SENtral™

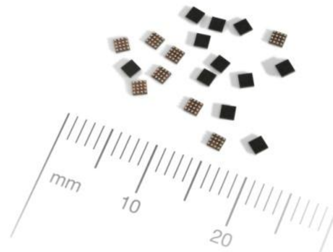
Motion Coprocessor

General Description

The SENtral™ Motion Coprocessor is a custom integrated circuit that makes it easy to quickly incorporate, optimize and operate multiple motion sensors on mobile consumer electronics devices. SENtral employs and manages a user-specified 3-axis magnetometer, 3–axis accelerometer, and 3–axis gyroscope to provide reliable motion tracking, and accurate heading and orientation data. SENtral gathers data from the individual sensors, then integrates and fuses this data using PNI's proprietary Kalman filtering and heuristic algorithms.

By offloading the sensor fusion and interface from a dedicated sensor hub MCU or the host CPU to SENtral, overall power requirements are dramatically lowered and processing power is opened up for other uses.

These advantages make SENtral the ideal choice for mobile and consumer electronics devices desiring ultra-lower power consumption and best-in-class sensor fusion.



Features

- Heading Accuracy of 2° rms.
- Ultra Low Power Consumption
- Continuous Soft and Hard-Iron Magnetic Auto-Calibration
- Magnetic Anomaly Compensation
- I^2C Interface – 100 to 3400 kHz
- Small Form-Factor
- Sensor Flexibility

Applications

- Cell Phones
- Tablets
- Ultrabooks
- TV Remote Controls
- Video Game Controllers

Ordering Information

Part #	Delivery Form
EM7180V1CS16B+	CSP on Tape & Reel 4K/Reel

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1 Product Overview

The SENtral™ Motion Coprocessor is an integrated circuit that makes it easy to quickly integrate, optimize and operate multiple sensors on mobile consumer electronics devices. SENtral manages and uses data from a user-specified 3-axis gyroscope, 3-axis accelerometer, and 3-axis magnetometer to provide reliable motion tracking and an accurate compass heading, while consuming about 1% of the power of a comparable sensor fusion microprocessor. The primary data output from SENtral are quaternions, which uniquely define device orientation, or Euler angles (heading, pitch, and roll). The quaternions easily can be converted to Euler angles, the rotation vector, and the rotation matrix (aka DCM), as discussed in Appendix I.

1.1 SENtral Features and Benefits

Features and benefits of the SENtral Motion Coprocessor include:

- **Low power consumption.** Offloads sensor processing from the less efficient host CPU, consuming <1% of the power of a Cortex M0 running a comparable sensor fusion algorithm. Provides the ability to tailor the tradeoff between power consumption and motion-tracking performance.
- **Industry-leading heading accuracy.** Unparalleled heading accuracy for consumer electronics applications.
- **Continuous hard and soft-iron magnetic auto-calibration.** Provides continual background calibration of the sensors. Leverages PNI's more than 20 years of experience and expertise in magnetic measurement.
- **Magnetic anomaly compensation.** Heading and motion tracking is unaffected by magnetic anomalies such as rebar in buildings, desks, speakers etc., that can easily throw off the accuracy. SENtral recognizes and compensates for these anomalies.
- **Sensor flexibility.** Works with the most common consumer electronic MEMS motion sensors, so system designers can choose the sensors most appropriate for their systems.
- **Small form-factor.** 1.6x1.6x0.5 mm chip-scale package on 0.4 mm pitch. Uses little PCB real estate, allowing for painless integration.
- **I^{2}C interface.** Uses the industry-standard I^{2}C protocol in a proprietary low-power implementation to interface to the sensors and the host, so system integration is straightforward. Standard, Fast, Fast Plus, and High Speed are supported on the host bus.
- **Outputs.** SENtral natively outputs quaternions, rotational velocity, linear acceleration, and magnetic field.

1.2 SENtral Functional Description

Figure 1-1 provides a diagram of SENtral's primary functional blocks, and a brief description of these functional blocks follows.

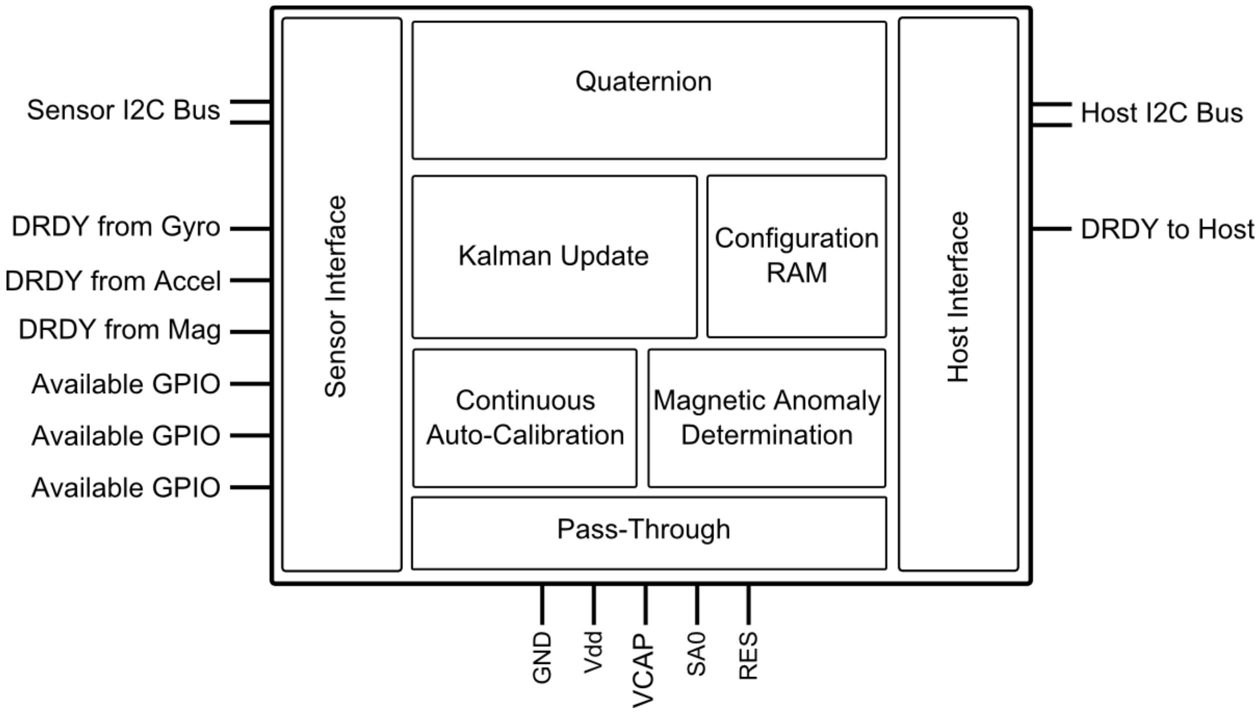


Figure 1-1: SENtral Block Diagram

- **Quaternion** provides the orientation output and is updated at a rate limited to the gyro output data rate (ODR), up to a maximum of 400 Hz.
- **Kalman Update** fuses data from the 3-axis gyroscope, 3-axis accelerometer, and 3-axis magnetometer, plus data from the magnetic anomaly determination and continuous auto-calibration blocks to generate intelligent orientation updates. The Kalman update involves a sophisticated multi-state Kalman algorithm, and this is where most of the heavy calculations are performed.
- **Continuous Hard and Soft-Iron Auto-Calibration**. SENtral is the only product in the market that auto-calibrates for both hard-iron and soft-iron magnetic distortions. While others may calibrate for hard-iron distortion, soft-iron distortion is more difficult to correct for, and it can be caused by EMI shielding tape and other shielding materials widely used in mobile and consumer electronic devices. It is important to correct for soft-iron distortions since they can contribute up to 90° of error. Additionally, since a host system's magnetic signature can change over time and temperature, SENtral's continuous auto-calibration ensures accuracy all the time.

- **Magnetic Anomaly Determination** establishes if a transient magnetic distortion is present and accounts for it.
- **Configuration RAM** allows for customizing SENtral to match the specific sensors being used and allows the user to tailor certain parameters for their specific system. The SENtral Configuration Tool generates the SENtral Configuration File, and this is subsequently uploaded into SENtral's Configuration RAM.
- **Pass-Through** allows for direct communication with devices on the sensor bus by connecting SENtral's I^2C Host Interface to the Sensor Interface.
- **Host Interface** communicates with the host system. Data is transmitted between the host and SENtral via the host I^2C bus, in which the host acts as the master and SENtral acts as a slave device. SENtral signals the host that new data is available by sending an interrupt signal on the host DRDY line.
- **Sensor Interface** communicates primarily with the sensors. Sensor data is transmitted from the sensors to SENtral via the sensor I^2C bus, in which SENtral acts as the master and the sensors as the slave devices.

2 SENtral Specifications[1]

2.1 Performance Characteristics

Table 2-1: Performance Characteristics

Parameter	Minimum	Typical	Maximum	Units
Heading Accuracy		2		° rms
Output Data Rate		200	400	Hz

2.2 Electrical Characteristics

Table 2-2: Absolute Maximum Ratings

Parameter		Symbol	Minimum	Maximum	Units
Supply Voltage		V_{DD}	-0.3	+3.6	VDC
Input Pin Voltage		V_{IN}	GND – 0.3	V_{DD} + 0.3	VDC
ESD	Human Body Model	HBM	-2000	+2000	V
	Machine Model	MM	-200	+200	V
Storage Temperature			-50°	+150°	C

CAUTION:

Stresses beyond those listed above may cause permanent damage to the device. These are stress ratings only. Operation of the device at these or other conditions beyond those indicated in the operational sections of the specifications is not implied.

Footnote

1. Specifications subject to change.

Table 2-3: Operating Conditions

<table>
<tr><th colspan="2">Parameter</th><th>Symbol</th><th>Min</th><th>Typ</th><th>Max</th><th>Units</th></tr>
<tr><td colspan="2">Supply Voltage</td><td>V_{DD}</td><td>1.6</td><td></td><td>3.3</td><td>VDC</td></tr>
<tr><td colspan="2">Power-On Reset Threshold, V_{REG}>V_{POR}</td><td>V_{POR}</td><td></td><td>V_{REG} – 0.125</td><td></td><td>VDC</td></tr>
<tr><td colspan="2">High Level Input Voltage</td><td>V_{IH}</td><td>0.7*V_{DD}</td><td></td><td>V_{DD}</td><td>VDC</td></tr>
<tr><td colspan="2">Low Level Input Voltage</td><td>V_{IL}</td><td>0</td><td></td><td>0.3*V_{DD}</td><td>VDC</td></tr>
<tr><td colspan="2">High Level Output Current, V_{OH} = V_{DD} – 0.3V</td><td>I_{OH}</td><td></td><td></td><td>-1</td><td>mA</td></tr>
<tr><td colspan="2">Low Level Output Current, V_{OL} = 0.3V</td><td>I_{OL}</td><td>1</td><td></td><td></td><td>mA</td></tr>
<tr><td rowspan="4">Current Consumption @ 1.8 V_{DD}[1]</td><td>Operation @ 30 Hz Kalman update rate</td><td></td><td></td><td>275</td><td></td><td>µA</td></tr>
<tr><td>Operation @ 7 Hz Kalman update rate</td><td></td><td></td><td>170</td><td></td><td>µA</td></tr>
<tr><td>Pass-Through State</td><td></td><td></td><td>45</td><td></td><td>µA</td></tr>
<tr><td>Standby State</td><td></td><td></td><td>7</td><td></td><td>µA</td></tr>
<tr><td rowspan="3">I^2C Interface Data Rate[2]</td><td>Host Bus</td><td></td><td></td><td></td><td>3400</td><td>kbits/sec</td></tr>
<tr><td>Sensor Bus</td><td></td><td></td><td></td><td>1000</td><td>kbits/sec</td></tr>
<tr><td>Pass-Through</td><td></td><td></td><td></td><td>400</td><td>kbits/sec</td></tr>
<tr><td colspan="2">Decoupling Capacitor (ESR <2Ω)</td><td>C_{reg}</td><td>0.33</td><td>0.5</td><td>1.8</td><td>µF</td></tr>
<tr><td colspan="2">Operating Temperature</td><td>T_{OP}</td><td>-40</td><td>+25</td><td>+85</td><td>C</td></tr>
</table>

Footnotes:

1. Sensor bus in I^2C Fast mode @ 400 kbits/sec, Accel ODR=100 Hz, Gyro ODR=190 Hz, and Mag ODR=Kalman rate. Operation current consumption is the average over 30 sec while the device is in motion. A 30 Hz Kalman update rate provides superior orientation-tracking performance when compared to a 7Hz Kalman rate. Pass-Through current consumption assumes SENtral previously was in Standby State, which is recommended.
2. SENtral's I^2C Host Interface supports Standard, Fast, Fast Plus, and High Speed Modes. High Speed Mode (3400 kHz) is supported with a reduced range of V_{DD} and bus capacitance. SENtral's I^2C sensor bus interface supports Standard, Fast, and Fast Plus Modes. Pass-Through State, which connects the sensor bus and host bus, supports Standard and Fast Modes.

