Automated calibration of an accelerometers, magnetometers and gyroscopes - A feasibility study

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Abstract

The report presents a automated calibration solution capable of evaluating the gains and biases of an accelerometer, magnetometer and gyroscope with minimal human intervention. The solution developed uses off-the-shelf components and distributable software. The results presented indicate that the solution is effective though greater accuracy may be achieved through further development.

1 Introduction

Attitude and Heading Reference Systems (AHRS) are self-contained units that provide a measurement of orientation relative to the Earth using an integrated array of gyroscopes, accelerometers and magnetometers. Inertial Measurement Units (IMUs) are similar device that do not include magnetometers and are limited to measuring an attitude relative to the Earth. The low cost, low power and low physical profile of modern Microelectromechanical system (MEMS) based sensors mean that AHRSs and IMUs are an increasingly accessible tool for robotics, Human Machine Interfacing (HMI) and Medical technologies.

MEMS sensors provide an output voltage or Analogue to Digital Conversion (ADC) result proportional to the measured physical quantity. Practical applications will require that this value is converted to a suitable engineering unit; for example, rads^{-1}, ms^{-2} and Gauss a typical units of gyroscopes, accelerometers, and magnetometers respectively. These units may be obtained by accounting for a calibrated bias and gain in the sensor output. Due to the mechanical properties of a MEMS device the characteristics of an individual sensor cannot be guaranteed during manufacture and may be altered after manufacture when soldered. Consequently, no two sensors may be guaranteed to be the same and each must be uniquely calibrated.

This report presents a low-cost automated calibration method to evaluate the gains and biases of accelerometers, magnetometers and gyroscopes with minimal human intervention. The method is implemented within single windows application which integrates to both a motorised calibration gimbal and the sensor device to be calibrated. The software was written in C# and MATLAB. The calibration gimbal was constructed from off-the-shelf components and the sensor devices used was the IMU tag v1.0. The software may easily be adapted to interface to alternative AHRS or IMU devices is discussed.

2 Theory

Gyroscopes, accelerometers and magnetometers are available in triple-axis packages comprised of 3 mutually orthogonal axis; x, y, and z. The sensor output may be assumed to be linear so that the calibrated measurement, $\boldsymbol{c}$, is obtained from the un-calibrated measurement, $\boldsymbol{u}$, using the relationship defined in (1). The vector $\boldsymbol{b}$ defines the sensor bias and $\boldsymbol{K}$ is a diagonal matrix defining the sensor gain; as defined in equations (3) and (4) respectively.

$$\boldsymbol{c} = \boldsymbol{K}\boldsymbol{u} - \boldsymbol{b} \tag{1}$$

$$\boldsymbol{u} = \begin{bmatrix} u_x & u_y & u_z \end{bmatrix}^T \tag{2}$$

$$\boldsymbol{b} = \begin{bmatrix} b_x & b_y & b_z \end{bmatrix}^T \tag{3}$$

$$\boldsymbol{K} = \begin{bmatrix} k_x & 0 & 0 \\ 0 & k_y & 0 \\ 0 & 0 & k_z \end{bmatrix} \tag{4}$$

2.1 Accelerometer and magnetometer

A stationary accelerometer will measure the direction and magnitude of the Earth's gravitational field due to the reaction force on the mass within the MEMS structure. A magnetometer will measure the direction and magnitude of the Earth's magnetic field compounded with local magnetic interference. For a calibrated sensor, the measured magnitude will be constant for all orientations of the sensor. That is, equation (5) will be true for all said measurements where m is the magnitude of the sensor's respective field. Therefore, $\boldsymbol{K}$ and $\boldsymbol{b}$ may be found as the solution to equation 6 where $\boldsymbol{u}_i$ represents the un-calibrated sensor measurement at the i'th orientation within a calibration dataset.

$$m = \|\boldsymbol{K}\boldsymbol{u} - \boldsymbol{b}\| \tag{5}$$

$$\min_{\boldsymbol{b},\boldsymbol{K}\in\Re} \left[\sum_i \left(m - \|\boldsymbol{K}\boldsymbol{u}_i - \boldsymbol{b}\|\right)^2 \right] \tag{6}$$

AHRS and IMU algorithms often only require the direction of the Earth's gravitational or magnetic field to be known so that the value of m used for calibration is unimportant. Typically, values of 9.8 ms^{-2} and 1 are used for an accelerometer and magnetometer respectively. For effective calibration, the calibration dataset should represent the full range of orientations of the sensor relative to the field.

