A Traceable Inertial Calibration Procedure
Suited for MEMS Sensing

Surya Singh
Australian Centre for Field Robotics
University of Sydney
New South Wales 2006, Australia
Email: spns@acfr.usyd.edu.au

Abstract—The wide availability of MEMS inertial sensors has lead to a diversity of applications for compact IMUs in mobile robotics. Determination of the sensitivity, bias, noise, and non-linear effects of these units is important for robust estimation and accurate operation. A traceable and dynamic off-line calibration procedure is presented based around MEMS device characterization equipment and/or equipment available in robotics laboratories. As with a full inertial calibration configuration, this procedure provides a traceable sensor model and a means of determining system alignment and cross-coupling. However, this is more accessible as the calibration can be performed locally. The method was tested with a custom, high-frequency, MEMS transducer based IMU with results different from nominal values, yet within manufacturer specifications.

I. INTRODUCTION

The combination of micro-electromechanical systems (MEMS) accelerometers and gyroscopes to form an inertial measurement unit (IMU) for the entire system is an increasingly prevalent aspect of mobile robotics, particularly for trajectory control and mapping problems. Such units are not only compact localization sensors, but also allow for increased performance on dynamic platforms even in the case of self-stabilizing, compliant designs.

The precise operating parameters governing the inertial transducers are not initially known as the values given by the manufacturer are typically against a linear sensor model and are specified within a significant range. Further, these values are for the individual parts and not for the IMU, for which the axis alignment and coupling for the orthogonal triad [1] (or related redundant configuration [2]) needs to be determined. Hence, for high accuracy operation, it is necessary to calibrate the sensor, even if the measurements are compensated by smoothing or filtering as later processing adds delay and does not directly address scaling [3].

Calibration is an integral part of the sensing process as it relates measurements back to a reference standard. While commercial calibration is possible, values can vary due to exact operating conditions (e.g., temperature and voltages), especially for compact, low-cost MEMS inertial transducers [4]. Online calibration affords a means for performing checks under operating conditions and is useful for tuning noise and cross coupling variances that might be used in later estimation processes [1].

In the case of inertial sensors, calibration checks measured accelerations and angular rate values against those from reference forces and motions, such as against the acceleration generated in a gravity oriented ground reference frame. This can be performed using a mechanical platform in which the IMU is precisely oriented while spinning at a known rate [1]; however, such platforms are complex and expensive. Various simplifications have been proposed. For example, the inertial sensor can be moved while being tracked optically [5] or optimization techniques can be applied while the IMU is spinning so as to determine the misalignment of its sensors to against gravity [6], [7]. The issue with the fist approach is that it requires access to an optical tracking apparatus, while the latter approach, while allowing for simultaneous calibrations, can only provide acceleration calibrations against a presumed known gravity reference (i.e., $\pm \approx 1g$) and thus provides no measure of accelerometer nonlinearity.

To get dynamic acceleration calibration and skewing, a procedure using MEMS resonator characterization equipment is proposed. The central idea is to integrate the inertial measurements and thus make comparison against a reference velocity measurement. The accelerometer calibration and axis alignment, which if presumed stable for the IMU, can then be used to simply the turntable calibration of the gyroscopes. In comparison to online estimation techniques [7], this method produces a traceable result and does not make assumptions about the functional representation of the noise or bias, which can lead to over-fitting of parameters.

Experiments were performed using a custom assembly built from best-of-breed MEMS transducers. Referred to as the Sensor Cube (shown in Fig. 1), it uses an orthogonal (cubic) configuration. Redundant sets of sensors were added for operation across multiple sensitivities and for part robustness, but were not aligned in using an optimal strategy. Indirectly inferable measurements, such as obtaining angular rates from the six accelerometers, were not computed and checked [8] for these experiments.