3 Layout

3.1 System Layout

Figure 3-1 provides a basic reference schematic for connecting SENtral with the host system and the various sensors.

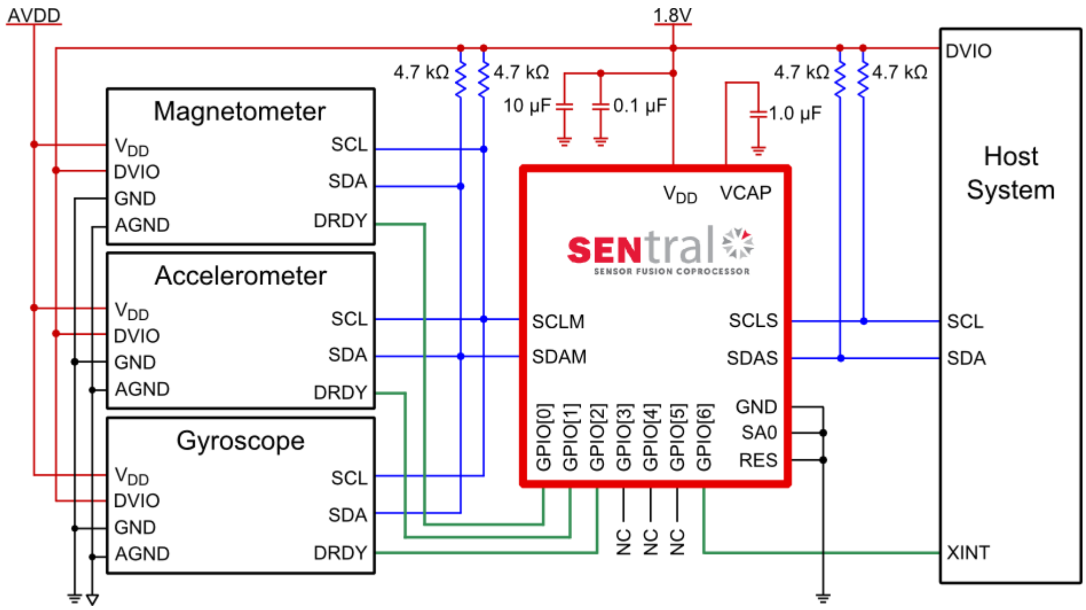


Figure 3-1: SENtral System Reference Schematic

A few points on system layout.

- SENtral communicates with the sensors as the master via a dedicated I²C sensor bus. The layout shows a discrete magnetometer, accelerometer, and gyroscope. SENtral also works with combo sensors, such as a single 9-axis sensor or a combo gyro/accel with a discrete magnetometer.
- SENtral acts as a slave on the host system's I²C bus. This does not need to be a dedicated bus, although it is shown this way in the schematic. SA0 establishes SENtral's slave address when communicating with the host. It is shown set to ground, but can be set HIGH instead. See Section 4.2.
- The pull-up resistance on the I²C lines depends on the number of devices on the bus and the bus speed. Normally 4.7 kΩ is appropriate for Standard or Fast modes (≤400 kbit/sec). See Section 4.4.
- There are three dedicated sensor interrupt lines between the sensors and SENtral, and one interrupt line between the host and SENtral. The default GPIO assignments are shown, but these can be altered with the SENtral Configuration Tool. See Section 6.

3.2 Pin Assignments

SENtral's pin-out is a 4x4 ball-grid array, as defined in Figure 7-1. The table below provides the pin assignments.

Table 3-1: SENtral Pin Assignments

Pin#	Pin Name	I/O Type*	Description
D1	V_{DD}	PWR	Supply voltage
D3	VCAP	PWR	External compensation capacitor for internal core voltage regulator
D2	GND	PWR	Ground
C3	SA0	I	I^2C slave address bit [0]
B1	SCL_S	IO	I^2C host bus SCL clock line
A1	SDA_S	IO	I^2C host bus SDA data line
B4	SCL_M	IO	I^2C sensor bus SCL clock line
A4	SDA_M	IO	I^2C sensor bus SDA data line
D4	GPIO[0]	IO / PUPD	General Purpose IO – Default mag interrupt
C4	GPIO[1]	IO / PUPD	General Purpose IO – Default accel interrupt
A3	GPIO[2]	IO / PUPD	General Purpose IO – Default gyro interrupt
B3	GPIO[3]	IO / PUPD	General Purpose IO – Default not connected
A2	GPIO[4]	IO / PUPD	General Purpose IO – Default not connected
B2	GPIO[5]	IO / PUPD	General Purpose IO – Default not connected
C1	GPIO[6]	IO / PUPD	General Purpose IO – Default host interrupt
C2	RES	-	Not Used – Connect to Ground

***I/O Types are:**

PWR: Power supply Connections
I: Digital Input
IO: Digital Input / Output
PU: Pull-Up
PD: Pull-Down

3.3 Sensor Layout

SENtral provides for considerable flexibility in sensor orientation and layout, but there are some basic requirements, as given below.

- All three axes of a sensor must be orthogonal to each other. This is by-design for most accelerometers, gyroscopes, and magnetometers.
- A sensor's X axis and Y axis should act parallel to the primary plane of the motherboard. A sensor's Z axis should act perpendicular to the primary plane.
- Either a sensor's X axis or Y axis should align parallel to the line-of-sight of the motion-tracking device.
- It is NOT necessary that the gyroscope, accelerometer, and magnetometer have their same-axis sensors (i.e. all X-axis sensors) point in the same direction, since sensor orientation is configured when running the SENtral Configuration Tool and stored in the SENtral Configuration File.

Assuming the Orientation Matrix is properly input in the SENtral Configuration Tool, SENtral will output data conforming to a North-East-Down (NED) convention. To convert to East-North-Up (ENU) see Appendix I.

In addition to the requirements listed above, there are several other recommendations regarding sensor layout, as listed below.

- Accelerometer
  - Locate the accelerometer near the expected center of rotation of the device to minimize rotational accelerations being interpreted as linear accelerations.
- Magnetometer
  - Locate the magnetometer >1 cm away from magnetic sources (hard-iron), such as speaker magnets or known magnetized metals. If uncertain about whether a component is a magnetic source, check it with a Gauss meter (magnetometer) if possible.
  - For non-magnetic components, try to avoid placing wireless antenna, power capacitors, inductors, ferrite beads, and components using ferromagnetic materials (Fe, Co, Ni) within 1 cm of the magnetometer. Examples of components in a cell phone which typically contain ferromagnetic materials are the memory card slot, battery, frame, electrical and magnetic noise shields, connectors, and hinges.
  - Materials that are magnetically transparent, and thus relatively safe, include aluminum, gold, titanium, copper, brass, and magnesium. Most stainless steel alloys have relatively weak magnetic properties and are not as safe as those just listed, but don't need as much attention as ferromagnetic materials.
  - Locate high-frequency signal lines away from the magnetometer.

- Locate power lines away from the magnetometer, per the table below.

Table 3-2: Recommended Power Line Distance from Magnetometer

Current (mA)	Recommended Distance (mm)
2	0.2
10	1
50	5
100	10
200	20

3.4 Dedicated EEPROM (Optional)

A crucial step in using the SENtral coprocessor is uploading the SENtral Configuration File into SENtral's RAM. This file contains information on how the sensor system is configured in the user's system, and is generated with the SENtral Configuration Tool, as discussed in Section 6. The Configuration File can be manually uploaded from non-volatile memory in the host CPU or automatically uploaded from a dedicated EEPROM. The primary advantages of using a dedicated EEPROM are freeing up host processor memory and minimizing the time from power-up until the upload is complete. The advantages of using host CPU memory are no additional cost and no additional system footprint requirement.

If implementing a dedicated EEPROM, connect it to SENtral as a slave device on the sensor bus, in parallel with the sensors shown in Figure 3-1. The EEPROM upload rate should be set with the SENtral Configuration Tool (see Section 6.1.3). Faster is generally better, although the sensor bus rate is limited to 1 Mb/sec. Writing the Configuration File onto the EEPROM can be accomplished either using an EEPROM programmer or by writing to the EEPROM from the host while SENtral is in Pass-Through State.

The primary EEPROM requirements are:

- ≥320 Kbit (40 Kb x 8 bits) of memory.
- Shifted address of 0xA0, 0xA2, 0xA4, 0xA6, 0xA8, or 0xAA. (Unshifted address of 0x50, 0x52, 0x54, 0x56, 0x58, or 0x5A.)

The following devices have been used with SENtral, but this list definitely is not exhaustive.

- Microchip 24LC256T-I/SN
- ST M24M01-DRCS
- Renesas R1EX24512ASAS0A

4 I²C Interface

Communication with the host processor and sensors is via an I²C interface and interrupt lines. The SENtral Motion Coprocessor acts as the I²C master with the sensors and as a slave with the host processor. The sensor interrupt lines let SENtral know when new data is available, while the host interrupt line lets the host system know when SENtral has updated the quaternions. The sensor and host output data rates are set by the MagRate, AccelRate, GyroRate, and QRateDivisor registers.

SENtral's I²C interface complies with NXP's UM10204 specification and user manual, rev 04. Standard, Fast, Fast Plus, and High Speed modes of the I²C protocol are supported by SENtral's I²C host interface. Below is a link to this document.

http://www.nxp.com/documents/user_manual/UM10204.pdf

4.1 I²C Timing

SENtral's I²C timing requirements are set forth below, in Figure 4-1 and Table 4-1. For the timing requirements shown in Figure 4-1, transitions are 30% and 70% of V_{DD}.

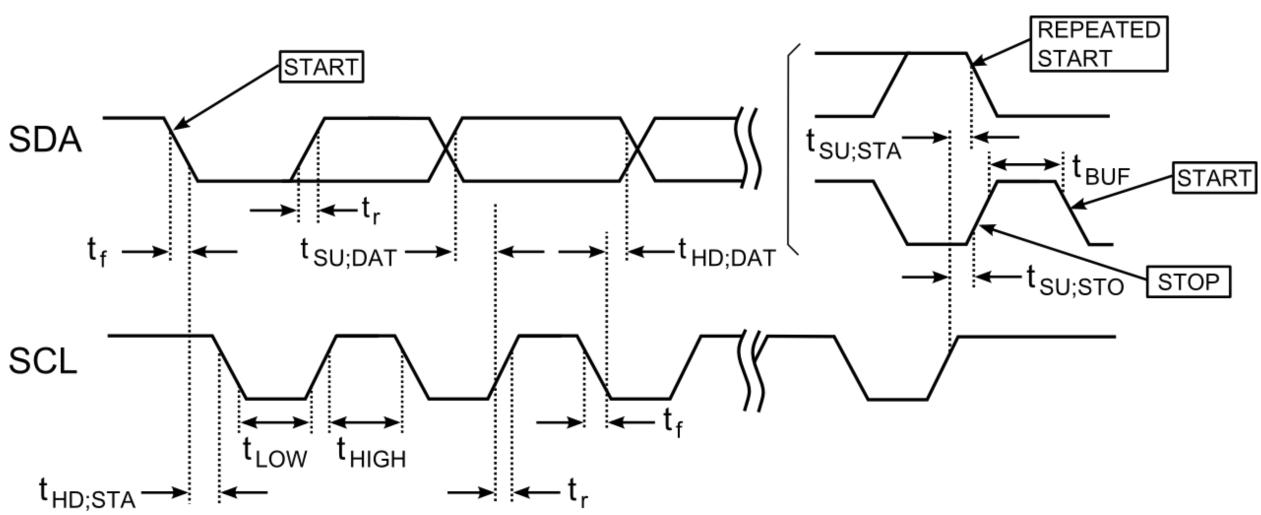


Figure 4-1: I²C Timing Diagram

Table 4-1: I²C Timing Parameters

Symbol	Parameter	Standard Min	Standard Max	Fast Min	Fast Max	Fast Plus Min	Fast Plus Max	Units
f_{SCL}	SCL Clock	0	100	0	400	0	1000	kHz
t_r	SDA & SCL Rise Time	-	1000	20	300		120	ns
t_f	SDA & SCL Fall Time	-	300	$20*(V_{DD}/5.5V)$	300	$20*(V_{DD}/5.5V)$	120	ns
t_{LOW}	LOW period of SCL Clock	4.7	-	1.3	-	0.5	-	µs
t_{HIGH}	HIGH period of SCL Clock	4.0	-	0.6	-	0.26	-	µs
$t_{HD;STA}$	Hold time (repeated) START	4.0	-	0.6	-	0.26	-	µs
$t_{HD;DAT}$	Data hold time	0	-	0	-	0	-	µs
$t_{SU:DAT}$	Data set-up time	250	-	100	-	50	-	ns
$t_{SU;STA}$	Set-Up time for repeated Start	4.7	-	0.6	-	0.26	-	µs
$t_{SU;STO}$	Stop set-up time	4.0	-	0.6	-	0.26	-	µs
t_{BUF}	Bus free time between STOP & START	4.7	-	1.3	-	0.5	-	µs

4.2 I²C Host Interface (Host Bus)

The host will control SENtral on the host bus via SENtral's I²C host interface. The host interface consists of 2 wires: the serial clock, SCLS, and the serial data line, SDAS. Both lines are bi-directional. SENtral is connected to the host bus via the SDAS and SCLS pins, which incorporate open drain drivers within the device. The host bus lines must be externally connected to a positive supply voltage (DVIO) via a pull-up resistor. See Section 4.4 for more on the pull-up resistor.

