MPU-9250 Accelerometer, Gyroscope and Compass Self-Test Implementation

Revision History

Revision Date	Revision	Description
5/30/2013	1.0	Initial release

CONTENTS

1. Purpose

This document explains the gyroscope, accelerometer and compass Self-Test implementation for the MPU-9250.

2. Self-Test Concept

Gyroscope and accelerometer Self-Test enables customers to perform a functional test of the mechanical and electrical integrity of InvenSense sensors without requiring physical device movement.

When the Self-Test is activated, on-board electronics actuate the MEMS device. This actuation moves the sensor masses equivalent to a pre-defined motion. This proof mass displacement results in a change of sensor output and is reflected in the output signal.

A customer runs Self-Test software in their factory and compares the output value against the value stored on chip during InvenSense's component production test. If the customer's gyroscope Self-Test response is >50% of the the value stored on chip during InvenSense product test, and the customer's accelerometer Self-Test response is between 50% and 150% of the value stored on chip during InvenSense product test, then Self-Test has passed and the component is deemed functional.

Passing Self-Test limits were derived by comparing the Self-Test results of 90k MPU-6500 parts against the values stored during production component testing. The MPU-6500 die is used within the MPU-9250 as the gyroscope and accelerometer. The results are shown in the table below.

Gyroscope Delta			
Axis	Average Δ (%)	Standard Deviation (%)	5σ (%)
X	0.37	0.39	2.3
Y	0.37	0.65	3.6
Z	0.11	0.31	1.7
Accelerometer Delta			
Axis	Average Δ (%)	Standard Deviation (%)	5σ (%)
X	0.027	0.48	2.4
Y	0.015	0.57	2.9
Z	0.02	0.46	2.3

For the gyroscope the highest delta is 3.6%. Additionally, the MPU-9250 product spec has gyro ZRO of ±20dps min/max, which at an FSR of 250dps results in an additional 8% deviation. After these two contributors, 38.4% of margin is available to account for noise, unintended movements, and other unwanted offsets created on the customer's production line. With 250dps FSR (the FSR used during self-test), the 50% limit results in 96dps of margin that is available after accounting for the standard deviation and ZRO.

Similarly for the accelerometer, the highest delta for the X/Y axis is 2.9%. The MPU-9250 product specification has a board-level X/Y accelerometer offset of ±120mg, which at an FSR of 2g (the FSR used during self-test) results in an additional 6% deviation. After these two contributors, 41.1% to 141.1% is available to account for noise, unintended movements and other unwanted offsets created on the customer's production line. With 2g FSR, the 50% to 150% limit results in 0.82g of margin available after accounting for the standard deviation and accelerometer offset.

InvenSense does not expect that noise and other unintended movements on the customer's production line will exceed these margins, making the Self-Test procedure robust.

In greater detail, the gyroscope Self-Test response (STR) is defined as follows:

$$Self\text{-}Test\ \ Response =$$
$$Gyroscope\ Output\ with\ Self\text{-}Test\ Enabled - Gyroscope\ Output\ with\ Self\text{-}Test\ Disabled$$

This Self-Test-response is used to determine whether the part has passed or failed Self-Test by finding the change from factory trim of the Self-Test response as follows:

$$Change\ from\ Factory\ Trim\ of\ the\ Self\text{-}Test\ Response(\%) = \frac{(STR - FT)}{FT}$$

where,

$$FT = Factory\ Trim\ Value\ of\ Self\text{-}Test\ \ Response$$

This change from factory trim of the Self-Test response must be within the limits provided in section 3 of this document for the part to pass Self-Test. Otherwise, the part is deemed to have failed Self-Test.

Similarly, when the accelerometer's Self-Test is activated, the on-board electronics will actuate the appropriate sensor. This actuation simulates an external force. The actuated sensor, in turn, will produce a corresponding output signal.