As an accelerometer will also measure the translational, centripetal, tangential and Coriolis accelerations associated with motion, it is important that the sensor is stationary during the acquisition of the calibration dataset. Magnetometer measurements may be corrupted by magnetic interferences fixed to the sensor frame (hard-iron distortion). Hard-iron distortions result in a constant bias error in each axis and so will therefore be incorporated to the estimated bias, $\boldsymbol{b}$, of the sensor. It may be impractical to use a location completely free from magnetic distortions; CRT monitors, metal future and steel within a building's structure have all been shown to influence magnetometer measures. It is acceptable for a calibration dataset to feature magnetic interference provided that the resultant magnetic field is homogenous. Magnetic interferences fixed to the sensor frame (hard-iron distortions) will be incorporated to the estimated bias, $\boldsymbol{b}$.

2.2 Gyroscopes

MEMS gyroscopes are subject to bias drift so calibration cannot assume a constant bias. Instead, AHRS and IMU algorithms will typically estimate the gyroscope bias in real-time. Consequently, gyroscope calibration need only be concerned with estimation of the sensor gains. Exposing the gyroscope to a constant angular velocity for any extended period of time would be impractical due to wires and cables. Alternatively, the gyroscope may be rotated around one axis by a known angle and the gain found as that which ensures the integrated angular velocity measured by the gyroscope is equal to the known angle of rotation. This can then be repeated for all three axes. The correct gain may therefore be found as the solution to (7) where r is the known angle of rotation, T is the sampling period, $u_{a,t}$ is the un-calibrated gyroscope measurement at time t, and b_t is the bias at time t.

$$\min_{k_a \in \Re} \left[r - T \sum_{t=0}^{n} \left(k_a u_{a,t} - b_{a,t} \right) \right]^2 , \; t = 0, 1, ...n \, , \; a = x, y, z \tag{7}$$

The bias can be sampled when the gyroscope is stationary at the start and end of the rotation; $b_{a,0}$ and $b_{a,n}$. To account for drift in the bias, $b_{a,t}$ can be calculated as the interpolated values between $b_{a,0}$ and $b_{a,n}$; as shown in equation (8).

$$b_{a,t} = b_{a,0} + \frac{t}{n} (b_{a,n} - b_{a,0}) \, , \; t = 0, 1, ...n \, , \; a = x, y, z \tag{8}$$

The change in angle should be monotonic and occur over a short period of time to minimise integral drift. The angular velocity should be maximised to ensure that a much of the gyroscopes output range is accounted for in calibration as possible.

3 Calibration gimbal

An automated calibration solution requires that the sensory unit is moved through a range of orientations relative to the Earth's gravitational and magnetic fields for the calibration of accelerometers and magnetometers. It must also be able to rotate the sensory unit around its x, y, and z axes independently for the calibration of gyroscopes. The solution was the actuated 3 Degrees Of Freedom (DOF) gimbal shown in 1. The components are made from aluminium and plastic to minimise magnetic interference. The gimbal can rotate with closed-loop positional control ±180°, ±180°, and ±90° independently around the pan, roll and tilt axis respectively. The IMU tag v1.0 to be calibrated was fixed to the gimbal via a small red cardboard box to distance the magnetic sensors from metallic screws; as seen in figure 1.