SENtral's 7-bit I²C slave address is 0b010100x, where the most significant 6 bits of the slave address are pre-defined in hardware and are the same for all SENtral devices. The least significant bit is user-configurable, using the SA0 pin to set the bit to '0' or '1'. For example, grounding the SA0 pin ('0' value) results in the 7-bit address of 0b0101000. This should be set so the SENtral slave address is unique to any other devices on the host bus. Note that setting SA0 to '1' requires utilizing microvia technology, as discussed in Section 8.

Data transfer is always initiated by the host. Data is transferred between the host and SENtral serially through the data line (SDAS) in an 8-bit transfer format. The transfer is synchronized by the serial clock line, SCLS. Supported transfer formats are single-byte read, multiple-byte read, single-byte write, and multiple-byte write. The data line can be driven either by the host or SENtral. Normally the serial clock line will be driven by the host, although exceptions can exist when clock-stretching is implemented in Pass-Through State.

4.2.1 I^{2}C Slave Transfer formats

Figure 4-2 illustrates writing data to registers in single-byte or multiple-byte mode.

START	SLAVE ADDRESS							RW	ACK	REGISTER ADDRESS (N)								ACK	DATA TO REGISTER (N)								ACK	DATA TO REGISTER (N+1)								ACK	STOP
S	A6	A5	A4	A3	A2	A1	A0	0	0	R7	R6	R5	R4	R3	R2	R1	R0	0	D7	D6	D5	D4	D3	D2	D1	D0	0	D7	D6	D5	D4	D3	D2	D1	D0	0	P

From Host to SENtral

From SENtral to Host

----------- Data Transferred (n bytes + acknowledge) -----------

Figure 4-2: I^{2}C Slave Write Example

The I^{2}C host interface supports both a read sequence using repeated START conditions, shown in Figure 4-3, and a sequence in which the register address is sent in a separate sequence than the data, shown in Figure 4-4 and Figure 4-5.

START	SLAVE ADDRESS							RW	ACK	REGISTER ADDRESS (N)								ACK	START	SLAVE ADDRESS							RW	ACK	DATA FROM REGISTER (N)								NACK	STOP
S	A6	A5	A4	A3	A2	A1	A0	0	0	R7	R6	R5	R4	R3	R2	R1	R0	0	SR	A6	A5	A4	A3	A2	A1	A0	1	0	D7	D6	D5	D4	D3	D2	D1	D0	1	P

Data Transferred
(n bytes + acknowledge)

Figure 4-3: I^{2}C Slave Read Example, with Repeated START

START	SLAVE ADDRESS							RW	ACK	REGISTER ADDRESS (N)								ACK	STOP
S	A6	A5	A4	A3	A2	A1	A0	0	0	R7	R6	R5	R4	R3	R2	R1	R0	0	P

Figure 4-4: I^{2}C Slave Write Register Address Only

START	SLAVE ADDRESS							RW	ACK	DATA FROM REG. (N)								ACK	DATA FROM REG. (N+1)								NACK	STOP
S	A6	A5	A4	A3	A2	A1	A0	1	0	D7	D6	D5	D4	D3	D2	D1	D0	0	D7	D6	D5	D4	D3	D2	D1	D0	1	P

From Host to SENtral

From SENtral to Host

------------- Data Transferred (n bytes + acknowledge) -------------

Figure 4-5: I^{2}C Slave read register from current address

4.3 I^2C Sensor Interface (Sensor Bus)

SENtral communicates with the accelerometer, gyroscope, and magnetometer over the sensor bus, where SENtral acts as the I^2C master and the sensors act as the I^2C slaves. On the sensor bus, SENtral initiates data transfer and generates the serial clock. SENtral's I^2C sensor interface supports Standard mode with a rate up to 100 kbit/s, Fast mode with a rate up to 400 kbit/s, and Fast Plus mode with a rate up to 1000 kbit/s.

The two wires comprising the sensor bus are SDAM, the serial data line, and SCLM, the serial clock. Both are bidirectional and driven by open drain transistors within SENtral. Each line should be attached to a pull-up resistor, which is further discussed in Section 4.4.

4.4 I^2C Pull-Up Resistance

The pull-up resistor value for both the host and sensor bus will depend on the I^2C data rate and the number of devices on the bus. Table 4-2 provides the maximum acceptable bus capacitance, as a function of bus rate, which can be accommodated with a 4.7 kΩ or 2.4 kΩ pull-up resistor. As a general rule, each device connected to the bus represents 10 pF of capacitance on the bus, so a bus with 4 devices would require a "Max Cb" value of >40 pF.

Table 4-2: I^2C Pull-Up Resistance Table

I2C Mode		Rate (kbit/s)	Rise Time (ns)	Max Cb (pF) 4.7 kΩ pull-up	Max Cb (pF) 2.4 kΩ pull-up
Standard		100	1000	251.1	491.8
Fast		400	300	75.3	147.5
Fast Plus		1000	120	30.1	59.0
High Speed-1.7 MHz	Clock	1700	80	20.1	39.3
	Data	1700	160	40.2	78.7
High Speed-3.4 MHz	Clock	3400	40	10.0	19.7
	Data	3400	80	20.1	39.3

As the table implies, for most Standard and Fast Mode implementations a 4.7 kΩ pull-up should work well, while a 2.4 kΩ pull-up normally should be used for Fast Plus. See Section 7.1 of NXP's UM10204 specification for additional information.

http://www.nxp.com/documents/user_manual/UM10204.pdf.

5 Operation

Prior to running SENtral, the Configuration File must be uploaded into SENtral's Configuration RAM. This file contains information regarding how the user's sensor system is configured, such as sensor models, sensor slave addresses, GPIO pin assignments, etc.. The Configuration File is generated with the SENtral Configuration Tool, as discussed in Section 6. It may be stored in the host processor's non-volatile memory or in a dedicated EEPROM connected to SENtral's sensor bus. Figure 5-1 provides a flow chart of the initialization process, and a detailed discussion of the initialization process follows in Section 5.1

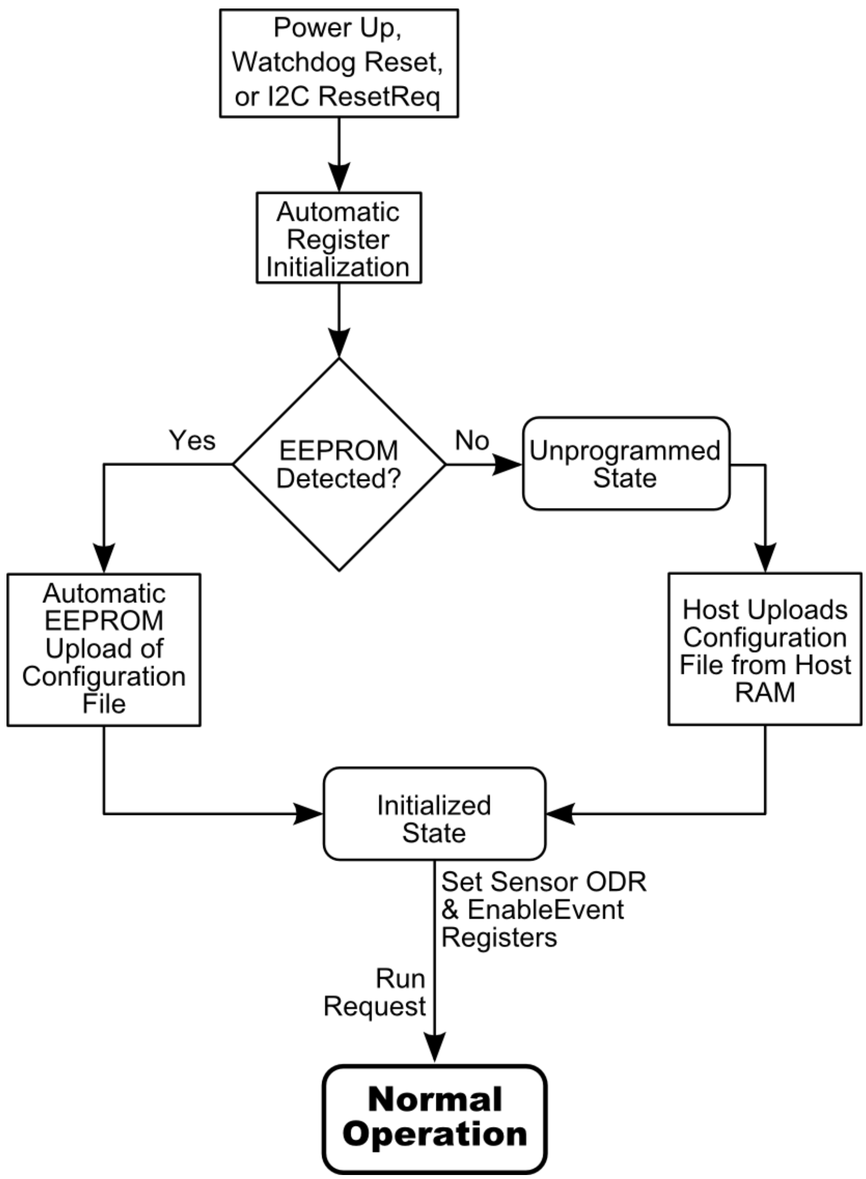


Figure 5-1: SENtral Initialization Sequence

Once the initialization sequence is complete, there are three states in which SENtral may reside: Normal Operation, Standby, and Pass-Through. Figure 5-2 indicates the recommended way to get from one state to another, and these states are discussed in detail in Sections 5.2 (Normal Operation), 5.3 (Standby), and 5.4 (Pass-Through).

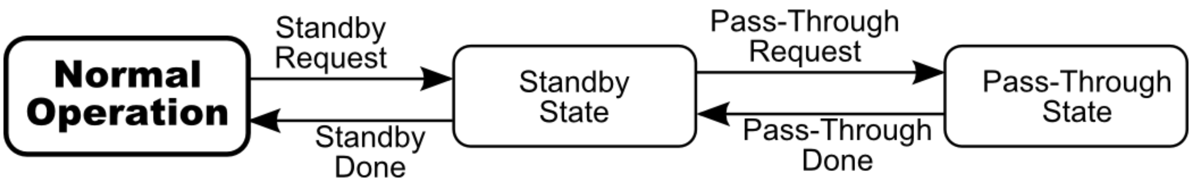


Figure 5-2: SENtral Operational States

5.1 Power-Up and Configuration File Upload

After powering up or issuing a ResetReq command, SENtral automatically initializes the registers, and then looks for an EEPROM on the sensor bus, as indicated in Figure 5-1.

The Configuration File must now be uploaded. This file contains information on how the sensor system is configured in the user's system, and is generated with the SENtral Configuration Tool, as discussed in Section 6. It can be stored in non-volatile memory in the host CPU or in a dedicated EEPROM. The primary advantages of using a dedicated EEPROM are freeing up host processor memory and minimizing the time from powering up until the upload is complete. The advantages of using the host CPU's memory are no additional cost and no additional system footprint requirement. If a dedicated EEPROM is used, the EEPROM needs to be connected to SENtral as a slave device on the sensor bus.