The Self-Test response (STR) is defined as follows:

$$\begin{aligned} Self\text{-}Test\ \ Response \\ &= Accelerometer\ Output\ with\ Self\text{-}Test\ Enabled \\ &- Accelerometer\ Output\ with\ Self\text{-}Test\ Disabled \end{aligned}$$

This Self-Test-response is used to determine whether the part has passed or failed Self-Test by finding the change from factory trim of the Self-Test response as follows:

$$Change\ from\ Factory\ Trim\ of\ the\ Self\text{-}Test\ Response(\%) = \frac{(STR - FT)}{FT}$$

where,

$$FT = Factory\ Trim\ Value\ of\ Self\text{-}Test\ \ Response$$

This change from factory trim of the Self-Test response must be within the limits shown in section 3 of this document for the part to pass Self-Test. Otherwise, the part is deemed to have failed accelerometer Self-Test.

Code for operating Self-Test is included within the MotionApps™ software provided by InvenSense. The software routine starts by measuring the digital output of the 3 gyroscopes and records them as GX_OS, GY_OS, and GZ_OS.

In order to enable the Self-Test mode for all gyroscopes, first the SW measures the digital output of each gyroscope and records them as GX_ST_OS, GY_ST_OS, and GZ_ST_OS. The Self-Test values are then reported as:

- GXST = GX_ST_OS - GX_OS
- GYST = GY_ST_OS - GY_OS
- GZST = GZ_ST_OS - GZ_OS

Similarly for the accelerometer, the reported Self-Test values are:

- AXST = AX_ST_OS - AX_OS
- AYST = AY_ST_OS - AY_OS
- AZST = AZ_ST_OS - AZ_OS

In compass Self-Test mode, a magnetic field is generated by an internal magnetic source. The compass then measures the field and compares it to a Self-Test measurement that was done at the factory. If the comparison is within the values shown in section 4.1, then the Self-Test is deemed to have passed. If Self-Test does not pass, the device is deemed to be defective.

3. Gyroscope/Accelerometer Self-Test Detailed Procedure

The rotation of the component being tested should vary less than 5 degrees during the Self-Test measurement. The device will fail gyroscope Self-Test if it rotates by more than ±2.5 deg during the test. A good part would however pass gyro Self-Test if it experiences a constant rotation during the two measurements.

Similarly, in order to maintain accuracy during the accelerometer Self-Test, changes in linear velocity should be less than 0.2m/s and changes in tilt angle should be less than 6 degree during the measurement.

The specific steps implemented in InvenSense's Self-Test software are:

1) The routine starts by measuring the digital output of all three gyroscopes. In order to do this, the following registers are modified:

   Gyroscope: Change the digital low pass filter (DLPF) code to 2 (Register Address: 26 (1Ah) Bit [2:0] – USR). The following table details the configuration of the component when the DLPF is configured to 2.

DLPF Config	LPF BW	Sampling Rate	Filter Delay
2	**92Hz**	**1kHz**	**3.9ms**

   Accelerometer: Change the DLPF Code to 2 (Register Address: 29 (1Dh) Bit [2:0] – USR). The following table details the configuration of the component when the DLPF is configured to 2.

DLPF Config	LPF BW	Sampling Rate	Filter Delay
2	**92Hz**	**1kHz**	**7.8ms**

   Gyroscope: Store the existing full scale range select code (Register Address: 27 (1Bh) Bit [4:3] – USR) as Old_FS, then select a full scale range of 250dps by setting the ACCEL_FS_SEL bits to 00.

   Accelerometer: Store the existing full scale range select code (Register Address: 28 (1Ch) Bit [4:3] – USR) as Old_FS, then select a full scale range of ±2g by setting the ACCEL_FS_SEL bits to 00.

2) Read the gyroscope and accelerometer output at a 1kHz rate and average 200 readings. The averaged values will be the LSB of GX_OS, GY_OS, GZ_OS, AX_OS, AY_OS and AZ_OS in the software.

3) Set USR_Reg: (1Bh) Gyro_Config, gdrive_axisCTST [0-2] to b111 to enable Self-Test.

   Set USR_Reg: (1Ch) Accel_Config, AX/Y/Z_ST_EN [0-2] to b111 to enable Self-Test.