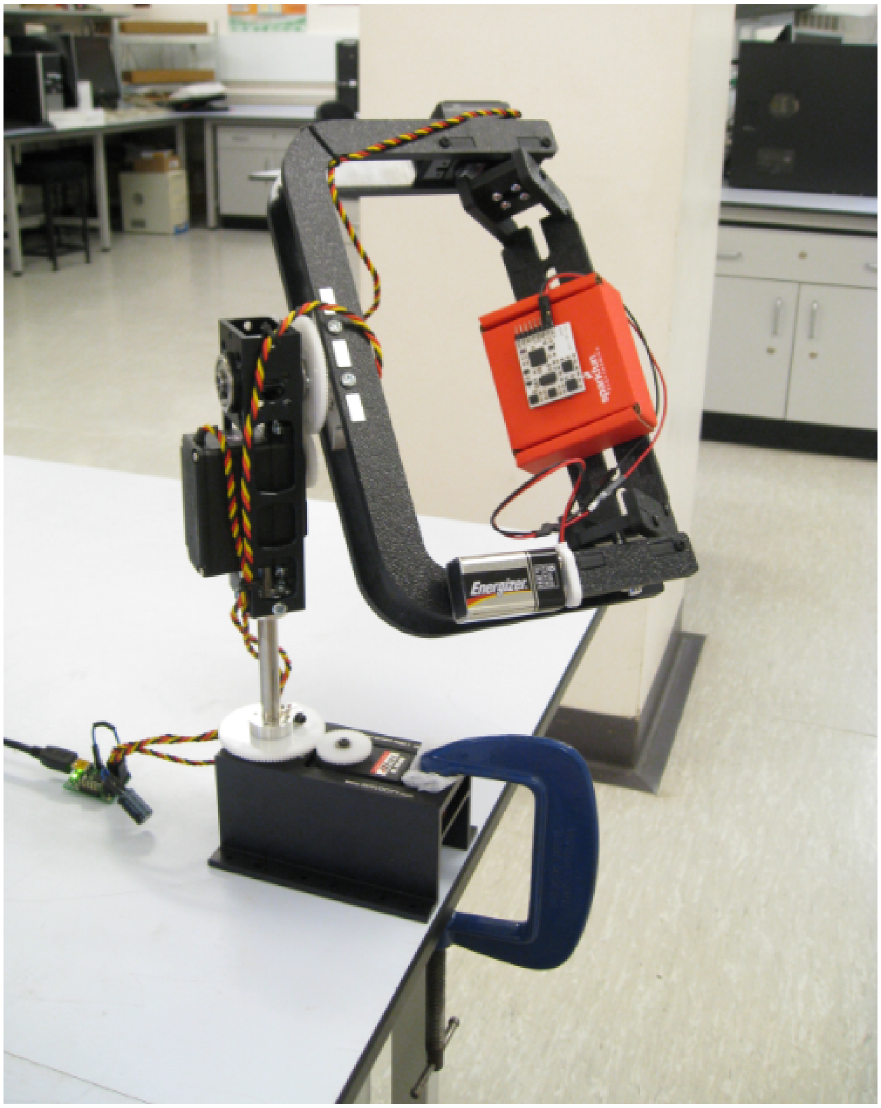

Figure 1: 3 DOF gimbal with attached IMU tag v1.0

3.1 Gimbal components

Table 1 details the individual components used to construct the 3 DOF gimbal. All parts were purchased from `www.servocity.com` with the exception of the Pololu Maestro Servo Controller which may be purchased from `www.pololu.com`.

Component	Manufacture part number
SPG785A-BM Bottom Mount (2:1, Plastic Gears)	SPG785A-BM
SPG785A-5.0 Servo Gearbox (2:1, Plastic Gears)	SPG785A-5.0
Direct Drive Cradle Tilt (Hitec 6")	DDT560H
HS-645MG Ultra Torque	32645S
18" Super-Duty Extension (S/JR/Z)	SE2218S
3/8" Bore Clamping Hub	3172CH
3/8" Bore Aluminum Collar (Clamping)	6157K13
3/8"×6.00" Precision Shaft	AAS-A5-33
End Cap Mount for 1"x1.5" Extrusion	ECM-125-75
Micro Maestro 6-Channel USB Servo Controller	1350

Table 1: 3 DOF gimbal bill of materials

3.2 Gimbal assembly and calibration

The Pololu drivers and Pololu Maestro Control Center software were installed prior to assembly of the gimbal so that servos could be held at the 1500 μs position (centre) during assembly. The pan (HS-785HB), roll (HS-785HB) and tilt (HS-645MB) servos where connected to channels 0, 1 and 2 on the Pololu Maestro Servo Controller respectively. A 500 mA resettable fuse connected the servo controller `PWR` pin to the `+5V` pin to enable the servos to be powered via USB. A 220 μF capacitor was connected in parallel with the servo controller `PWR` and `GND` pins to prevent the servo controller from resetting during spikes in the servo current demand. These components can be seen in 2.