5.1.1 Configuration File Upload from EEPROM

If a dedicated EEPROM is used to store the Configuration File, then this EEPROM initially would be loaded with the Configuration File either using an EEPROM programmer or by writing the file into the EEPROM from the host while SENtral is in Pass-Through State. This later method also can be used if a new revision of the SENtral algorithm is available or if the user is testing a variety of sensors and consequently needs to change the Configuration File depending on the sensors. As previously mentioned, the EEPROM should be connected to SENtral via SENtral's sensor bus.

Table 5-1: Configuration File Upload from EEPROM Registers

Register Name	Address	Register Value
SentralStatus	0x37	[0] EEPROM. 1 = EEPROM detected [1] EEUploadDone. 1 = EEPROM upload completed [2] EEUploadError. 1 = Calculated CRC of EEPROM is correct. Only valid when EEUploadDone = 1. [3] Idle. 1 = Device in Unprogrammed or Initialized state. [4] NoEEPROM. 1 = No EEPROM detected.
ResetReq	0x9B	[0] ResetRequest. 1 = Emulate a hard power down/power up.

SENtral automatically checks the sensor bus after powering up or reseting to see if an EEPROM is connected on the sensor bus. If an EEPROM is detected, SENtral checks the first 2 bytes of the EEPROM file, which are fixed for all SENtral Configuration Files, and if these match then it automatically uploads the SENtral Configuration File. Once the upload is complete, SENtral enters Initialized State and waits for instructions from the host. If an EEPROM is not detected, SENtral enters Unprogrammed State.

The host should confirm a successful EEPROM upload by following the steps below:

- Read the value from the SentralStatus register.
- Check bit [0], the EEPROM bit, to ensure an EEPROM is detected by SENtral.
- Check bit [1], the EEUploadDone bit. If this is '0' then the Configuration File upload is not complete, and reread the SentralStatus register until bit [1] = 1.
- Once bit [1] = 1, check bit [2], the EEUpload Error bit. If this is '0', then the upload was successful.

If the Configuration File upload failed, try the following:

- Reinitialize SENtral and retry the process. Send a Reset command by writing 0x01 to the ResetReq register.
- Upload the Configuration File from the host, as discussed in the next section.
- Download the Configuration File from the EEPROM and verify its contents, as discussed in Section 5.1.3.
- Reload the Configuration File from the host into the EEPROM.

5.1.2 Configuration File Upload from Host

If an EEPROM is not used for storing the Configuration File, then SENtral will enter Unprogrammed State after failing to identify an EEPROM. The host now should upload the Configuration File from host memory. The registers involved are given below:

Table 5-2: Configuration File Host Upload Registers

Register Name	Address	Register Value
HostControl	0x34	[0] 1 = RunEnable [1] 1 = HostUpload Enable
UploadAddr	0x94 to 0x95	Initial RAM address (0x0000)
UploadData	0x96	Data to be uploaded
CRCHost	0x97 to 0x9A	CRC32 of the uploaded data since host upload was enabled
ResetReq	0x9B	[0] 1 = Reset SENtral

To upload the Configuration File from the host, perform the following transactions:

- Write value 0x01 to the ResetReq register. This results in a hard reset of SENtral. This is unnecessary if SENtral has just been powered up or Reset.
- Verify the Configuration File image, as discussed in Section 5.1.3. Specifically:
    - Ensure the Magic Numbers are correct.
    - Ensure the Uploaded Image Length matches the Uploaded Firmware Image Size.
    - Ensure the Upload Image Length is a multiple of 4 bytes.
    - Ensure the Configuration File version matches ROM version.
- Write 0x02 to the HostControl register. This sets the UploadEnable bit, which enables uploading of the Configuration File.
- Write the initial RAM address, 0x0000, into the UploadAddr register. This normally is an unnecessary operation, since the default after powering up or sending a ResetReq is 0x0000.
- Upload the Configuration File to SENtral's program RAM. This represents the range from 0x10 to 0x10+UIL-1 in the Configuration File image, as discussed in Section 5.1.3. The file is sent one byte at a time, using the UploadData register. Data can be burst uploaded. Each group of 4 bytes should be sent in byte-reverse order (i.e. little Endian format). Table 5-3 provides an example.

Table 5-3: Sample Host Upload Data Order

Byte Order in Config File Image	i	i+1	i+2	i+3	i+4	i+5	i+6	i+7
Config File Image Example	0x01	0x02	0x03	0x04	0x05	0x06	0x07	0x08
Byte Order During Host Upload	i+3	i+2	i+1	i	i+7	i+6	i+5	i+4
Example Bye Sent during Host Upload	0x04	0x03	0x02	0x01	0x08	0x07	0x06	0x05

- Read the CRCHost register. Compare this to the host-calculated CRC-32 to confirm a successful upload.
- After the reset, write value 0x00 to the HostControl register, which clears the HostUpload bit and places SENtral in Initialized State.

5.1.3 Configuration File Image Format

Table 5-4 provides the format for the Configuration File image, which contains the Configuration File. While understanding the Configuration File image format is not mandatory for operation, it can be useful when debugging errors.

Table 5-4: Configuration File Image Format

Byte Index	Content	Note
0x00	Magic Number Lower Byte	0x2A is expected value
0x01	Magic Number Upper Byte	0x65 is expected value
0x02 & 0x03	Flags	Bit [0] – EEPROMNoExec Bit [8] to [10] – I2CClockSpeed Bit [11] to [14] – ROMVerExp. See Table 5-5
0x04 to 0x07	CRC32 of uploaded image	Stored in Little Endian Format
0x08 to 0x0B	Reserved	0x00000000
0x0C & 0x0D	Uploaded Image Length (UIL)	Stored in Little Endian Format
0x0E & 0x0F	Reserved	0x0000
0x10 to 0x10+UIL-46	Uploaded Image – Instructions & Configuration File Data	CRC32 is calculated over uploaded image
0x10+UIL-45 to 0x10+UIL-1	Uploaded Image –Config. File Data Structure. See Table 5-6.	

Table 5-5: ROMVerExp Definition

ROMVerExp	Content	Version
0x00	Any ROM version	Any value
0x01	ROM version DI01	0x7A8
0x02	ROM version DI02	0x9E6

Table 5-6: Configuration File Data Structure

Byte Index	Content	Note
0x00	Signature Lower Byte	Value is 0x8B. Can be used to locate the data structure within the image.
0x01	Signature Upper Byte	Value is 0xC8. Can be used to locate the data structure within the image.
0x02 to 0x07	Reserved	
0x08 & 0x09	RAM Version	Firmware version number
0x0A	Version	Configuration Structure Version
0x0B	Boot Protocol	Used for standalone applications
0x0C to 0x13	PinSelection	Bit 0-3 Host IRQ pin selection Others – reserved
0x14 to 0x1B	PullSelection	Bit 0 & 1 GPIO0 pull selection 0=no pulls, 1=pull-down, 2=pull-up, 3=keep defaults Bit 2 & 3 GPIO1 pull selection Bit 4 & 5 GPIO2 pull selection Bit 6 & 7 GPIO3 pull selection Bit 8 & 9 GPIO4 pull selection Bit 10 & 11 GPIO5 pull selection Bit 12 & 13 GPIO6 pull selection Others – reserved
0x1C to 0x2B	Device Name	16 character string

When uploading the Configuration File from a dedicated EEPROM, SENtral first checks the Magic Number upper and lower bytes to ensure they match the expected values. If they do, then the upload will commence, and during the upload SENtral calculates the CRC32 value over the incoming data. At the end of the upload process, the calculated CRC32 value is compared with the valued stored in the header. If they match and the

EEPROMNoExec bit is not '1', then the Configuration File has been successfully uploaded.

When uploading the Configuration File from the host, the host should check the Magic Numbers and confirm the expected SENtral ROM version, given in Table 5-5, is correct.

5.2 Normal Operation

During Normal Operation the sensors and SENtral algorithm will run and it will be possible to obtain real-time orientation and motion-tracking data from SENtral. The registers used in Normal Operation are given in Table 5-7.

Table 5-7: Normal Operation Registers

Register Name	Address	Register Value
HostControl	0x34	[0] 1 = RunEnable 0 = Enable Initialized State
MagRate	0x55	Requested magnetometer output data rate
AccelRate	0x56	Requested accelerometer output data rate divided by 10
GyroRate	0x57	Requested gyroscope output data rate divided by 10
QRateDivisor	0x32	Along with GyroRate, establishes output data rate for quaternion data.
EnableEvents	0x33	'1' indicates an interrupt to the host will be generated for the event. [0] CPUReset. Non-maskable [1] Error [2] QuaternionResult [3] MagResult [4] AccelResult [5] GyroResult [6] Reserved [7] Reserved
EventStatus	0x35	'1' indicates a new event has been generated. [0] CPUReset [1] Error [2] QuaternionResult [3] MagResult [4] AccelResult [5] GyroResult

Prior to executing the SENtral algorithm it is necessary to perform the following.

- Set the sensor output data rates (ODRs): MagRate, AccelRate, and GyroRate. If a sensor rate is set to 0x00, SENtral will shutdown the sensor and disable SENtral background calibration. There are two major points regarding setting these registers:
  - The AccelRate and GyroRate register values should be 1/10th the desired rate, while the MagRate value should match the desired ODR. For example, if the desired ODR is 30 Hz for the magnetometer, 100 Hz for the accelerometer, and 200 Hz for the gyroscope, then the respective register values should be 0x1E (30_d), 0x0A (10_d), and 0x14 (20_d).
  - The actual accelerometer and gyro ODRs are limited to the ODRs supported by the specific sensors. **If the AccelRate or GyroRate register values do not correspond to a supported ODR, then the next highest ODR will be used.** For instance, if the GyroRate register is set to 0x14, which corresponds to 200 Hz, but the gyro supports 95 Hz, 190 Hz, and 380 Hz, then the actual gyro ODR will be 380 Hz since this is the closest supported rate above that requested by the register.
- Establish the quaternion output data rate, where the quaternion output data rate equals GyroRate divided by QRateDivisor. The default for QRateDivisor is 0x00, which is interpreted as '1' and results in the quaternion output data rate equaling GyroRate.
- Establish which events will trigger an interrupt to the host by configuring the EnableEvent register. PNI specifically recommends enabling bit [1], the Error interrupt bit, in addition to whichever other interrupts the user wants.

Example steps to do this are below:

- Write 0x640A0F to the MagRate register. Since SENtral automatically increments to the next register, this also populates the AccelRate and GyroRate registers. This sets MagRate to 100 Hz, AccelRate to 100 Hz, and GyroRate to 150 Hz.
- Write 0x01 to the QRateDivisor Register. This sets the quaternion output data rate to equal the GyroRate. For writing 0x01 this step is optional, since the default also sets the quaternion output data rate equal to GyroRate.
- Write 0x07 to the EnableEvents register. This sets up the host to receive interrupts from SENtral whenever the quaternion results registers are updated, an error has been detected, or when SENtral needs to be reset.

After performing the steps listed above, SENtral is ready to start generating orientation data. Below are the steps to follow when operating in Normal Operation state.

a) Write 0x01 to the HostControl register. This sets the RunEnable bit to '1' and enables the sensors and the SENtral algorithm.

b) If operating in an interrupt-driven mode, then the host waits until it receives an interrupt signal from SENtral. Alternatively the host may operate on a polling basis, rather than an interrupt-driven basis, in which case the interrupt line may not be used.
c) Once an interrupt is received by the host or the host otherwise decides to read new data, read the EventStatus register.
d) Interpret and act on the EventStatus register in the priority shown in Figure 5-3. If bit [1], the Error bit, is '1', see Section 5.2.1. If bit [0], the CPUReset bit, is '1', see Section 5.2.2. If bits [2], [3], [4], or [5], the Results bits, are '1', see Section 5.2.1.
e) Repeat steps c – e until new orientation data is not needed and/or the host decides to enter a different state.

Reading the EventStatus register clears it. It is possible for more than one bit position to be '1' in the EventStatus register, especially if the host does not always read the EventStatus register after receiving an interrupt. Similarly, if multiple bits are set to '1' in the EventStatus register, once the register is read all the bits will be set to '0'. For this reason the EventStatus register should be processed in the priority shown in Figure 5-3, as information will be cleared for events that are not handled.

