]. A basic description of each is presented below.

A. *WIMU and Base-station*

The TinyOS code on the WIMU implements timers set to provide the desired sampling rate for IMU data. When a timer fires, the device creates an appropriately sized empty packet and begins polling the individual sensors or their attached ADC for data. The complete packet containing the IMU data, some additional device and state identifiers as well as a short header and footer are sent via 2.4GHz RF to the base station's receiver. Once transmission is complete the timer on the WIMU restarts.

The base station receives the transmitted packet, removing the header and footer, and re-formatting the raw data before streaming it to the USB attached PC. The base-station appears as a virtual COM port.

B. *Motor Controller*

The motor controller has several tests implemented on its internal memory. On receipt of a command from the PC it begins the associated test. These involve rotating at a specified number of different rotation rates or "steps", between a specified upper and lower limit and remaining at a constant rotation rate during each step for a specified amount of time. As an example, the command "exec gyrtst2p" will execute the

Gyro Test 2P program, performing a series of rotations between -2500°/s and +2500°/s in 50 steps with a 3 second period of constant rotation rate at each step, for a total test time of about 5 minutes. A graph of motor rotation rate versus time would yield a roughly staircase shaped line between the upper and lower testing limits. During the test the motor controller monitors several values such as turntable rotational speed, turntable acceleration state, step count, emergency shutoff switch status and test state. These are reported back to the PC via serial cable to help the PC side software perform several tasks such as identifying when to collect data or move to the next stage of the test.

C. PC Software

The PC software has 2 separate GUI based software tools. The first is a “Data Gathering” tool; the second is a “Data Analysis” tool.

1) Data Gathering Tool

The Data Gathering tool is responsible for communicating with the attached devices and handling the raw IMU data according to the following procedure:

- Set up – Open software and enter COM port settings, select WIMU, sensor of interest and logging location
- Start – User initiates test by pressing start button.
- Initiate Communications – Start command sent to motor controller, data begins streaming from USB attached base-station
- Display Data - IMU data and motor status displayed to user as graphs for each sensor, status LEDs and text
- Create Log Files – A header file and log file created, a new data file is created at beginning of each step
- Check Data – Program waits until the motor controller indicates it is not accelerating and transients have settled down to start recording. Raw IMU data packet is split and each component checked to make sure it is within logical sensor range, if not the entire packet is disposed of. If all data passes, raw IMU data is combined with a comment and current rotation rate from the motor controller and appended to the appropriate log file. It remains in a loop here until the current step is complete
- Step End – Motor controller signals the end of each step, the step log file is closed. If the motor controller signals a new step, a new data file is created and the previous check data procedure is repeated until the test complete signal is given
- Test Complete – All open log files are closed, the motor controller is sent the stop command, the COM port resources are closed and the location of the log files is displayed to the user

2) Data Analysis Tool

The Data Analysis tool converts the values contained in the logged data files to a simple calibration results file according to the following procedure:

- Set Up – Open software and specify the location of the logged data, the column number of the sensor data of interest and a threshold to identify the limit of accurate sensing
- Removing Useful Data – Each file is opened and the data of interest is copied
- Calculate data points – Arithmetical mean and standard deviation for the data of interest copied from each file is calculated
- Find Useful Data Points – Upper and lower limits of accurate sensing range are identified by comparing local slopes between adjacent data points to the near 0 slope using the supplied threshold value. Data beyond this range is disposed of
- Generate Response Curve – A best fit line equation is generated using the remaining values for rotation rate, average sensor response and standard deviation
- Calculating Calibration Values – Using the response curve, 0 offset, sensitivity, maximum and minimum sensing range are calculated
- Display Data – Calculated values are graphed against the rotation rate and saved to a human and machine readable file format

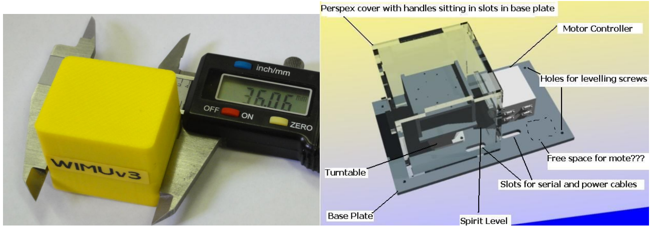

Figure 1. Tyndall WIMU (left) and Calibration Tunrtable (right)

V. RESULTS

Simple calibration values obtained using the automated tools for 6 gyroscope axes are shown below along with the ideal values based on manufacturers’ datasheets. The difference between the ideal and calibrated values can vary considerably. In test 1, the value for 0 offset differs by less than 1 bit, whereas in test 2, the difference is 167 bits. In spite of the similarity in 0 offset for test 1, the sensitivity is less than half of the ideal. For test 2, the sensitivity is quite close in spite of the large difference in 0 offset. The effect of these often significant differences can be more clearly seen after performing a simple orientation estimation test.