4) Wait 20ms for oscillations to stabilize

5) Read the gyroscope and accelerometer output at a 1kHz rate and average 200 readings. The averaged values will be the LSB of GX_ST_OS, GY_ST_OS, GZ_ST_OS, AX_ST_OS, AY_ST_OS and AZ_ST_OS in the software.

6) Calculate the Self-Test response as follows:

- GXST = GX_ST_OS - GX_OS
- GYST = GY_ST_OS - GY_OS
- GZST = GZ_ST_OS - GZ_OS
- AXST = AX_ST_OS - AX_OS
- AYST = AY_ST_OS - AY_OS
- AZST = AZ_ST_OS - AZ_OS

3.1. External Configuration Cleanup

To cleanup the configuration after the test:

1) Set USR_Reg: (1Bh) Gyro_Config, gdrive_axisCTST [0-2] to b000.

   Set USR_Reg: (1Ch) Accel_Config, AX/Y/Z_ST_EN [0-2] to b000.
2) Wait 20ms.
3) Restore previous FS code (Old_FS).

3.2. Self-Test Pass/Fail Criteria

1) Retrieve factory Self-Test code (ST_Code) from USR_Reg in the software:
   - X-gyro: selftest1 (00): xg_st_data [0-7]
   - Y-gyro: selftest1 (01): yg_st_data [0-7]
   - Z-gyro: selftest1 (02): zg_st_data [0-7]
   - X-Accel: selftest1 (0D): xa_st_data [0-7]
   - Y-Accel: selftest1 (0E): ya_st_data [0-7]
   - Z-Accel: selftest1 (0F): za_st_data [0-7]
2) Calculate factory Self-Test value (ST_OTP) based on the following equation:

   The ST_Code is based on the Self-Test value (ST_ FAC) determined in InvenSense's factory final test and calculated based on the following equation

$$ST\_code = round\left(\frac{\log(ST\_FAC/(2620/2^{FS}))}{\log(1.01)}\right)+1$$

   The factory Self-Test value (ST_OTP) is calculated based on ST_Code and is calculated based on the following equation, where "FS" is the full scale value:

$$ST\_OTP = (2620/2^{FS})*1.01^{(ST\_code-1)}\ \text{(lsb)}$$

   ST_OTP is then the value that is stored in OTP of the device.
3) Determine passing or failing Self-Test

   a. If factory Self-Test values ST_OTP≠0, compare the current Self-Test response (GXST, GYST, GZST, AXST, AYST and AZST) to the factory Self-Test values (ST_OTP) and report Self-Test is passing if all the following criteria are fulfilled:

Axis	Pass criteria
X-gyro	(GXST / GXST_OTP) > 0.5
Y-gyro	(GYST / GYST_OTP) > 0.5

Z-gyro	(GZST / GZST_OTP) > 0.5
X-Accel	0.5 < (AXST / AXST_OTP) < 1.5
Y-Accel	0.5 < (AYST / AYST_OTP) < 1.5
Z-Accel	0.5 < (AZST / AZST_OTP) < 1.5

b. If factory Self-Test values ST_OTP=0, compare the current Self-Test response (GXST, GYST, GZST, AXST, AYST and AZST) to the ST absolute limits (ST_AL) and report Self-Test is passing if all the following criteria are fulfilled.

Axis	Pass criteria
X-gyro	|GXST| ≥ 60dps
Y-gyro	|GYST| ≥ 60dps
Z-gyro	|GZST| ≥ 60dps
X-Accel	225mgee ≤ |AXST| ≤ 675mgee
Y-Accel	225mgee ≤ |AXST| ≤ 675mgee
Z-Accel	225mgee ≤ |AXST| ≤ 675mgee

c. If the Self-Test passes criteria (a) and (b), it's necessary to check gyro offset values. Report passing Self-Test if the following criteria fulfilled.