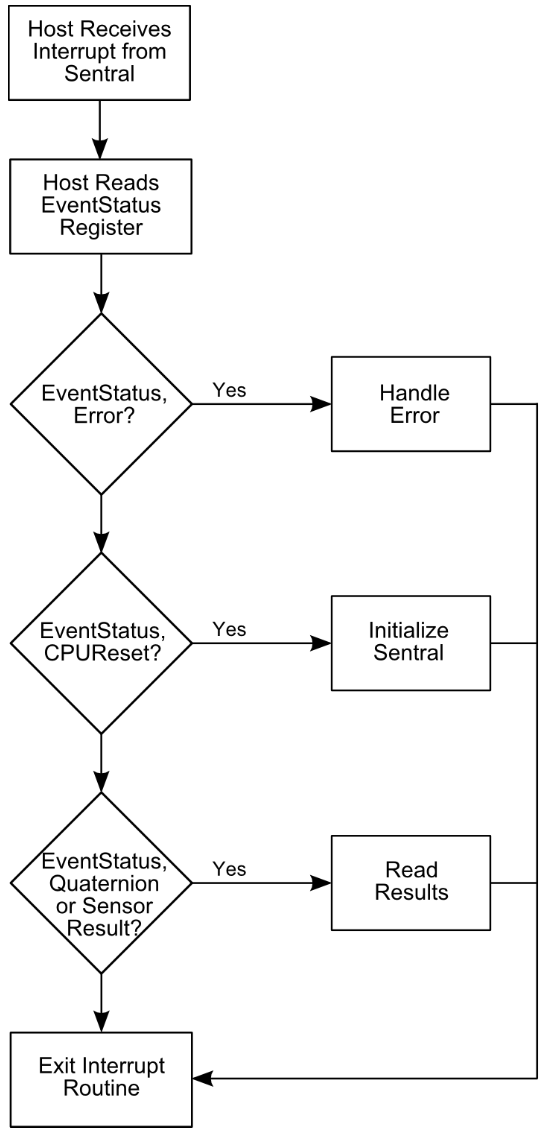


Figure 5-3: SENtral Normal Operation Flow

A discussion of how to handle the various events follows.

5.2.1 Error

In the event of an error, SENtral will trigger an error interrupt and SENtral will enter Standby State. See the Section 5.5 for recommendations on Troubleshooting and/or reset SENtral by sending 0x01 to the ResetReq register, at address 0x9B.

5.2.2 CPUReset

SENtral will report a CPUReset event after the ResetReq command has been issued, and prior to uploading the Configuration File. In this case, SENtral is in Unprogrammed

State and needs the Configuration File to be uploaded. If a dedicated EEPROM is used to store the Configuration File, then CPUReset should not be encountered as the Configuration File is automatically uploaded.

5.2.3 Read Results

SENtral orientation results either can be quaternions or heading, pitch, and roll (HPR), while sensor outputs either may be scaled data or raw data. Which types of outputs are given in the Results Registers is controlled by the AlgorithmControl register, as given in Table 5-8: RawDataEnable and HPROutput The default for the AlgorithmControl register is 0x00, corresponding to quaternion orientation data and scaled sensor data.

Table 5-8: RawDataEnable and HPROutput

Register Name	Address	Register Value
AlgorithmControl	0x54	[1] RawDataEnable. 1 = Raw data provided in MX, MY, MZ, AX, AY, AZ, GX, GY, & GZ. 0 = Scaled sensor data. [2] HPRoutput. 1 = Heading, pitch, and roll output in QX, QY, & QZ. QW = 0.0. 0 = Quaternion outputs.

The Results Registers' addresses, formats, and full-scale ranges are given below in Table 5-9. For an explanation of how to convert quaternions to the rotation vector, the rotation matrix, or heading, pitch, and roll (Euler angles), see Appendix I. The resolution is 32 kHz for all timestamps.

Note: *All multi-byte elements are stored and transmitted using the Little Endian convention: the least significant byte is stored at the lowest address and transmitted first over the I^2C bus.*

Table 5-9: Results Registers

Name	Address (Hex)	Description	Format	Full-Scale Range
QX	00 – 03	Normalized Quaternion – X, or Heading	Float32	0.0 – 1.0, or ±π
QY	04 – 07	Normalized Quaternion – Y, or Pitch	Float32	0.0 – 1.0, or ±π/2
QZ	08 – 0B	Normalized Quaternion – Z, or Roll	Float32	0.0 – 1.0, or ±π
QW	0C – 0F	Normalized Quaternion – W, or 0.0	Float32	0.0 – 1.0
QTime	10 – 11	Quaternion Data Timestamp	UInt16	0 – 2048 msec
MX	12 – 13	Magnetic Field – X Axis, or Raw Mag Data	Int16	±1000 µT when scaled
MY	14 – 15	Magnetic Field – Y Axis, or Raw Mag Data	Int16	±1000 µT when scaled

MZ	16 – 17	Magnetic Field – Z Axis, or Raw Mag Data	Int16	±1000 µT when scaled
MTime	18 – 19	Magnetometer Interrupt Timestamp	UInt16	0 – 2048 msec
AX	1A – 1B	Linear Acceleration – X Axis, or Raw Accel Data	Int16	±16 g when scaled
AY	1C – 1D	Linear Acceleration – Y Axis, or Raw Accel Data	Int16	±16 g when scaled
AZ	1E – 1F	Linear Acceleration – Z Axis, or Raw Accel Data	Int16	±16 g when scaled
ATime	20 – 21	Accelerometer Interrupt Timestamp	UInt16	0 – 2048 msec
GX	22 – 23	Rotational Velocity – X Axis, or Raw Gyro Data	Int16	±5000°/s when scaled
GY	24 – 25	Rotational Velocity – Y Axis, or Raw Gyro Data	Int16	±5000°/s when scaled
GZ	26 – 27	Rotational Velocity – Z Axis, or Raw Gyro Data	Int16	±5000°/s when scaled
GTime	28 – 29	Gyroscope Interrupt Timestamp	UInt16	0.0 – 2.048 sec

5.3 Standby State

In Standby State overall system power consumption is dramatically reduced because both the SENtral algorithm and the sensors are shut down.

Table 5-10 provides the registers associated with Standby State.

Table 5-10: Standby Registers

Register Name	Address	Register Value
AlgorithmControl	0x54	[0] 1 = StandbyEnable 0 = Disable Standby State
AlgorithmStatus	0x38	[0] 1 = SENtral in Standby State 0 = SENtral not in Standby State

The steps to enter and exit Standby State are given below:

- Write 0x01 to the AlgorithmControl register. This places SENtral in Standby State.
- Read the AlgorithmStatus register. If bit [0] is '1', then SENtral is in Standby State. This step is optional.
- When you are ready to exit Standby State, write 0x00 to the AlgorithmControl register. This takes SENtral out of Standby State and normally will place it back into Normal Operation.
- Read the AlgorithmStatus register. If bit [0] is '0', then SENtral is not in Standby State. This step is optional.

5.4 Pass-Through State

SENtral can be configured so the host communicates directly with devices on the sensor bus by placing SENtral into Pass-Through State. In Pass-Through State, SENtral's sensor and host interfaces are connected by internal switches so the host system communicates directly with the sensors and/or dedicated EEPROM. To enter Pass-Through State, SENtral first should be in either Standby, Initialized, or Unprogrammed State. Consequently, in Pass-Through State the SENtral algorithm, host interrupt line, and sensors are disabled, unless a sensor is directly turned on by the host. When exiting Pass-Through State, SENtral will return to its prior state.

Note: *When entering Pass-Through State the sensor's registers retain the values established by SENtral, and when exiting Pass-Through State any register changes will be retained.*

Uses for the Pass-Through State include:

- Direct control of sensors, if desired.
- Debugging.
- Communication with the dedicated EEPROM, if implemented. Specifically, if a new Configuration File is generated, the host can write this into the EEPROM when in Pass-Through State.

Since operating in Pass-Through State requires stopping the SENtral algorithm, Pass-Through State is not recommended for accessing sensor data unless reliable heading data is not required. If sensor data and reliable heading data are both desired, scaled sensor data can be accessed during Normal Operation from the Results Registers, as given in Table 5-9.

Table 5-11 provides the registers associated with Pass-Through State.

Table 5-11: Pass-Through Registers

Register Name	Address	Register Value
AlgorithmControl	0x54	[0] 1 = StandbyEnable 0 = Disable Standby State
AlgorithmStatus	0x38	[0] 1 = SENtral in Standby State 0 = SENtral not in Standby State
PassThroughControl	0xA0	[0] 1 = Enable Pass-Through State 0 = Disable Pass-Through State
PassThroughStatus	0x9E	[0] 1 = SENtral in Pass-Through State. 0 = SENtral not in Pass-Through State.

The steps to go in and out of Pass-Through State are given below.

- Write 0x01 to the AlgorithmControl register. This places SENtral in Standby State.
- Write 0x01 to the PassThroughControl register. This places SENtral in Pass-Through State.
- Read the PassThroughStatus register. If bit [0] is '1', then SENtral is in Pass-Through State. This step is optional.
- When you are done in Pass-Through State, write 0x00 to the PassThroughControl register. This terminates Pass-Through mode and returns SENtral to Standby State.
- Write 0x00 to the AlgorithmControl register. This takes SENtral out of Standby State and normally will place it back into Normal Operation.

5.5 Troubleshooting

This section provides guidance in troubleshooting SENtral, and is divided into hardware-related and software-related errors.

5.5.1 Hardware-Related Error Conditions

Possible indications of a hardware-related problem are given below in Table 5-12.

Table 5-12: Hardware-Related Error Indications

Register Name	Address	Error Indication
EventStatus	0x35	[0] 1 = CPURest. SENtral Configuration File needs uploading. See Section 5.1.
SentralStatus	0x37	[2] 1 = EEUploadError. Issue with uploading from the dedicated EEPROM. See Section 5.1.
MagRate	0x55	0x00 – Value lost
AccelRate	0x56	0x00 – Value lost
GyroRate	0x57	0x00 – Value lost

In the event of such errors, SENtral will enter Standby State, shut down the sensors, and generate an interrupt to the host. Possible reasons for hardware-related errors include problems with an external EEPROM upload, power transients detected by power management, and errors in software detected by Watchdog. Often the error can be cleared by sending the ResetReq command and reloading the Configuration File.

5.5.2 Software-Related Error Conditions

Possible indications of software-related errors are given below in Table 5-13:

Table 5-13: Software-Related Error Indications

Register Name	Address	Error Indication
EventStatus	0x35	[1] 1 = Error.
SensorStatus	0x36	Non-zero value indicates sensor-related error. Check sensors by communicating in Pass-Through State. See Table 5-14
SentralStatus	0x37	[3] 1 = Idle. SENtral in Initialized or Unprogrammed State.
ErrorRegister	0x50	Non-zero value indicated an error. See Table 5-15.

If the SensorStatus register indicates a non-zero value, then the value provides additional information on the sensor that is causing a problem, as given in Table 5-14.

Table 5-14: SensorStatus Register Indications

Register Name	Address	Error Indication
SensorStatus	0x36	[0] MagNACK. 1 = NACK from magnetometer [1] AccelNACK. 1 = NACK from accelerometer [2] GyroNACK. 1 = NACK from gyroscope [4] MagDeviceIDErr. 1 = Unexpected DeviceID from magnetometer [5] AccelDeviceIDErr. 1 = Unexpected DeviceID from accelerometer [6] GyroDeviceIDErr. 1 = Unexpected DeviceID from gyroscope.

If the ErrorRegister indicates a non-zero value, then the value provides additional information on the sensor that is causing a problem, as given in Table 5-15.

Table 5-15: ErrorRegister Indications

Value	Error Condition	Response
0x00	No error	
0x80	Invalid sample rate selected	Check sensor rate settings.
0x30	Mathematical Error	Check for software updates
0x21	Magnetometer initialization failed	This error can be caused by a wrong driver, physically bad sensor connection, or incorrect I^2C device address in the driver
0x22	Accelerometer initialization failed	
0x24	Gyroscope initialization failed	
0x11	Magnetometer rate failure	This error indicates the given sensor is unreliable and has stopped producing data.
0x12	Accelerometer rate failure	
0x14	Gyroscope rate failure	

6 SENtral Configuration Tool

Prior to using the SENtral Motion Coprocessor, it is necessary to generate the SENtral Configuration File using the SENtral Configuration Tool. The Configuration File contains information on how the sensor system is configured in the user's system. It should be stored in a dedicated EEPROM or in the host processor's memory. When SENtral is powered up the Configuration File needs to be uploaded into SENtral's RAM, as discussed in Section5.1.