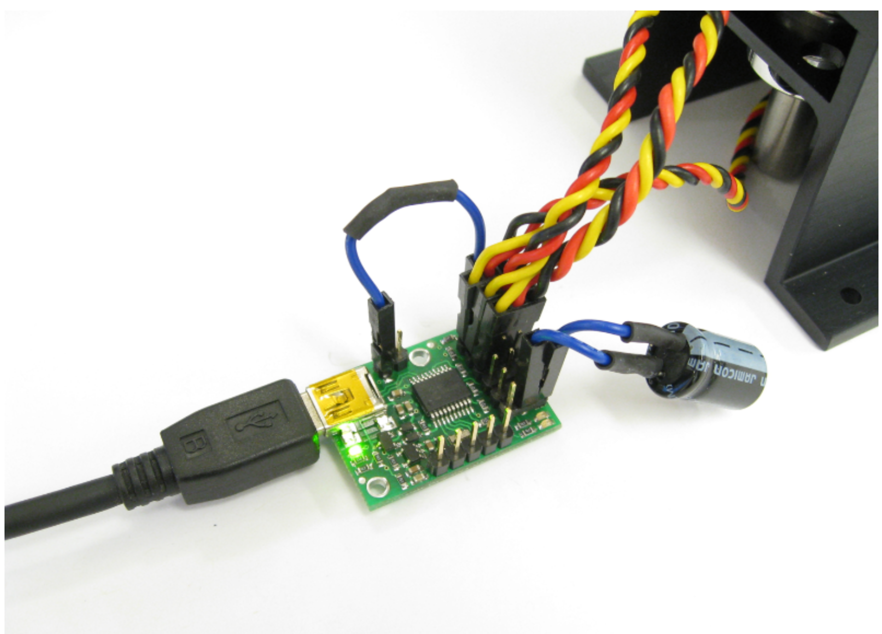

Figure 2: Additional components connected to the Pololu Maestro Servo Controller by blue wires; a 500 mA resettable fuse and 200 μF capacitor

The Pololu Maestro Servo Controller firmware settings were altered using the Pololu Maestro Control Center to enable serial port communication and set appropriate limits for servo rotations. Specifically: *USB Dual Port* was enabled in *Serial Settings*, and *Min/Max* values of 1248/1744 and 496/2544 where set in *Channel Settings* for the HS-785HB and HS-645MB servos respectively. The settings may be loaded directly from the `maestro_settings.txt` file.

The gimbal was assembled in the orthogonal arrangement shown in 3 with servos held at the 1500 μs position. The 'cogged' design of the HS-645MB servo shaft prevents the tilt platform from being orthogonal while held at the 1500 μs position. This platform was instead be installed at the smallest obtuse angle as can be seen in 3. **The gimbal must be assembled as described to match calibrated centre positions in software.**