By rotating the WIMU through known angles and integrating the converted gyroscope data, an estimate of the angle travelled through can be calculated. By comparing the estimation to the known values of azimuth, the utility of calibration can be easily illustrated. In this case, the WIMU is rotated to azimuths of 0-180-0-360-180-0 degrees. A comparison of this data can be seen for 2 tests in Fig. 2, showing how closely the calibrated data matches the ideal as well as the significant differences between this and the datasheet derived data. Sample results from the validation test for each of the 6 gyroscopes in table 3 further illustrate this. With the datasheet derived results differing wildly from the actual azimuth in almost every case. Using the calibration data our values for azimuth remain with 11°/s for step 2, 24°/s for step 4 and 36°/s for step 6. With average drifts of 1°/s, 2.2°/s and 0.8°/s at each step respectively.

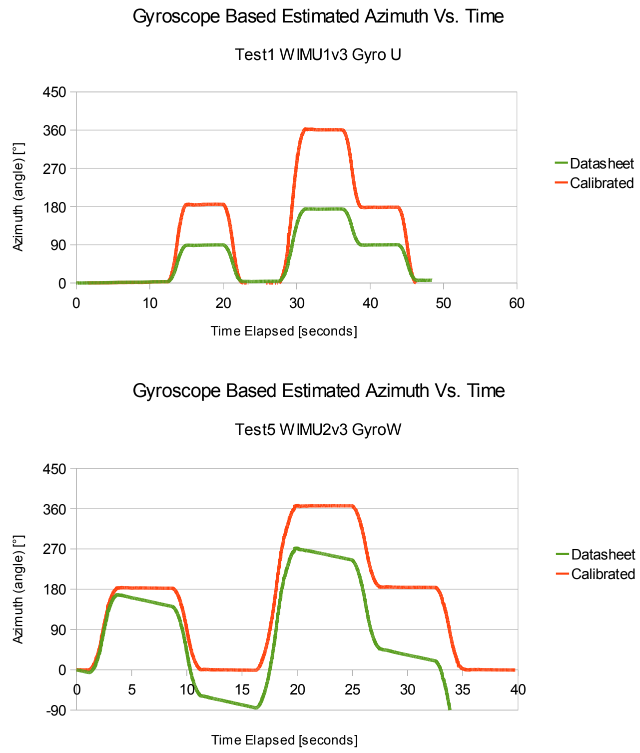

Figure 2. Azimuth Estimation comparisons showing poor results when using datasheet values of sensitivity (top) and 0 offset (bottom)

TABLE II. GYROSCOPE CALIBRATION VALUES

Data Origin	**Raw Sensor Data Conversion Values**	
	0 Offset [lsb]	***Sensitivity [lsb/(°/s)]***
Datasheet	2211.84*	3.719168*
Test 1	2211.265489	1.740461
Test 2	2378.852656	3.702272
Test 3	2192.587658	3.803676
Test 4	2169.163836	3.668113
Test 5	2285.943634	3.761703
Test 6	2243.469107	1.799089

* Based on voltage reference value and ADC used

TABLE III. DATASHEET & CALIBRATED CALCULATED VERSUS ACTUAL AZIMUTH

	Step 2 - 180°		**Step 4 - 360°**		**Step 6 - 0°**	
	Datash.	**Calib.**	**Datash.**	**Calib.**	**Datash.**	**Calib.**
Test1	89°	185°	174°	361°	7°	-2°
Test2	689°	169°	1581°	336°	1894°	-36°
Test3	154°	182°	259°	366°	-196°	0°
Test4	-31°	184°	-165°	372°	-821°	20°
Test5	-104°	186°	-264°	376°	-918°	20°
Test6	-119°	180°	-169°	362°	-477°	3°

VI. CONCLUSION

From this work it can be seen that modern MEMS inertial sensors show considerable variability in their performance from that indicated on their datasheets. However, in spite of this, it is possible to get useful and accurate data from them using a suitable calibration method. Further improvements to the calibration method could potentially be made by adding factors to take account of other external variables such as temperature and voltage level. However, this greatly increases the complexity of calibration, further demonstrating the utility of an automated calibration such as that demonstrated in the paper.

REFERENCES

[1] C. Ó Conaire, "Tennis Stroke Recognition Using Wireless Accelerometers", 2009, CLARITY: Centre for Sensor Web Technologies: Dublin.

[2] M. Walsh, J. Barton, B. O'Flynn, C. O'Mathuna, M. Tyndyk, "A Multi-technology Approach to Identifying the Reasons for Lateral Drift in Professional and Recreational Darts", IEEE BSN 2011.

[3] M. Gaffney et al., "Wearable wireless inertial measurement for sports applications", Proc. IMAPS-CPMT Poland 2009, Gliwice–Pszczyna, Poland, 22-24 Sept, 2009.

[4] Newmark Systems Inc., Rotary Stages, http://www.newmarksystems.com/

[5] B. O'Flynn, S. Bellis, K. Mahmood, M. Morris, G. Duffy, K. Delaney, C. O'Mathuna, A 3D miniaturised programmable transceiver. Microelectronics International, 2005. 22(2): p. 8-12.

[6] P. Levis et al., "Tinyos: An operating system for sensor networks", Ambient intelligence, 2005, 35.

[7] Intelligent Motion Systems Inc., MicroLYNX Programming Manual, 2006, Intelligent Motion Systems Inc.

[8] National Instruments, Labview - Laboratory Virtual Instrumentation Engineering Workbench, 2011, www.ni.com/labview