Traceability is provided by comparing the INS output signal to synchronized recordings made by a reference instrument with a NIST traceable calibration standard. Thus, the final Sensor Cube measurements relate to standard units within the variance of the instruments, the operating assumptions made, and the limits of uncertainty associated with this procedure.
Fig. 1. The Sensor Cube features a redundant sets of gyros and accelerometers in an orthogonal configuration to sense motions of up to 10g acceleration, 572°/sec angular rate, at rates up to 400-Hz, in an ≈ 0.1kg package.

II. ACCELERATION CALIBRATION

Calibration of inertial measurements is complicated by both the coupling of gravity and the IMU dynamics as the sensing axis are not necessarily aligned, oriented, and intersecting. This results in the output signal being coupled to various factors. In the case of an accelerometer, the output signal, \( s_a \), absent of noise is

\[
s_a = s_o R \left( (a - o R g) + \alpha \times r + \omega \times (\omega \times r) \right)
\]

(1)

where \( s_o R \) is the rotation of the sensor relative to the calibration frame, \( o R \) is the rotation of the gravity (g) frame relative to the calibration frame, and \( \omega \) and \( \alpha \) are the angular rates and accelerations respectively.

If care is taken to prevent the frame from rotating, the secondary tangential and centripetal accelerations can be assumed to be negligible. Thus the object becomes to estimate the actual acceleration and the frame orientations. A controlled sinusoid testing configuration allows for filtering and extended testing.

Based on this notion, the this accelerometer calibration procedure builds on techniques for checking the resonant properties of MEMS cantilevers [9]. The setup as shown in Figures 2 and 3 consists of: a Laser Doppler Vibrometer (LDV: Polytech OFV 3001), a two-channel signal analyzer (HP 89410A), an oscilloscope (HP 54542A), a piezoelectric shaker, and a linear signal filter (Krohn-Hite Model 3750 R). These parts are supported on a vibration isolated table (Newport I-2000 series isolator).

The signal analyzer is programmed to generate a sinusoid of various frequencies with the amplitudes adjusted to maintain a consistent power level. This signal is then amplified and sent to the piezoelectric shaker. The expected accelerations are:

\[
V_{signal} = A \sin(\omega t)
\]

(2)

\[
x_{drive} = k x_{signal} = k A \sin(\omega t)
\]

(3)

\[
a_{drive} = \frac{d^2 x_{drive}}{dt^2} = -\omega^2 x_{drive}
\]

(4)

where \( V_{signal} \) is the signal voltage, \( x_{drive} \) is the driven position of the shaker, \( a_{drive} \) is the driven acceleration, and the terms \( A \) and \( k \) are proportionality constants reflecting apparatus settings. Assuming that the accelerometer acts as a linear transducer gives:

\[
a_{sensor} = S_1 V_{sensor} + S_0
\]

(5)

\[
v_{sensor} = \frac{a_{sensor}}{2\pi f}
\]

(6)

where \( V_{sensor} \) is the transducer voltage, \( S_1 \) is the sensitivity, \( S_0 \) is the offset, and \( v \) is the measured velocity. Since the sensor and LDV are sensing the same motion, the calibration equation becomes (for a known LDV gain, \( G \)):

\[
v_{(LDV)} = v_{sensor}
\]

(7)

\[
S_1 V_{out} + S_0 = 2\pi f G_{LDV} V_{LDV}
\]

(8)
The technique for solving for the online noise model involved static and dynamic operations of the sensor elements during which the signal was taken. The procedure followed standard noise quantification protocols except for modifications that removed the extensive shielding and associated precautions typically in place as the goal is to obtain a pragmatic noise model rather than determine performance limits. As expected, at lower frequencies the signal has higher noise densities. It is suspected that this is due to the flicker noise effects common in transistorized integrated circuits such as those integrated with the sensor elements.