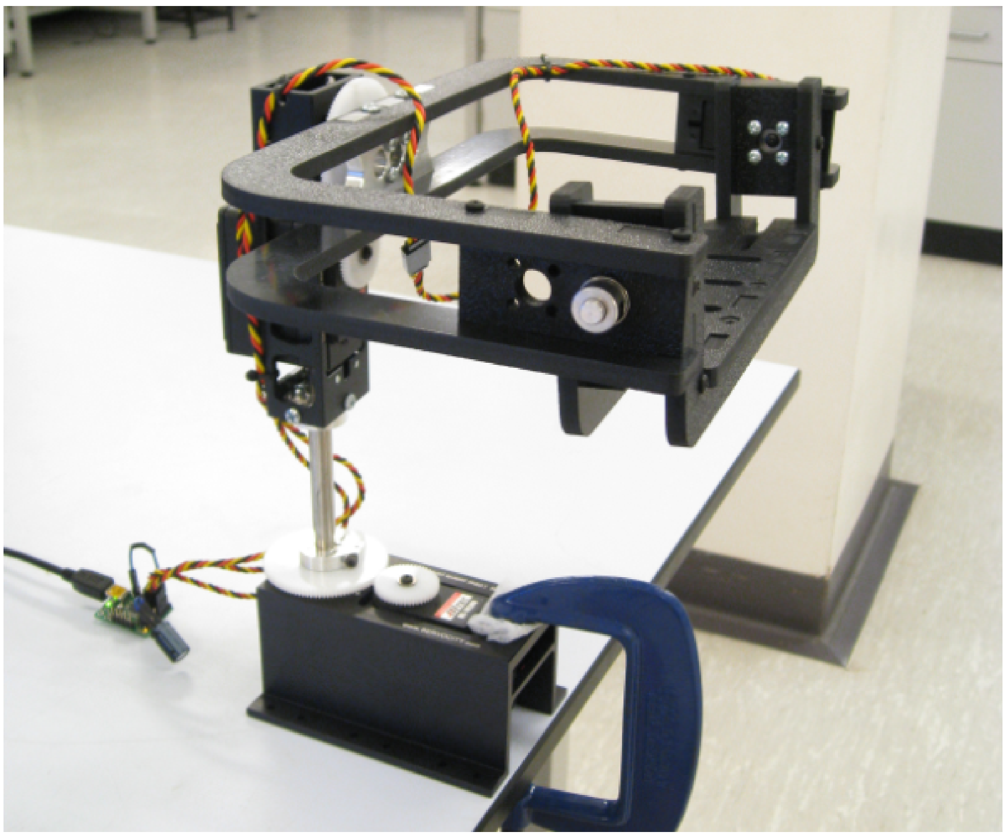

Figure 3: 3 DOF gimbal with each servo at the 1500 μs position (centre)

4 Software

The complete automated calibration solution is implemented within a single Windows application. This application enables control of the gimbal, logging of sensor data, and the execution of a the calibration algorithms presented in section 2.

4.1 MATLAB functions

The calibration methods presented in section 2 were implemented as two MATLAB functions; `calibrateAccelMag.m` and `calibrateGyro.m`. Each function uses the Optimisation toolbox function `fminunc` to minimise their respective objective functions; `objFunAccelMag.m` and `objFunGyro.m` representing equations (6) and (7) respectively. Documentation for these functions exists as the comemnts within the source code.

The MATLAB functions were compiled for C# using the MATLAB Builder NE toolbox. The MATLAB Component Runtime (MCR) must be installed (`MCRInstaller.exe`) if a MATLAB installation is not present on the machine.

4.2 Windows application

The Windows application functions as a Graphical User Interface (GUI) front-end to the automated calibration solution, written in c#. The GUI allows manual control of the gimbal and enables the execution of a 'command script' composed within the source code. The command script enables sequencing of gimbal control, sensor data logging and algorithm execution. Software documentation exists as the comments within the source code.

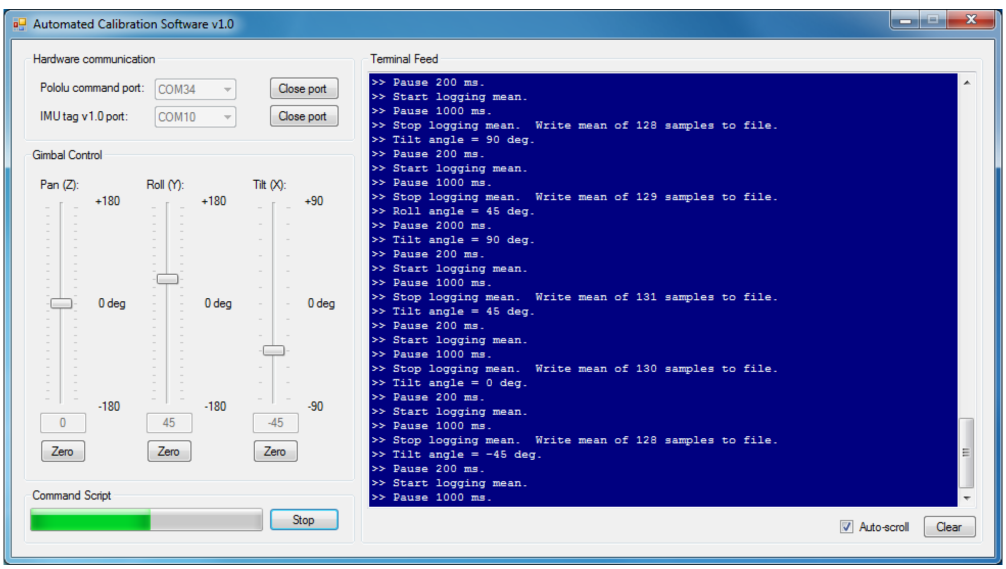

Figure 4: Windows application GUI

5 Interfacing to other sensors

Software was developed to interface to the IMU tag v1.0. The software may easily be modified to interface to any IMU or AHRS sensor by making the following changes:

- Enable communication with the chosen sensor within the C# project using appropriate user code or product Software Development Kit (SDK).
- Call `updateSensorData(int[] data)` each time new sensor data is available at a fixed sampling rate. Function details available in source code.

