InvenSense In-Use Calibrations

PURPOSE AND SCOPE

With the increase in Motion Interface application-enabled handsets, tablets, wearable sensors and other consumer electronic devices, it is very important to provide accurate sensor fusion data to applications. This can be achieved if there is minimal bias on the individual motion sensors, i.e. gyroscopes, accelerometers and magnetometers.

InvenSense implements several proprietary calibration algorithms in their DMP enabled devices and also software Motion Processing Libraries to dramatically improve the accelerometer, gyroscope, and magnetometer data used for Sensor Fusion processing. The algorithms are provided to customers in binary code format, which requires to be manually enabled in the code, or as part of the DMP downloadable image in the InvenSense software. The algorithms are enabled to run at all times in the background.

This application note focuses on the gyroscope and accelerometer and shows how InvenSense software helps to reduce the biases on these sensors. InvenSense parts and software which this application applies to are MPU6050/MPU65xx/MPU9150/MPU9250/ICM206xx.

GYROSCOPE IN-USE CALIBRATION

An inherent issue to resolve in all gyroscopes is the natural drift in data due to no points of reference. Gyros left on its own will naturally drift and change due to noise, package stress, and temperature. InvenSense implemented two in-use algorithms, gyro temperature compensation and gyro motion/no motion calibration, to increase the gyro data accuracy by compensating for the gyro biases.

GYRO MOTION/NO MOTION CALIBRATION

InvenSense In-Use Gyro Motion/No Motion Calibration calculates the gyro biases whenever a motion to no motion event is triggered and removes the biases from the gyro data. When the device is in no motion, the expected value in the gyro data is 0 dps (degrees per second) on each axis. Therefore whatever gyro measurements are sampled during a no motion state is considered the bias offsets. The bias offsets are calculated on each gyro axis and then removed from the gyro raw data to be feed into the sensor fusion calculations.

Motion to No Motion Event

A motion to no motion event is required to trigger the gyro calibration algorithm. High level requirements need to be met before determining whether a no motion event occurred.

- A motion and no motion state are based on the several consecutive samples of data from the accelerometer and gyroscope for 6-axis solutions, and accel, gyro, and mag for 9-axis solutions.
- The minimums and maximums of the samples are calculated for each axis of each sensors and compared to a set threshold value within the algorithm
- If the delta between the max and min values exceeds the threshold the device is considered in a motion state, if the delta is under the threshold the device is considered in a no motion state
- Only when a motion state to a no motion state occurs will the algorithm be triggered to run and executed once
- A change in state can be detected within milliseconds depending on Output Data Rate

Some real world examples of how a no motion event is triggered are when the device is picked up and then put down on the table. Typically a no motion will not be triggered if the device is in the customers hand or worn on the body.

Calibration Calculations

When the calibration is triggered the bias value calculations are based on the following

- The device is in a no motion state which means the expected values for each gyro axis ideally would be 0 dps.
- Several samples of each axis are read and average
- Averaged samples are applied to previous biases(if applicable) to result in the new bias for that axis

- New biases are applied and saved to the raw gyro sensor data

Total typical timeframe for in-use calculations is 400ms.

Expected Results

Improvements on the gyro biases are expected every time when an in-use calibration is triggered. The following example data was recorded from an ICM206xx device in a No Motion State using the InvenSense software after the gyro in-use motion/no motion calibration triggered in the DMP.

```
-- enabled printing on screen          Gyro X      Gyro Y          Gyro Z
## enabling 'MPL Raw Gyroscope' @ 5 Hz (200 ms)
DATALOG MPL Raw Gyroscope   ,  +0.017044,  +0.035154,  -0.01278317356204294286,
DATALOG MPL Raw Gyroscope   ,  +0.006392,  +0.037284,  -0.02556617356398568189,
DATALOG MPL Raw Gyroscope   ,  +0.013848,  +0.031958,  -0.01065317356592888322,
DATALOG MPL Raw Gyroscope   ,  +0.003196,  +0.023436,  -0.02663217356787205846,
DATALOG MPL Raw Gyroscope   ,  +0.014914,  +0.025566,  -0.02876217356981537091,
DATALOG MPL Raw Gyroscope   ,  +0.012783,  +0.010653,  -0.02663217357175864630,
DATALOG MPL Raw Gyroscope   ,  +0.024501,  +0.019175,  -0.01704417357370185573,
DATALOG MPL Raw Gyroscope   ,  +0.011718,  +0.017044,  -0.02237117357564510817,
DATALOG MPL Raw Gyroscope   ,  +0.026632,  +0.012783,  -0.01384817357758833836,
DATALOG MPL Raw Gyroscope   ,  +0.028762,  +0.023436,  -0.01278317357953159388,
DATALOG MPL Raw Gyroscope   ,  +0.013848,  +0.019175,  -0.02343617358147489334,
DATALOG MPL Raw Gyroscope   ,  +0.021305,  +0.013848,  -0.02343617358341806732,
DATALOG MPL Raw Gyroscope   ,  +0.027697,  +0.021305,  -0.01171817358536133658,
```