The SENtral Configuration Tool provides an intuitive GUI which allows the user to easily generate the Configuration File. A screen shot of the tool is given in Figure 6-1, and a discussion of the settings follows. Once the various fields are correctly populated, click <Generate> to create the SENtral Configuration File. It will automatically download a zip file onto your computer containing the Configuration File, "sentral_[SDKrev]_[mag]_[accel]_[gyro].fw", and containing a .cfg file which provides the information input into the Configuration Tool. The .cfg file can be opened with a text editor. Additionally, the .cfg file can be uploaded into the Configuration Tool by clicking <Load Config> and then selecting the desired .cfg file.

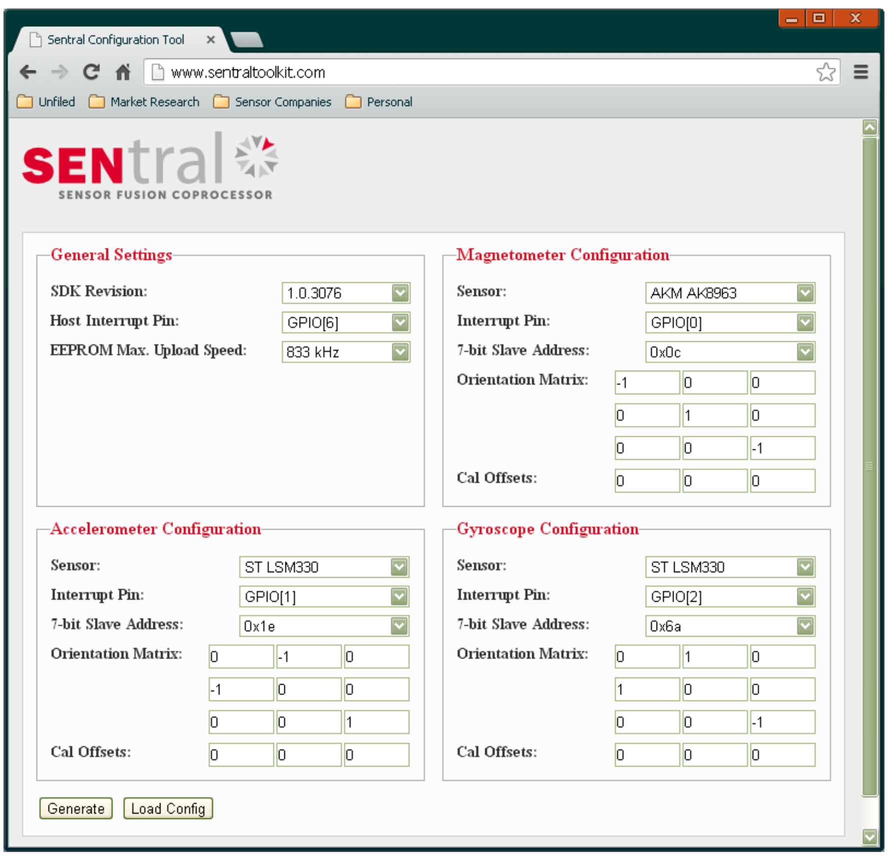


Figure 6-1: SENtral Configuration Tool

6.1 Configuration Tool General Settings

6.1.1 SDK Revision

This establishes the revision of the firmware to be generated. Normally the latest revision is most desirable, but prior revisions are retained for customers that have qualified older revisions.

6.1.2 Host Interrupt Pin

This establishes which GPIO pin is used to send an event interrupt to the host system. The default is GPIO[6], but any of the GPIO pins can be used for this function.

6.1.3 EEPROM Max. Upload Speed

If the user incorporates a dedicated EEPROM to store the SENtral's Configuration File, then this field establishes the maximum data rate the configuration EEPROM can accommodate. If there is no EEPROM, this setting has no meaning. SENtral automatically determines if a dedicated EEPROM is present.

6.2 Configuration Tool Sensor Configuration

The sensors attached to SENtral must be configured correctly for SENtral to properly function. The magnetometer, accelerometer, and gyroscope are configured in a similar manner, so the parameters discussed below apply to all three sensors.

6.2.1 Sensor

The drop-down menus are used to select the sensor models incorporated into the user's system. If a sensor is not listed, then a driver has not been developed for that sensor.

6.2.2 Interrupt Pin

This drop-down menu establishes which General Purpose IO pin is used to send a sensor interrupt signal to SENtral. As shown in the reference schematic, Figure 3-1, the default is to use GPIO[0] for the magnetometer, GPIO[1] for the accelerometer, and GPIO[2] for the gyroscope. However, the GPIO pins are interchangeable and can be configured as is most convenient for the user.

6.2.3 Slave Address

This establishes the slave address for the respective sensor, and the user needs to input the sensor's slave address here. The 7-bit slave address will be provided in the sensor's technical data sheet and normally will be a function of 5 or 6 fixed bits and 1 or 2 bits that are configurable by 1 or 2 of the sensor's pins.

6.2.4 Orientation Matrix

This matrix defines how the sensors are physically laid out in the host system. The values are normally 1s, -1s, or 0s. The matrix is used to convert the physical layout into a north-east-down (NED) convention, where "north" is defined as the line-of-sight or direction of travel. The matrix is defined as shown in the equation below:

$$\begin{bmatrix} N \\ E \\ D \end{bmatrix} = \begin{bmatrix} A & B & C \\ D & E & F \\ G & H & I \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

where A through I are the matrix values that need to be populated (1s or 0s), X, Y, and Z represent the orientation of the x-axis, y-axis, and z-axis sensors, where north is defined as the line of sight, and NED is the north-east-down convention that the orientation matrix converts [X, Y, Z] into.

For the accelerometer matrix, it is necessary to multiply the matrix by –1.

Examples:

Below are three examples. The first is if the sensor is laid out in an NED convention, such that the x-axis points north, the y-axis points east, and the z-axis points down. Recall that "north" is defined as the line-of-sight or direction of travel. In this case the orientation matrix is the identity matrix, as given below.

$$\begin{bmatrix} N \\ E \\ D \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} N \\ E \\ D \end{bmatrix}$$

Another common convention is east-north-up (ENU), where the x-axis points east, the y-axis points north, and the z-axis points up, in which case the orientation matrix and associated matrix math are given below.

$$\begin{bmatrix} N \\ E \\ D \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} E \\ N \\ U \end{bmatrix}$$

The final example is west-south-down (WSD). This matrix would be appropriate for an ENU accelerometer, since it incorporates the -1 multiplication factor. The orientation matrix and associated matrix math are given below.

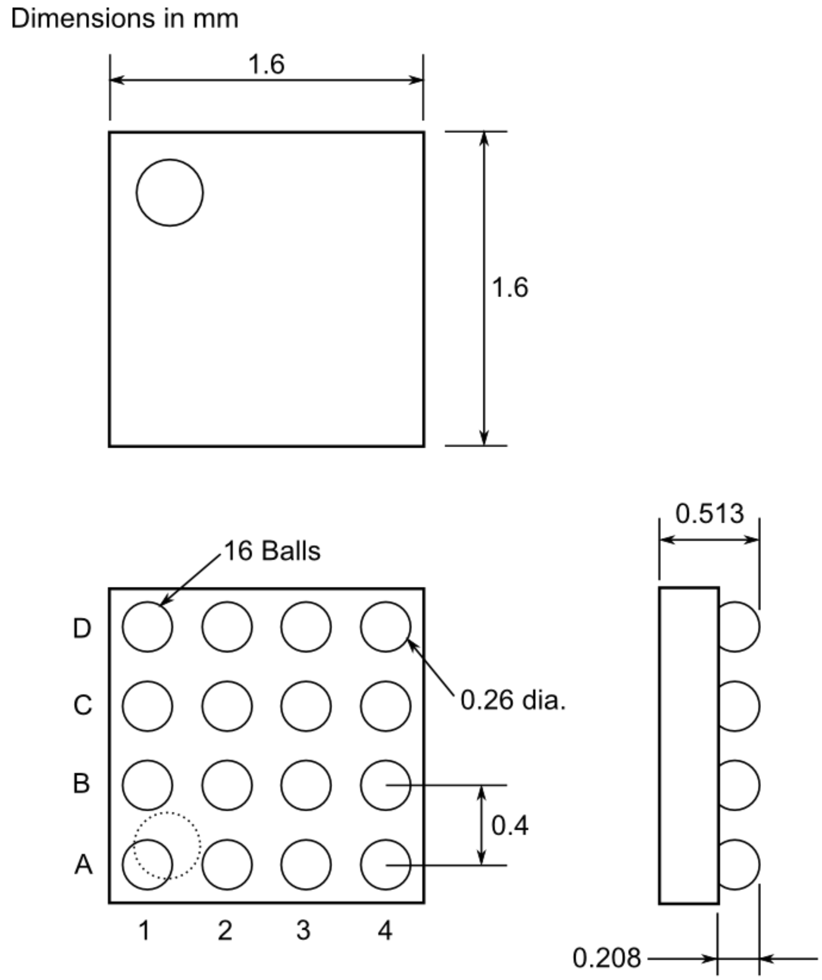
$$\begin{bmatrix} N \\ E \\ D \end{bmatrix} = \begin{bmatrix} 0 & -1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} W \\ S \\ D \end{bmatrix}$$

6.2.5 Cal Offsets

Normally these fields will be '0'. However if the user has information indicating a given model of sensor consistently has a fixed measurement offset, then these fields allow the user to tailor the SENtral algorithm. For example, assume statistical data from a manufacturer regarding their accelerometer indicates their z-axis sensor has an average reading of 1.1 g when actually experiencing 1.0 g of gravitational force. In this case, the user can enter an offset on the z-axis of 0.1g for the accelerometer. The fields are given in X, Y, Z order, and the units are as follows:

- Magnetometer: 1.0 = +50 µT
- Accelerometer: 1.0 = +1 g
- Gyroscope: 1.0 = +1 radian/second

7 Package Information



Note: **For Pin-Out, see**

Table 3-1

Figure 7-1: Mechanical Drawing

Dimensions in mm

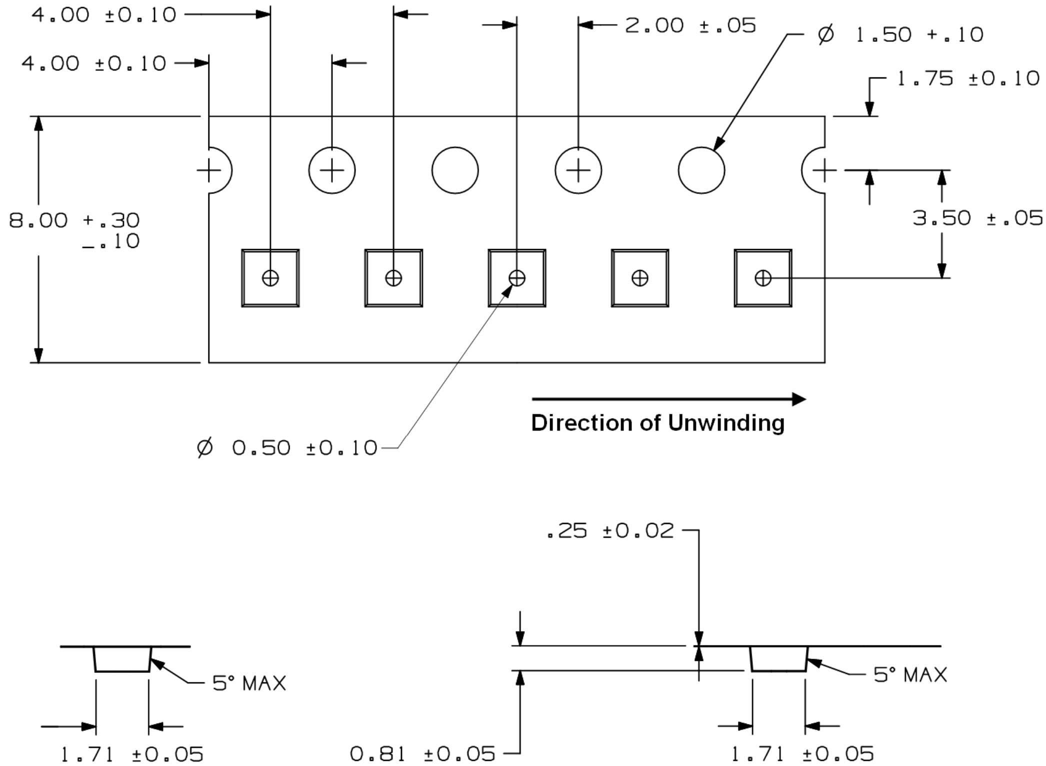


Figure 7-2: Tape Dimensions

8 Assembly Guidelines

SENtral is provided in a lead-free wafer-level chip-scale package (WL-CSP). General design guidelines can be found in Amkor's "Application Note for Surface Mount Assembly of Amkor's Eutectice and Lead-Free CSP^{nl} ™ Wafer Level Chip Scale Packages", which is available from Amkor's website. Specific assembly guidelines are discussed below.