- Specify the correct sampling period and suitable values for an 'initial guess' of sensor bias and gains when calling the calibration algorithms at the end of the command script.

6 Calibration routine

The command script was composed to calibrate the accelerometer, magnetometer and gyroscope on the IMU tag v1.0 without human intervention. The script first collects the accelerometer and magnetometer dataset by logging the mean sensor measurements for 1 second at each orientation achieved through 45° steps over the full range of each gimbal axis. The script then collects each gyroscope axis calibration dataset as logged sensor measurements during a rotation of 180° around each axis. The mean sensor measurements were logged for 2 seconds while the IMU tag v1.0 was stationary before and after each rotation to represent the gyroscope bias as the first and last samples within the dataset. Finally, the script executes the calibration algorithms for each dataset and the results are written to files. This routine is represented as the pseudo code below.

```
create file "accelMagData.csv"
for gimbal pan = -180 : 45 : 180
{
    for gimbal roll = -180 : 45 : 180
    {
        for gimbal tilt = -90 : 45 : 90
        {
            log mean sensor data for 1 second
        }
    }
}
close file

for $ = x, y, z
{
    create file "gyro$Data.csv"
    log mean sensor data for 2 seconds
    start logging sensor data to file
    rotate gimbal around $ by 180
    stop logging sensor data to file
    log mean sensor data for 2 seconds
    close file
}

run calibration algorithms
```

Geographic dependency: The magnetometer calibration dataset requires that each sensitive axis is exposed to varied magnitudes of the Earth's magnetic field. This is achieved in the calibrations script by rotating the gimbal pan axis on the assumption that the Earth's magnetic field is horizontal relative to the Earth's surface. In the UK (where testing was conducted), the inclination of Earth's magnetic field is $\approx 70°$ and so rotations around the gimbal pan axis were be omitted from the above calibration routine in favour of reducing the time required by the calibration process.

7 Results

The calibration routine was run several times to verify consistency of results. The routine required 2 minutes to complete. An annotated video of the complete calibration routine has been posted on YouTube and is available at:

`http://www.youtube.com/watch?v=XqQCbkncVYI`

Figures 5 and 6 show the calibrated accelerometer and magnetometer measurements for a typical calibration dataset respectively. Each figure consists of two plots. The upper plot represents the calibrated individual x, y and z measurements and the lower verifies the success of the calibration as a comparison comparing the measured and known magnitudes of the senor's respective field.