Un-calibrated Averaged –

X = .017126154 dps
Y = .02370538 dps
Z = -.019666635 dps

```
-- enabled printing on screen
## enabling 'MPL Gyroscope' @ 5 Hz (200 ms)
DATALOG MPL Gyroscope   ,  +0.005376,  +0.010544,  +0.00521017287714916649,
DATALOG MPL Gyroscope   ,  +0.005376,  -0.011826,  -0.00011717287909241192,
DATALOG MPL Gyroscope   ,  +0.012833,  +0.007348,  -0.00331217288103568029,
DATALOG MPL Gyroscope   ,  +0.014964,  -0.003304,  +0.00627517288297892145,
DATALOG MPL Gyroscope   ,  +0.010702,  -0.009696,  +0.00201417288492215859,
DATALOG MPL Gyroscope   ,  -0.006342,  +0.000957,  +0.00734017288686539783,
DATALOG MPL Gyroscope   ,  +0.006441,  +0.005218,  +0.00947117288880865129,
DATALOG MPL Gyroscope   ,  +0.007507,  +0.011610,  +0.00201417289075194381,
DATALOG MPL Gyroscope   ,  -0.004211,  +0.004153,  +0.00734017289269517708,
DATALOG MPL Gyroscope   ,  -0.003146,  -0.001174,  +0.00734017289463840692,
DATALOG MPL Gyroscope   ,  +0.010702,  +0.005218,  +0.00734017289658164887,
```

Calibrated Average –

X = .005472909 dps
Y = .001731636 dps
Z = .004628746 dps

Customers should expect an increase in accuracy from a gyro motion/no motion calibration. Typical data retrieved after a calibration from a no motion device depends on noise and assembly factors but customers should expect the calibrated data to read less than .5 dps on each axis.

GYRO TEMPERATURE COMPENSATION

In addition to the motion/no motion gyro calibration, InvenSense implemented an in-use temperature compensation for gyro which runs in parallel with the motion/no motion algorithm. Gyro offsets are susceptible to small variations of change depending on the internal package temperature. The Gyro Temp Comp will build a temperature slope over time and compensate for the offset variations while the gyro is in a motion state. Some things to keep in mind are

- Gyro Temp Comp works mainly within the spec temperature range of the InvenSense device, typically -40 degrees Celsius to 85 degrees Celsius.
- A temperature slope is built over time and requires several data points from a motion to no motion calibration
- Gyro Temp Comp will compensate for motion data, when a device is in no motion the data will not need to be compensated

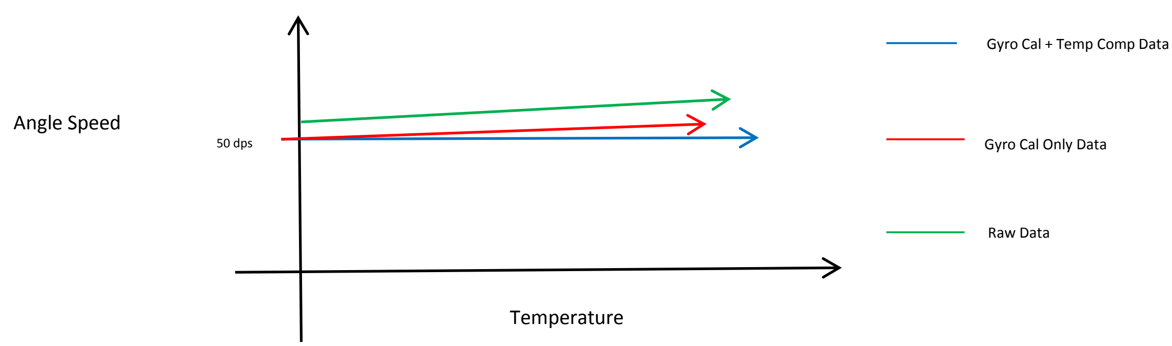
Building and Applying the Temperature Slope

On a new device, the temperature slope will need to be built. The Gyro Temp Comp algorithm is designed to build and continuously modify the temperature slope through normal usage of the device. To build the slope, the Gyro Temp Comp requires the following