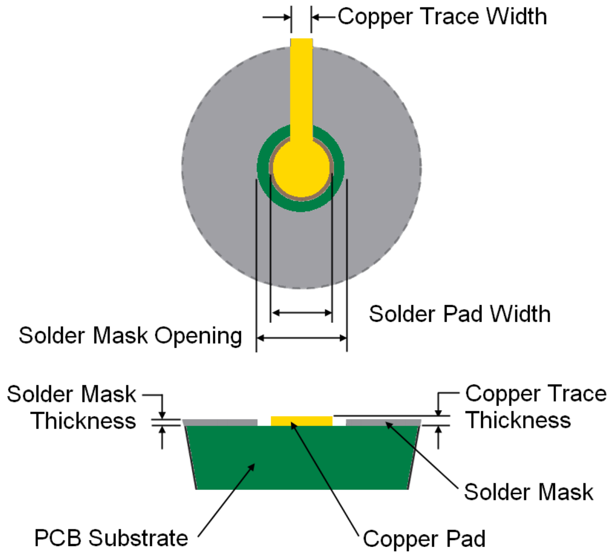
Comments specific to SENtral include:

- Microvia technology is NOT required if GPIO[3] and GPIO[5] are not used and the slave address pin, SA0, is set LOW. In this case the slave address pin, C3, should be connected to C2 (unused), and C2 should be connected to D2, which is GND. Pins B2, GPIO[5], and B3, GPIO[3], should be left unconnected.
- If either GPIO[3] and GPIO[5] are to be used or the slave address pin, SA0, is to be set HI, then microvia technology is required. Due to SENtral's ball-grid-array 0.4 mm pitch and 0.26 mm ball diameter, connections to these inner pins should be made with a via-in-pad design using microvias.

General CSP assembly guidelines for SENtral include:

- A non-solder mask defined (NSMD) land pattern is recommended.
- Solder mask registration is critical and the correct solder mask opening dimension should be 50um either side of the copper pad.
- The actual size of the copper pad should be between 80% and 100% of the diameter of the solder ball.
- The copper layer thickness should 30 um or less.
- The copper pads should be finished with Organic Solderability Preservative (OSP) coating, such as ENTEK-PLUS Cu 106A.
- Standard epoxy glass PCB substrates are compatible. High temperature FR4 is preferred over standard FR4 for improved package reliability.

Figure 8-1 provides design parameters for a typical SENtral solder mask and pad pattern.



Pitch	0.4 mm
Nominal Sphere Diameter (µm)	250
UBM Diameter (µm)	205
Bump Height (µm)	210
Bump Diameter (µm)	260

PCB Design Parameters

Solder Pad Width (µm)	225
Solder Mask Opening (µm)	325
Solder Mask Thickness (µm)	25
Copper Trace Thickness(µm)	30
Copper Trace Width (µm)	100

Figure 8-1: Typical Solder Mask and Land Pad Parameters

A typical recommended solder reflow profile is given in Figure 8-2 and the associated processing parameters are given in Table 8-1, both on the following page. Oven type and tolerances, thermocouple tolerance, solder type, and the temperature difference across the board will affect the actual implemented profile.

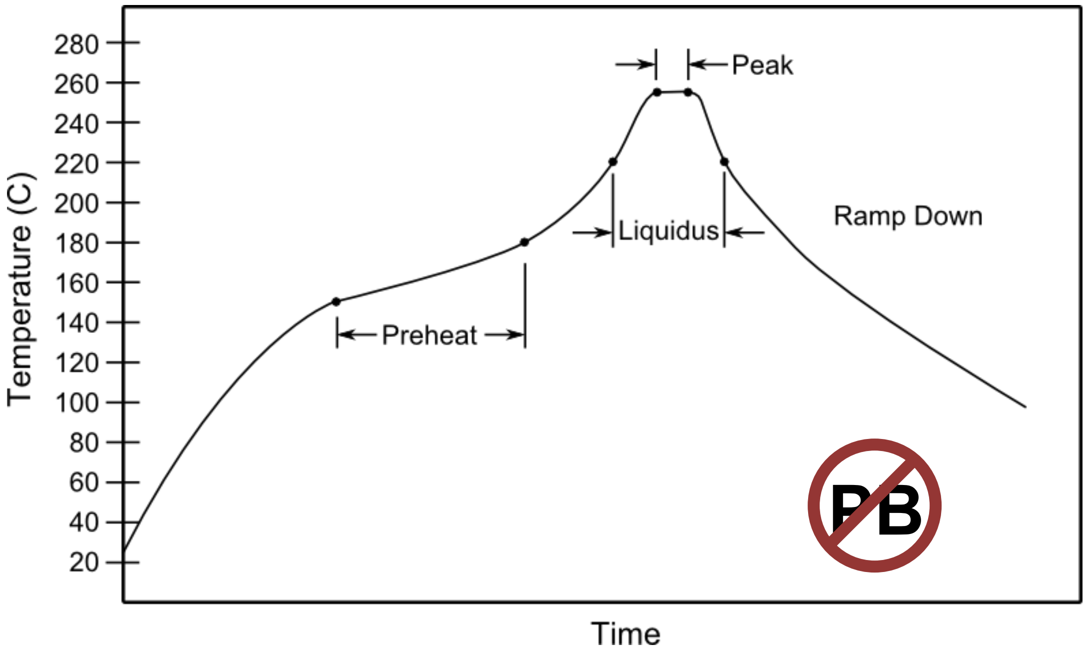


Figure 8-2: Typical Solder Reflow Profile

Table 8-1: Typical Solder Processing Parameters

Parameter	Value
Ramp Up Rate	3°C/second
Preheat Temperature Range	150°C to 180°C
Preheat Time	60 – 180 seconds
Liquidus Temperature	220°C
Time above Liquidus	30 – 90 seconds
Peak Temperature	255°C ±5°C
Time within 5°C of Peak Temperature	10 – 20 seconds
Ramp Down Rate	6°C/second maximum

Appendix I – Converting Quaternions

SENtral outputs orientation data in quaternions, using a North-East-Down (NED) convention. This is done to avoid the singularities inherent in using Euler angles (heading, pitch, and roll), and because the fusion algorithms are easier to implement with quaternions. However, normally quaternions are not the desired final output format. Most end users will want heading, pitch, and roll, while Android looks for a rotation vector and generally uses a rotation matrix for orientation. Plus, Android and Win8 both expect data to be presented in the East-North-Up (ENU) convention. This appendix discusses how to convert SENtral's output quaternions into these other output formats.

Converting from NED to ENU

While the North-East-Down (NED) convention is common in many industries, both Android and Windows 8 use the East-North-Up convention. Below is the equation to convert from NED to ENU.

$$Q_{ENU} = \left(\begin{pmatrix} 0.707 & 0.707 & 0 & 0 \end{pmatrix} \begin{bmatrix} Qw & -Qz & Qy & -Qx \\ Qz & Qw & -Qx & -Qy \\ -Qy & Qx & Qw & -Qz \\ Qx & Qy & Qz & Qw \end{bmatrix}_{NED} \right) \begin{bmatrix} 0 & 0 & -0.707 & 0.707 \\ 0 & 0 & 0.707 & 0.707 \\ 0.707 & -0.707 & 0 & 0 \\ -0.707 & -0.707 & 0 & 0 \end{bmatrix}$$

Heading, Pitch, and Roll

Most end users will want orientation data reported as heading, pitch, and roll. Below are the Excel transformation equations. Note that for other programs, such as Matlab, the ATAN2 arguments may be reversed.

- Heading = atan2[($Qx^2 – Qy^2 – Qz^2 + Qw^2$), 2*(QxQy + QzQw)]
- Pitch = asin[-2*(QxQz – QyQw)]
- Roll = atan2[($–Qx^2 – Qy^2 + Qz^2 + Qw^2$), 2*(QxQw + QyQz)]

Where:

- Results are in radians.
- The quaternions are the outputs from SENtral in NED convention.
- Heading increases as the device rotates clockwise around a positive Z axis, and the range is 0° – 360°. (i.e. it matches what you would expect on a compass.)
- Pitch increases when pitching upward and the range is ±180°.
- Roll increases when rolling clockwise and the range is ±90°.

Rotation Vector

The rotation vector is the first three elements of the quaternion output, Qx, Qy, and Qz. The fourth element, Qw, is not included in the rotation vector. The rotation vector in ENU convention will be the first three elements of Q_{ENU}, discussed above.

Rotation Matrix, or Direction Cosine Matrix (DCM)

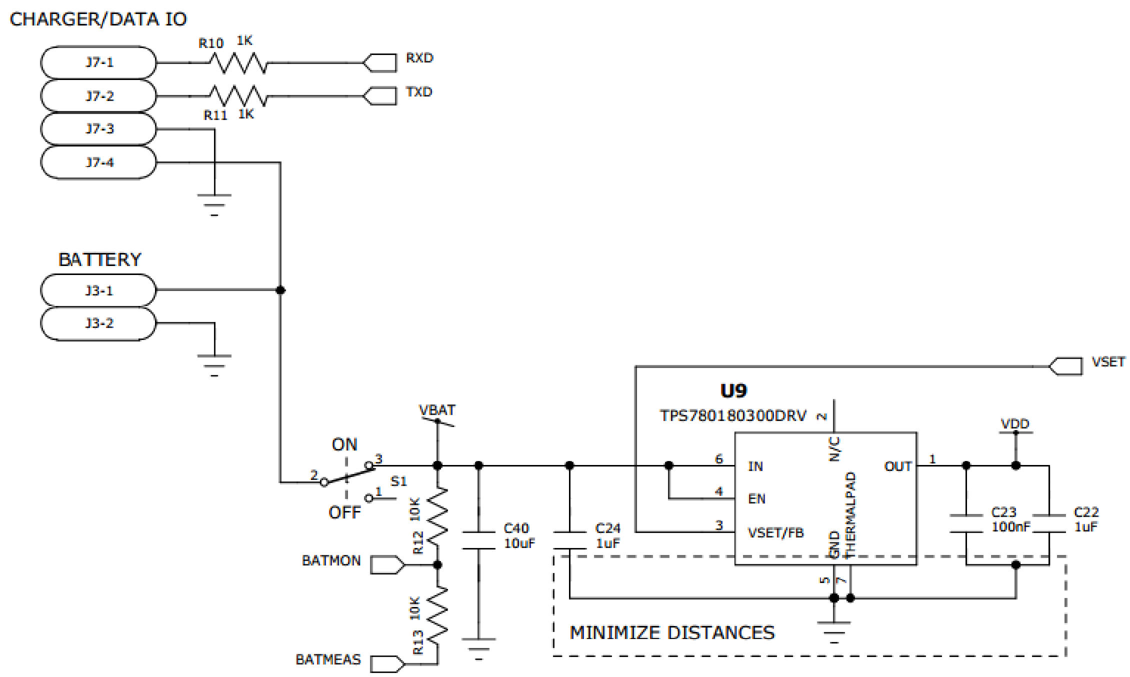
The rotation matrix, also known as the direction cosine matrix (DCM), can be established from the quaternion output using the following conversion. Q_{ENU} values can be substituted to give the rotation matrix with an ENU convention.