Axis	Pass criteria
X-gyro	|GXOFFSET| ≤ 20dps
Y-gyro	|GYOFFSET| ≤ 20dps
Z-gyro	|GZOFFSET| ≤ 20dps

4. Compass Detailed Self-Test Procedure

The specific steps required to implement compass Self-Test are:

1. Set the compass into power-down mode.
2. Write "1" to the SELF bit of the ASTC register. Other bits in this register should be set to zero.
3. Set the self test mode in the "Mode" register.
4. Check if data is ready or not by polling the DRDY bit of the ST1 register. When the data is ready, proceed to step 5.
5. Read the measurement data in the compass measurement data registers.
6. Write "0" to SELF bit of the ASTC register.
7. Set the compass to power-down mode.

4.1. Set Pass/Fail Criteria

When measurement data read by the above sequence is in the range of following tables after sensitivity adjustment (refer to the ASAX, ASAY, ASAZ: Sensitivity Adjustment values register) the Self-Test is deemed to have passed.

14-bit Mode

	HX[15:0]	HY[15:0]	HZ[15:0]
Criteria	$-50 \leq HX \leq 50$	$-50 \leq HY \leq 50$	$-800 \leq HZ \leq -200$

16-bit Mode

	HX[15:0]	HY[15:0]	HZ[15:0]
Criteria	$-200 \leq HX \leq 200$	$-200 \leq HY \leq 200$	$-3200 \leq HZ \leq -800$

5. Self-Test Register Definitions

Below are the definitions for all registers related to Self-Test.

5.1. Registers 0 to 2 – Gyroscope Self-Test Registers

Serial IF: R/W

Reset value: 0x00

Register	BIT	NAME	FUNCTION
0	[7:0]	xg_st_data	The value in this register is loaded via OTP to indicate the Self-Test output generated during manufacturing tests. This value is to be used to check against subsequent Self-Test outputs performed by the end user.
1	[7:0]	yg_st_data	The value in this register is loaded via OTP to indicate the Self-Test output generated during manufacturing tests. This value is to be used to check against subsequent Self-Test outputs performed by the end user.
2	[7:0]	zg_st_data	The value in this register is loaded via OTP to indicate the Self-Test output generated during manufacturing tests. This value is to be used to check against subsequent Self-Test outputs performed by the end user.

5.2. Registers 13 to 15 – Accelerometer Self-Test Registers

Serial IF: R/W

Reset value: 0x00

Register	BIT	NAME	FUNCTION
13	**[7:0]**	XA_ST_DATA[7:0]	Contains Self-Test data for the X Accelerometer
14	**[7:0]**	YA_ST_DATA[7:0]	Contains Self-Test data for the Y Accelerometer

15	**[7:0]**	ZA_ST_DATA[7:0]	Contains Self-Test data for the Z Accelerometer

5.3. Register 26 – Configuration

<table>
<tr><th>BIT</th><th>NAME</th><th>FUNCTION</th></tr>
<tr><td>[7]</td><td>Reserved</td><td></td></tr>
<tr><td>[6]</td><td>FIFO_MODE</td><td>When set to ‘1’, when the fifo is full, additional writes will not be written to fifo. When set to ‘0’, when the fifo is full, additional writes will be written to the fifo, replacing the oldest data.</td></tr>
<tr><td>[5:3]</td><td>EXT_SYNC_SET[2:0]</td><td>Enables the FSYNC pin data to be sampled.
<table>
<tr><th>EXT_SYNC_SET</th><th>FSYNC bit location</th></tr>
<tr><td>0</td><td>function disabled</td></tr>
<tr><td>1</td><td>TEMP_OUT_L[0]</td></tr>
<tr><td>2</td><td>GYRO_XOUT_L[0]</td></tr>
<tr><td>3</td><td>GYRO_YOUT_L[0]</td></tr>
<tr><td>4</td><td>GYRO_ZOUT_L[0]</td></tr>
<tr><td>5</td><td>ACCEL_XOUT_L[0]</td></tr>
<tr><td>6</td><td>ACCEL_YOUT_L[0]</td></tr>
<tr><td>7</td><td>ACCEL_ZOUT_L[0]</td></tr>
</table>
Fsync will be latched to capture short strobes. This will be done such that if Fsync toggles, the latched value toggles, but won’t toggle again until the new latched value is captured by the sample rate strobe. This is a requirement for working with some 3rd party devices that have fsync strobes shorter than our sample rate.</td></tr>
<tr><td>[2:0]</td><td>DLPF_CFG[2:0]</td><td>For the DLPF to be used, fchoice[1:0] must be set to 2’b11, fchoice_b[1:0] is 2’b00.