- At least 2 motion to motion calibration events with the internal temperatures at minimum degree apart between the 2 calibration events (example - 5 degrees difference between first no motion cal to the second no motion cal)
- Temp Comp algorithm will take the delta between the 2 bias calculations from the no motion cal and build a temperature slope
- Each gyro axis will have its own temperature slope
- More data points will build a better temperature slope
- As the device is moving, the gyro biases will change along with the temperature changes and removed from the gyro raw data

Expected Results

The expected results of the gyro temp comp is that in a device which is constantly moving while the temperature fluctuates the accuracy will improve. For example in a device in which the gyro is moving at 50 dps constantly and the temperatures increases



The combined result of the motion/no motion calibration plus the temperature compensation will give you the most accurate data.

ACCELEROMETER IN-USE CALIBRATION

The biases on the 3-axes accelerometer could shift over the lifetime of the device. This shift, for example, could result into settling artifacts in gaming and other such applications, as well as inaccurate magnetometer tilt compensation, which adversely affects compass heading accuracy. Therefore, it is important to compensate for accelerometer biases over time.

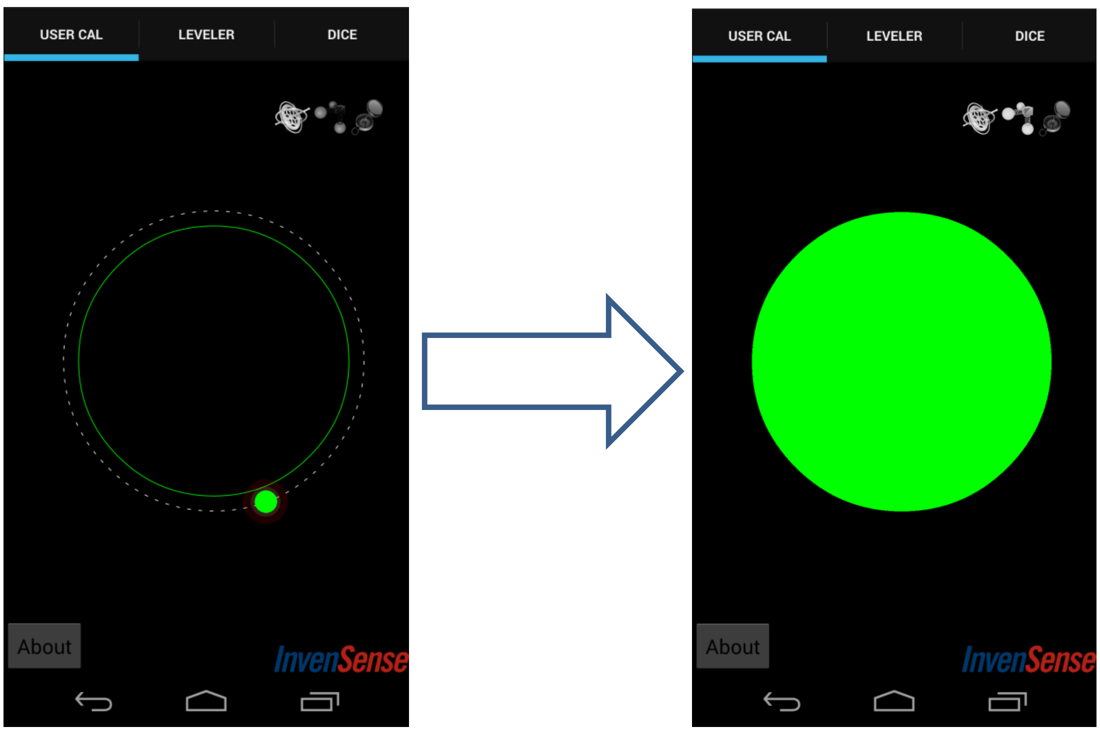
USAGE

This in-use calibration algorithm observes user motion over time. Like the temp comp, it requires a certain set of data before building the bias model and corrects the accelerometer bias. Data samples are recorded over normal usage. To build the bias model of the accelerometer, the following requirements need to be met

- Device needs 3 different orientation data

- The orientation data needs the device to be relatively stable for a small duration of time. The device can still be in held or worn and does not need to be set down.

Two examples of activities that typically provide this motion are: (i) a user changing screen orientation to go from portrait to landscape or vice versa, (ii) answering an incoming call by taking the handset out of the pocket. For Android software, InvenSense provides a sample APK which helps users to orient to 3 different directions and displays when the in-use calibration biases are found. This example APK is not necessary for the in-use accel calibration but helps speed up the process to find the bias.