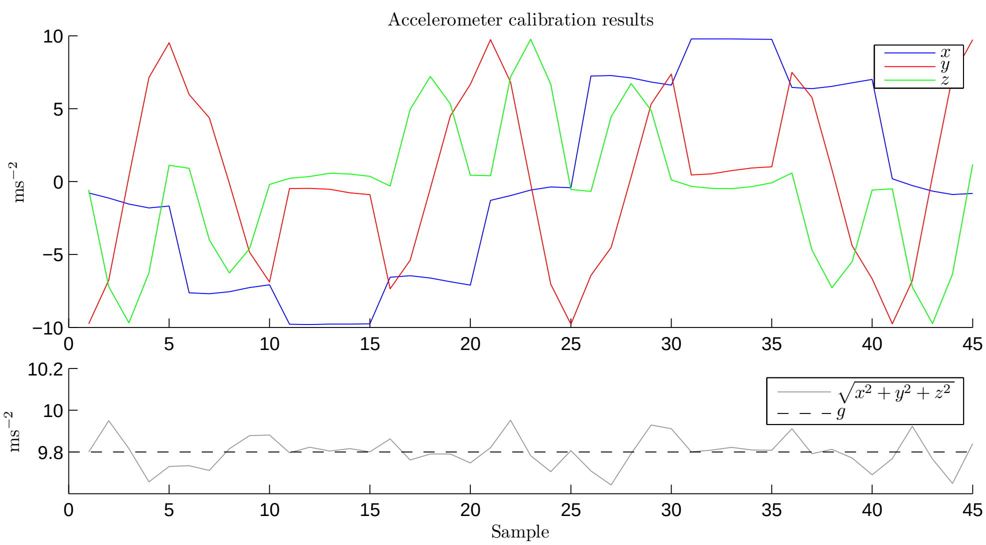

Figure 5: Typical results for accelerometer calibration

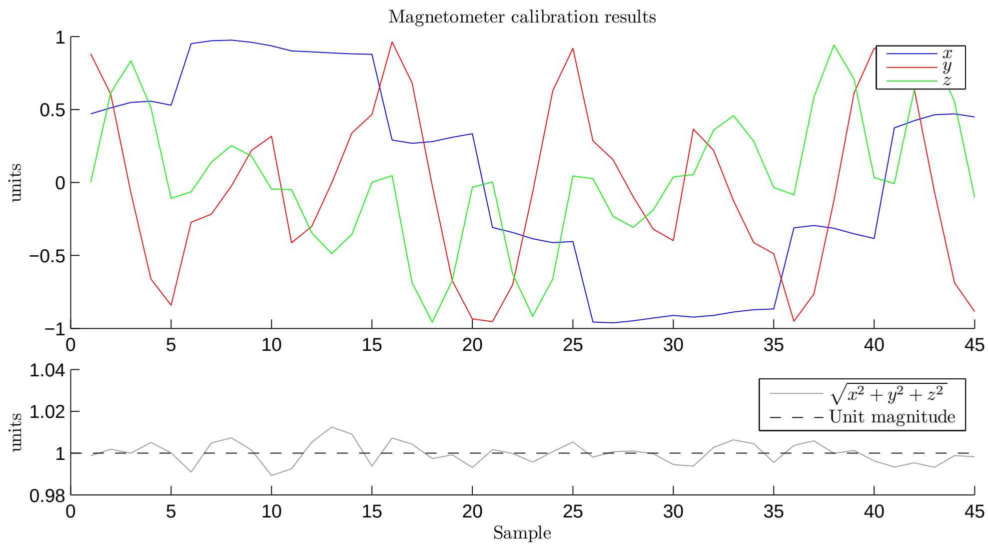

Figure 6: Typical results for magnetometer calibration

Figures 7 to 9 show the calibrated gyroscope measurements for a typical calibration dataset. Each plot represents the calibrated angular velocity, the calculated angle of rotation, the target angle of rotation and the interpolated bias. The calibration may be verified by comparing the final calculated angle and the target angle. The slower and over-damped response of the HS-785HB servos result in the asymmetrical velocity profile observed in figures 8 and 9.