See the table below.</td></tr>
</table>

The DLPF is configured by *DLPF_CFG,* when *FCHOICE_B* [1:0] = 2b’00. The gyroscope and temperature sensor are filtered according to the value of *DLPF_CFG* and *FCHOICE_B* as shown in the table below. Note that FCHOICE mentioned in the table below is the inverted value of *FCHOICE_B* (e.g. FCHOICE=2b’00 is same as FCHOICE_B=2b’11).

FCHOICE		DLPF_CFG	Gyroscope			Temperature Sensor	
<1>	<0>		Bandwidth	Delay	Fs (kHz)	Bandwidth	Delay

			(Hz)	(ms)		(Hz)	(ms)
x	0	x	8800	0.064	32	4000	0.04
0	1	x	3600	0.11	32	4000	0.04
1	1	0	250	0.97	8	4000	0.04
1	1	1	184	2.9	1	188	1.9
1	1	2	92	3.9	1	98	2.8
1	1	3	41	5.9	1	42	4.8
1	1	4	20	9.9	1	20	8.3
1	1	5	10	17.85	1	10	13.4
1	1	6	5	33.48	1	5	18.6
1	1	7	3600	0.17	8	4000	0.04

5.4. Register 27 – Gyroscope Configuration

Serial IF: R/W

Reset value: 0x00

BIT	NAME	FUNCTION
[7]	XGYRO_Cten	X Gyro Self-Test
[6]	YGYRO_Cten	Y Gyro Self-Test
[5]	ZGYRO_Cten	Z Gyro Self-Test
[4:3]	GYRO_FS_SEL[1:0]	Gyro Full Scale Select: 00 = ±250dps 01= ±500dps 10 = ±1000dps 11 = ±2000dps
[2]	-	Reserved
[1:0]	Fchoice_b[1:0]	Used to bypass DLPF.

5.5. Register 28 – Accelerometer Configuration

Serial IF: R/W

Reset value: 0x00

BIT	NAME	FUNCTION
[7]	ax_st_en	X Accel Self-Test
[6]	ay_st_en	Y Accel Self-Test
[5]	az_st_en	Z Accel Self-Test

BIT	NAME	FUNCTION
[7]	ax_st_en	X Accel Self-Test
[6]	ay_st_en	Y Accel Self-Test
[5]	az_st_en	Z Accel Self-Test
[4:3]	ACCEL_FS_SEL[1:0]	Accel Full Scale Select: ±2g (00), ±4g (01), ±8g (10), ±16g (11)
[2:0]	Reserved	

5.6. Register 29 – Accelerometer Configuration 2

Serial IF: R/W

Reset value: 0x00

BIT	NAME	FUNCTION
[7:6]	Reserved	
[5:4]	Reserved	
[3]	accel_fchoice_b	Used to bypass DLPF.
[2:0]	A_DLPFCFG	Accelerometer low pass filter setting as shown in section 3 above.

5.7. Compass ST1: Status 1

Addr	Register name	D7	D6	D5	D4	D3	D2	D1	D0
Read-only register									
02H	ST1	0	0	0	0	0	0	0	DRDY
Reset		0	0	0	0	0	0	0	0

DRDY: Data Ready

"0": Normal

"1": Data is ready

DRDY bit turns to “1” when data is ready in single measurement mode or Self-Test mode. It returns to “0” when any one of ST2 register or measurement data register (HXL to HZH) is read.