Note that this algorithm is not meant to replace factory calibration of the accelerometer which is useful for a good first time out-of-the-box experience.

CALCULATIONS

The calculations for the in-use accel biases are based on stable data and linear acceleration calculations. Linear acceleration is a calculation of the acceleration of the device without the effects of gravity. When the device is held stable the linear acceleration is expected to be ideally 0. Therefore any biases sampled during that time would be considered the bias. Here are the criteria's for the in-use acceleration calculations

- Device needs to be oriented in 3 different orientations
- Several samples of data needs to be measured on each stable orientation
- Average of the data is used to calculate the linear acceleration for each accelerometer's axis
- The readings on each axis is measured against the previous biases to determine if data is valid
- Once all 3 axis biases is determined, new biases are applied to raw accel data
- Accel will constantly be monitored for changes to the biases and will be modified accordingly

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EXPECTED RESULTS

The accel in-use calibration requires 3 stable orientations but does not require it to be completely motionless like in a fixture or to be set down on a table. Expected results of the offset compensated data to be within 35mg of ideal data.

Here is an example of the results from an ICM206xx device before and after running the in-use accel calibration on the DMP. The readings are pulled when device is set still with ideal data as 0, 0, and 9.8 m/s^2.

-- enabled printing on screen		Accel X	Accel Y	Accel Z
## enabling 'MPL Accelerometer' @ 5 Hz (200 ms)				
DATALOG MPL Accelerometer	,	+0.000000,	-0.368707,	+9.55286543456246481,
DATALOG MPL Accelerometer	,	-0.028730,	-0.239420,	+9.37090643651943032,
DATALOG MPL Accelerometer	,	-0.009577,	-0.306458,	+9.55765343847639237,
DATALOG MPL Accelerometer	,	-0.028730,	-0.306458,	+9.46667444239208538,
DATALOG MPL Accelerometer	,	-0.019154,	-0.359130,	+9.34696444434841324,
DATALOG MPL Accelerometer	,	+0.095768,	-0.282516,	+9.30865644630474762,
DATALOG MPL Accelerometer	,	+0.038307,	-0.325611,	+9.49061644826117689,
DATALOG MPL Accelerometer	,	-0.004788,	-0.320823,	+9.33259945021740176,
DATALOG MPL Accelerometer	,	+0.047884,	-0.387861,	+9.52413545217380602,
DATALOG MPL Accelerometer	,	-0.043096,	-0.215478,	+9.66778745412910771,
DATALOG MPL Accelerometer	,	-0.067038,	-0.296881,	+9.51934645608588149,

Accel Raw Data Average –

X = -.001741273 m/s^2
Y = -.309940273 m/s^2
Z = 9.467109628 m/s^2

-- enabled printing on screen				
## enabling 'MPL Accelerometer' @ 5 Hz (200 ms)				
DATALOG MPL Accelerometer	,	-0.029928,	-0.154127,	+9.86650619383617939632,
DATALOG MPL Accelerometer	,	-0.053870,	-0.125396,	+9.80904519383813780856,
DATALOG MPL Accelerometer	,	-0.058658,	-0.087089,	+9.78031319384009657763,
DATALOG MPL Accelerometer	,	-0.092177,	+0.032621,	+9.71806419384205481209,
DATALOG MPL Accelerometer	,	-0.092177,	-0.010475,	+9.88565919384401340183,
DATALOG MPL Accelerometer	,	+0.037110,	-0.015263,	+9.69891119384793078778,
DATALOG MPL Accelerometer	,	-0.178368,	-0.077512,	+9.74679519384988945867,
DATALOG MPL Accelerometer	,	-0.207098,	-0.082301,	+9.81383319385184809843,
DATALOG MPL Accelerometer	,	-0.073023,	-0.082301,	+9.81383319385380661907,
DATALOG MPL Accelerometer	,	-0.077812,	+0.003891,	+9.70369919385576534835,
DATALOG MPL Accelerometer	,	-0.010774,	-0.072724,	+9.75158319385772400964,
DATALOG MPL Accelerometer	,	-0.192733,	-0.096666,	+9.78510219385968260423,
DATALOG MPL Accelerometer	,	-0.001197,	-0.139762,	+9.68933419386359948583,
DATALOG MPL Accelerometer	,	-0.077812,	-0.082301,	+9.84735219386555804945,

Accel Data (after in-use cal) Average –

X = -.079179786 m/s^2
Y = -.070671786 m/s^2
Z = 9.77928798 m/s^2

REVISION HISTORY

REVISION DATE	REVISION	DESCRIPTION
10/12/2016	x.x	Initial Draft

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