This leads to a procedure where a sweep of frequencies allows for calibration of various acceleration values. The frequency needs to be selected so as not to exceed the accelerometer bandwidth while being large enough to be driven by the shaker. Typical ranges used were from 20 to 500 Hz. Although it may be measured by a monitoring oscilloscope, the frequency, $f$, is obtained from the signal generator (by assuming that damping effects are negligible). Example output is shown in Figure 4 and 5. Although the vibration isolation table and careful setup minimized axis cross-coupling during actuation, data was recorded from all three accelerometer axes.

Analysis of the resulting data via linear least-squares allowed for the determination of the sensitivity and offset values for all directions on each of three accelerometer units. This also allowed for a determination of the noise bandwidth and verified that the noise from the MEMS units was non-trivial and colored.

III. GYROSCOPE CALIBRATION

In a similar motivation as with the accelerometer procedure, calibration of the gyroscopic sensors (gyros) was undertaken using an encoder instrumented turntable. This provides a reference measure of the angular position, from which standard rotational rates were obtained by differentiation. Processing of this standard against sensor output gives a mean sensitivity specification and offset result, which is used to form the linear sensor model relating the transducer signal to measured rates. As with the acceleration procedure, care is taken to align the axis of the sensor to all three axes.

The calibration apparatus is shown in Fig. 6 and consists of a phonograph turntable (Technics SL-BD10) to which a 1000-count traceable, calibrated, reference encoder (US Digital USD#611-2”-1000-9040-B00 disk with Agilent HEDS-9040 module) is installed on the platen shaft. Sensor output is then passed through a trimmed unity gain buffer circuit (based on Texas Instruments TLC2274 amplifiers) so as to reduce signal propagation losses and multiplexing effects. The data from both sources is then simultaneously captured using a 16-channel multiplexed PC-104-based data acquisition card (Measurement Computing PC104-DAS16JR/16). Each signal is digitized at 3125 Hz using a 16-bit analog to digital converter (Texas Instruments ADS7805) and then logged using custom software.

As expected, the turntable operates at two nominal rates: $33 \frac{1}{3}$ and 45 revolutions per minute (rpm) (or 198°/sec and 270°/sec respectively). However, these rates are not guaranteed or regulated. Further, the additional weight of the sensing apparatus results in a slight imbalance and in additional friction so that the manufacturer’s tuning is no longer valid. Thus, the unit is operated primarily at these two rates but with additional values observed due to various perturbations present (e.g., friction). The reference rotational rates (or simple angular velocities) are found from the encoder data by measuring the elapsed interval time, $t_e$, between one encoder unit (i.e., one transparent and opaque patch). This gives in radians:

$$\dot{\theta}_{\text{reference}} = \frac{2\pi}{C \cdot t_e}$$

and in degrees:

$$\dot{\theta}_{\text{reference}} = \frac{360^\circ}{C \cdot t_e}$$

where $C$ is the total number of encoder units on the disk ($C = 1000$ for this setup). Quadrature is treated as an increase in this count. This definition does introduce the possibility of a digitization error as the encoder signal measurement is synchronized with the sensor readings, but not necessarily the
Fig. 6. The gyroscope calibration has the sensor was placed level with the platen surface of an instrumented turntable. Simultaneous measurements were recorded by the data acquisition PC, which was controlled using an external laptop rising and falling edge of the encoder pulse train. With this particular setup, the highest speed will result in 750 encoder units per second, which is near the sampling rate. Under these conditions, the maximum error for a single particular measurement is 10%. This is treated through the use of a moving average as this error only effects instantaneous measurements not the average. An alternative solution is to use a data acquisition system providing for simultaneous readings of multiple channels (i.e., non-multiplexed) and data types (i.e., digital and analog sources).