5.8. Compass HXL to HZH: Measurement Data

Addr	Register name	D7	D6	D5	D4	D3	D2	D1	D0
Read-only register									
03H	HXL	HX7	HX6	HX5	HX4	HX3	HX2	HX1	HX0
04H	HXH	HX15	HX14	HX13	HX12	HX11	HX10	HX9	HX8
05H	HYL	HY7	HY6	HY5	HY4	HY3	HY2	HY1	HY0
06H	HYH	HY15	HY14	HY13	HY12	HY11	HY10	HY9	HY8
07H	HZL	HZ7	HZ6	HZ5	HZ4	HZ3	HZ2	HZ1	HZ0
08H	HZH	HZ15	HZ14	HZ13	HZ12	HZ11	HZ10	HZ9	HZ8
Reset		0	0	0	0	0	0	0	0

Measurement data of magnetic sensor X-axis/Y-axis/Z-axis

HXL[7:0]: X-axis measurement data lower 8bit
HXH[15:8]: X-axis measurement data higher 8bit
HYL[7:0]: Y-axis measurement data lower 8bit
HYH[15:8]: Y-axis measurement data higher 8bit
HZL[7:0]: Z-axis measurement data lower 8bit
HZH[15:8]: Z-axis measurement data higher 8bit

Measurement data is stored in two's complement and Little Endian format. Measurement range of each axis is from -32760 ~ 32760 decimal in 16-bit output.

Measurement data (each axis) [15:0]			Magnetic flux density [μT]
Two's complement	Hex	Decimal	
0111 1111 1111 1000	7FF8	32760	4912(max.)
|	|	|	|
0000 0000 0000 0001	0001	1	0.15
0000 0000 0000 0000	0000	0	0
1111 1111 1111 1111	FFFF	-1	-0.15
|	|	|	|
1000 0000 0000 1000	8008	-32760	-4912(min.)

Table 1 Measurement data format

5.9. Compass CNTL1: Control 1

Addr	Register name	D7	D6	D5	D4	D3	D2	D1	D0
Read-only register									
0AH	CNTL1	0	0	0	BIT	MODE3	MODE2	MODE1	MODE0
Reset		0	0	0	0	0	0	0	0

MODE[3:0]: Operation mode setting

"0000": Power-down mode
"0001": Single measurement mode
"0010": Continuous measurement mode 1
"0110": Continuous measurement mode 2
"0100": External trigger measurement mode
"1000": Self-Test mode
"1111": Fuse ROM access mode
Other code settings are prohibited

BIT: Output bit setting

"0": 14-bit output
"1": 16-bit output

When each mode is set, AK8963 transits to set mode.

5.10. Compass ASTC: Self-Test Control

Addr	Register name	D7	D6	D5	D4	D3	D2	D1	D0
Write/read register									
0CH	ASTC	-	SELF	-	-	-	-	-	-
Reset		0	0	0	0	0	0	0	0

SELF: Self-Test control

"0": Normal

"1": Generate magnetic field for Self-Test

Do not write “1” to any bit other than SELF bit in ASTC register. If “1” is written to any bit other than SELF bit, normal measurement cannot be done.

5.11. Compass ASAX, ASAY, ASAZ: Sensitivity Adjustment values

Addr	Register name	D7	D6	D5	D4	D3	D2	D1	D0
Read-only register									
10H	ASAX	COEFX7	COEFX6	COEFX5	COEFX4	COEFX3	COEFX2	COEFX1	COEFX0
11H	ASAY	COEFY7	COEFY6	COEFY5	COEFY4	COEFY3	COEFY2	COEFY1	COEFY0
12H	ASAZ	COEFZ7	COEFZ6	COEFZ5	COEFZ4	COEFZ3	COEFZ2	COEFZ1	COEFZ0
Reset		-	-	-	-	-	-	-	-

Sensitivity adjustment data for each axis is stored to fuse ROM on shipment.

ASAX[7:0]: Magnetic sensor X-axis sensitivity adjustment value

ASAY[7:0]: Magnetic sensor Y-axis sensitivity adjustment value

ASAZ[7:0]: Magnetic sensor Z-axis sensitivity adjustment value

- Sensitivity Adjustment

The sensitivity adjustment is done by the equation below;

$$Hadj = H \times \left(\frac{(ASA - 128) \times 0.5}{128} + 1 \right),$$

where *H* is the measurement data read out from the measurement data register, *ASA* is the sensitivity adjustment value, and *Hadj* is the adjusted measurement data.