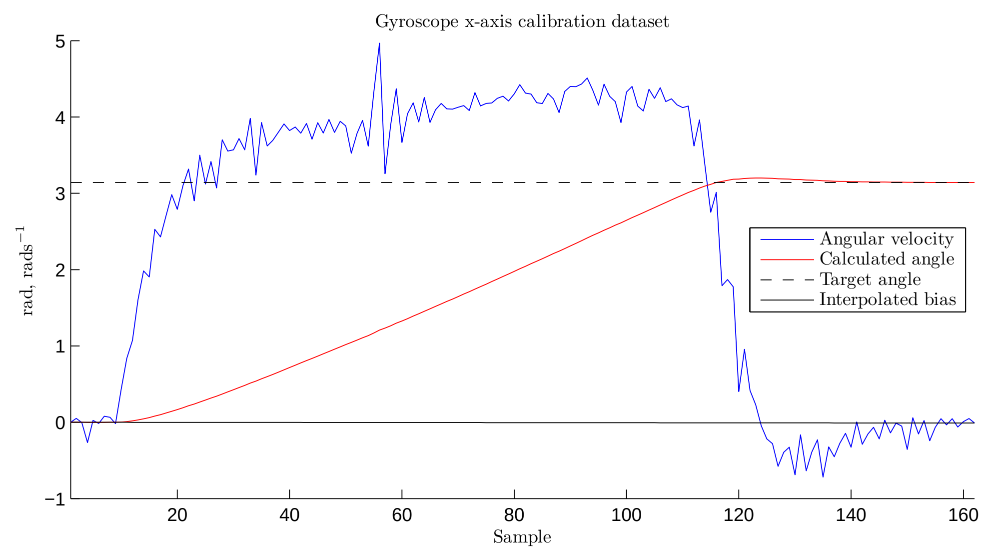

Figure 7: Typical results for gyroscope x-axis calibration

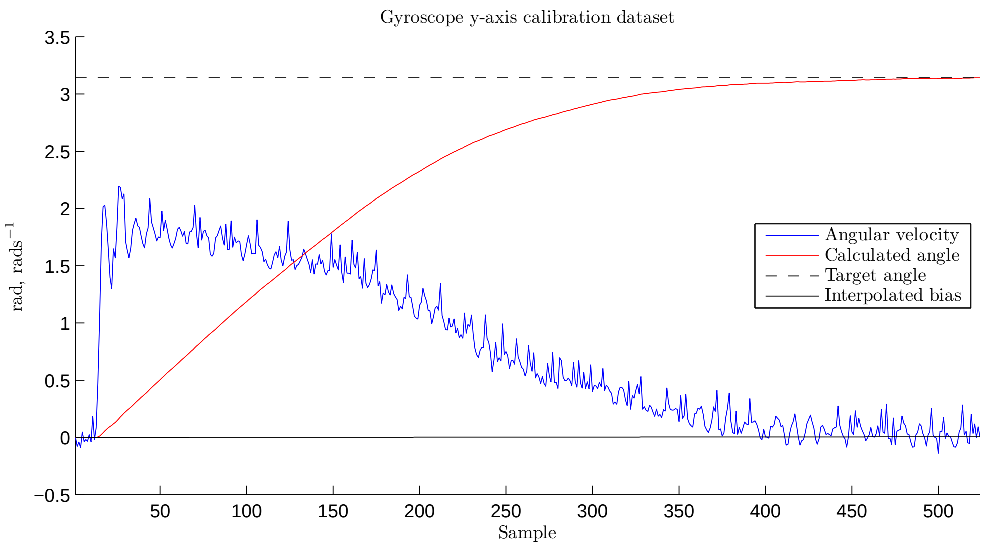

Figure 8: Typical results for gyroscope y-axis calibration

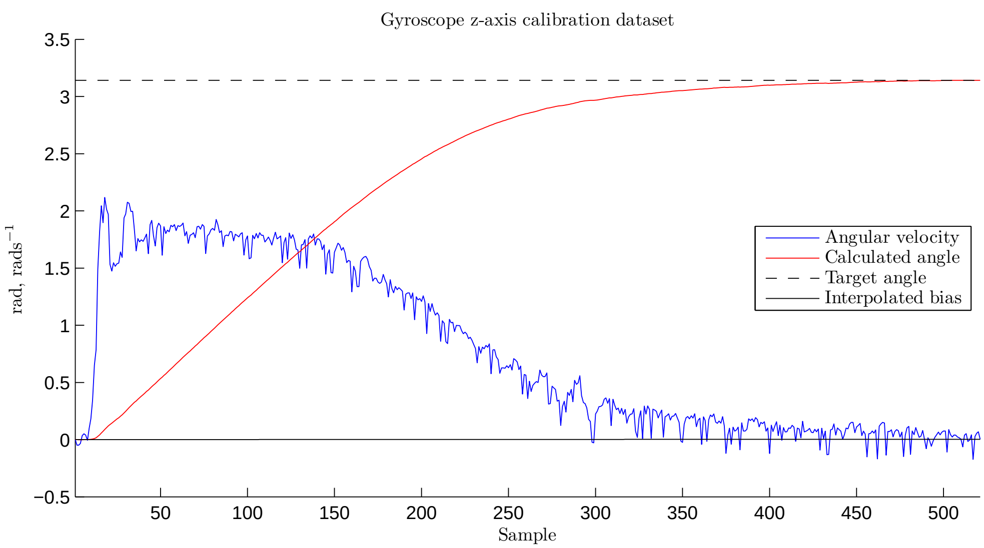

Figure 9: Typical results for gyroscope z-axis calibration

8 Conclusion

The report has presented a simple automated calibration method capable of evaluating the gains and biases of an accelerometer, magnetometer and gyroscope with minimal human intervention. Software may be adapted to enable the simultaneous calibration of multiple devices provided that their close proximity on the gimbal does not affect magnetometer measurements. The limitations of the system are the simplified sensor model (assuming a first order linear relationship in 3 decoupled axes) and the limited calibration datasets. These limitations can be address through further development of the solution presented in this report.