The sensitivity of the gyros is found via least squares techniques. In order to encode direction (i.e., rotational sense) the output of the gyros is biased to a half of the input voltage (i.e., nominally 2.5 V). For simplicity the term $V_{R}$ is introduced to represent this voltage. In the case of the Silicon Sensing CRS 3-11 gyros this is given by:

$$V_{CRS}^R \equiv \frac{5}{2} \left[ \frac{2V_o - V_s}{V_s} \right]$$  \hspace{1cm} (11)

where $V_o$ is the output and $V_s$ is the supply voltage. Thus the rate output of the gyros, which is given in Equation (11) becomes:

$$\text{RATE} \cdot S = V_{CRS}^R$$  \hspace{1cm} (12)

where the sensitivity ($S$) is given in units relative to that of the rate (typically $\frac{\text{Volts}}{\text{sec}}$).

The sensitivity maybe found directly by solving Eq. (12) directly with:

$$S = \frac{V_R}{\text{RATE}}$$  \hspace{1cm} (13)

Fig. 7. Average sensitivity found by application of Eq. (13). The mean sensitivity is shown as a dashed line. Negative value since reference sensor is CW positive (shown for the roll axis).

An alternative solution is to apply a least squares estimate between the reference value and the measured signal (as $V_R$). This approach has the advantage of reducing the computation by providing a least-squares value for the sensitivity and accounts for minor biases present in the transduction of the signal. It does, however, assume that the noise is symmetric and thus may be colored by outliers. For the sensors under consideration the difference in sensitivities by both methods is typically less than 1%. A result of this calculation is given in Fig. 8.

Fig. 8. Least-squares sensitivity estimate (for the roll axis)
IV. Example Calibration Results

The calibration procedure was applied to the aforementioned Sensor Cube (see also Fig. 1). The result of the calibration process is a series of transducer coefficients. A tabulation for the accelerometers is give in Table I. A similar tabulation of the values for the three primary (Silicon Sensing) gyros and an average value for the secondary (Analog Devices) gyros on the sensor cube is given in Table II.

<table>
<thead>
<tr>
<th>Accelerometer</th>
<th>Sensitivity (mV/g)</th>
<th>Deviation (mils/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2g Unit</td>
<td>Calibration 650</td>
<td>Reference 660</td>
</tr>
<tr>
<td>10g Unit</td>
<td>97</td>
<td>100</td>
</tr>
</tbody>
</table>

**TABLE I**
Sensor Cube Accelerometer Calibration Values

<table>
<thead>
<tr>
<th>Axis</th>
<th>Sensitivity (mV/°/sec)</th>
<th>Deviation (°/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Calibration</td>
<td>Reference</td>
</tr>
<tr>
<td>Pitch</td>
<td>3.61</td>
<td>3.49</td>
</tr>
<tr>
<td>Roll</td>
<td>3.67</td>
<td>3.49</td>
</tr>
<tr>
<td>Yaw</td>
<td>3.71</td>
<td>3.49</td>
</tr>
<tr>
<td>Backup</td>
<td>5.19</td>
<td>5.00</td>
</tr>
</tbody>
</table>

**TABLE II**
Sensor Cube Gyroscope Calibration Values

![Graph](image)

Fig. 9. Overlaying the measurement based on the calibrated model and the reference values shows that sensor transduction is generally linear. For comparison, calculation based on the default sensitivity is included.

V. Conclusions

A calibration procedure is presented for MEMS IMUs based on techniques for resonator characterization. By using a driven, but not necessarily precision controlled, shaker and Laser Doppler Vibrometer it is possible to calibrate an custom inertial suite at a variety of dynamic modes. Processing can be performed at the bench using a vector signal analyzer, or off-line using a digital signal processing software. While the equipment used is not common in robotics laboratory circles, it is available in MEMS and clean-room characterization facilities.

Future work is considering means of relating on-line estimated to the calibrated values. Thus calibration from one unit can be used to qualify additional units on the mobile robot. Future work is also considering a simpler means of traceable calibration for the accelerometers as MEMS characterization equipment, while available in university clean-rooms and MEMS research, is too specialized for general robotics laboratories.

VI. Acknowledgments

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References