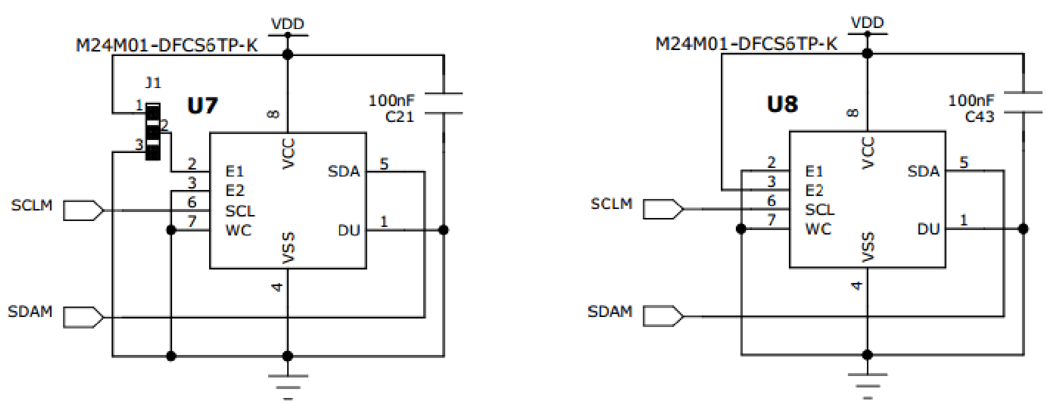
R =

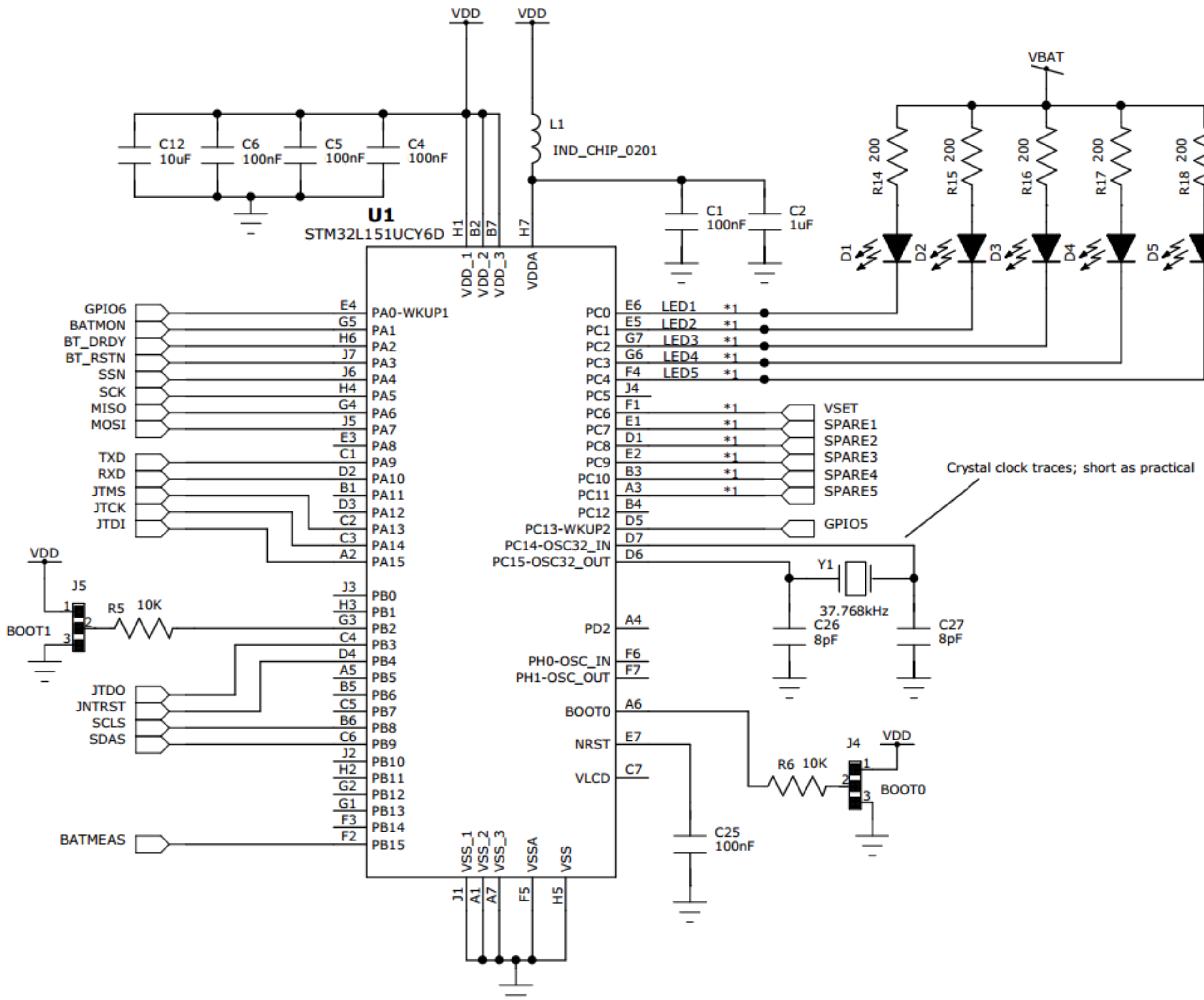
$Qw^2 + Qx^2 – Qy^2 – Qz^2$	2*(Qx*Qy + Qw*Qz)	2*(Qx*Qz – Qw*Qy)
2*(Qx*Qy – Qw*Qz)	$Qw^2 – Qx^2 + Qy^2 – Qz^2$	2*(Qy*Qz + Qw*Qy)
2*(Qx*Qz + Qw*Qy)	2*(Qy*Qz – Qw*Qy)	$Qw^2 – Qx^2 – Qy^2 + Qz^2$

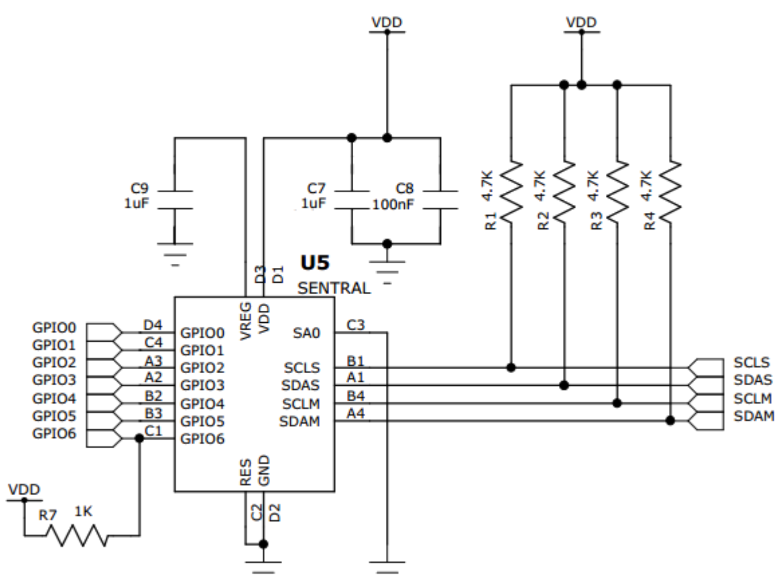
Appendix II – Sample Schematic Set

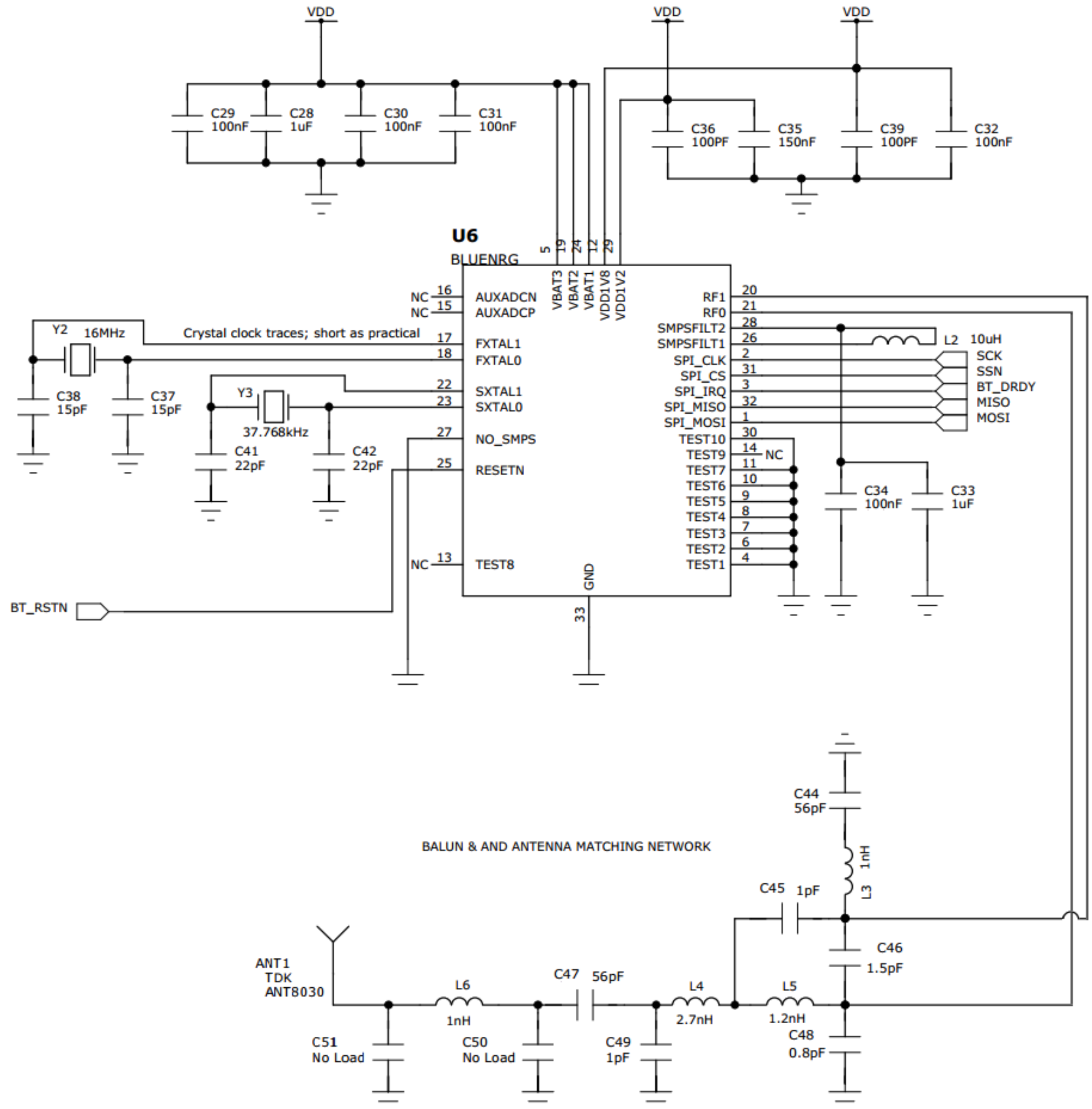
The schematics provided are for a complete Bluetooth-enabled device incorporating SENtral and either an ST LSM9DS0 9-axis sensor or an ST LSM330 gyro/accel combo sensor with an AKM AK8963C magnetometer. Except for the last schematic, the schematics are common regardless of sensors.



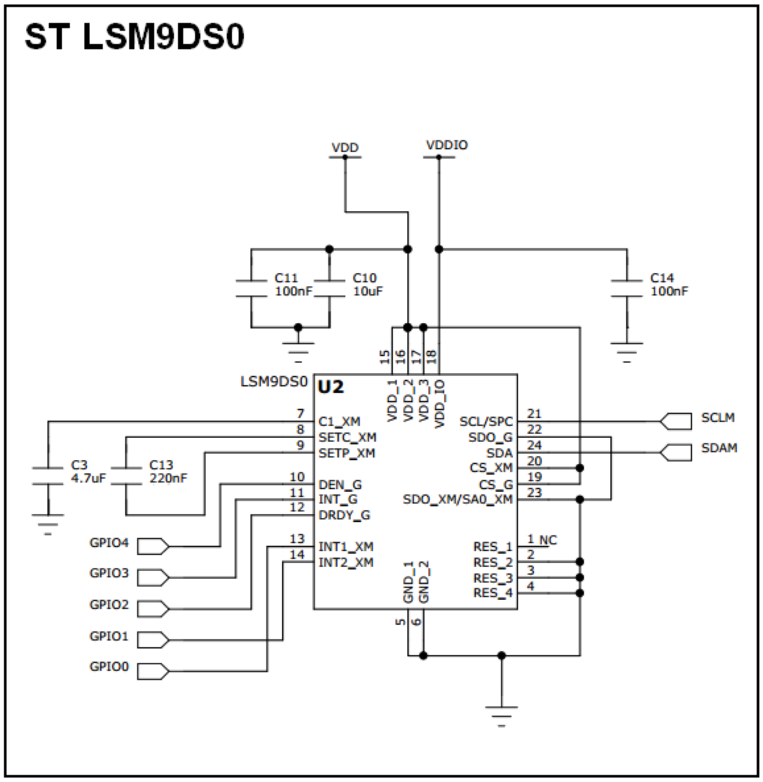


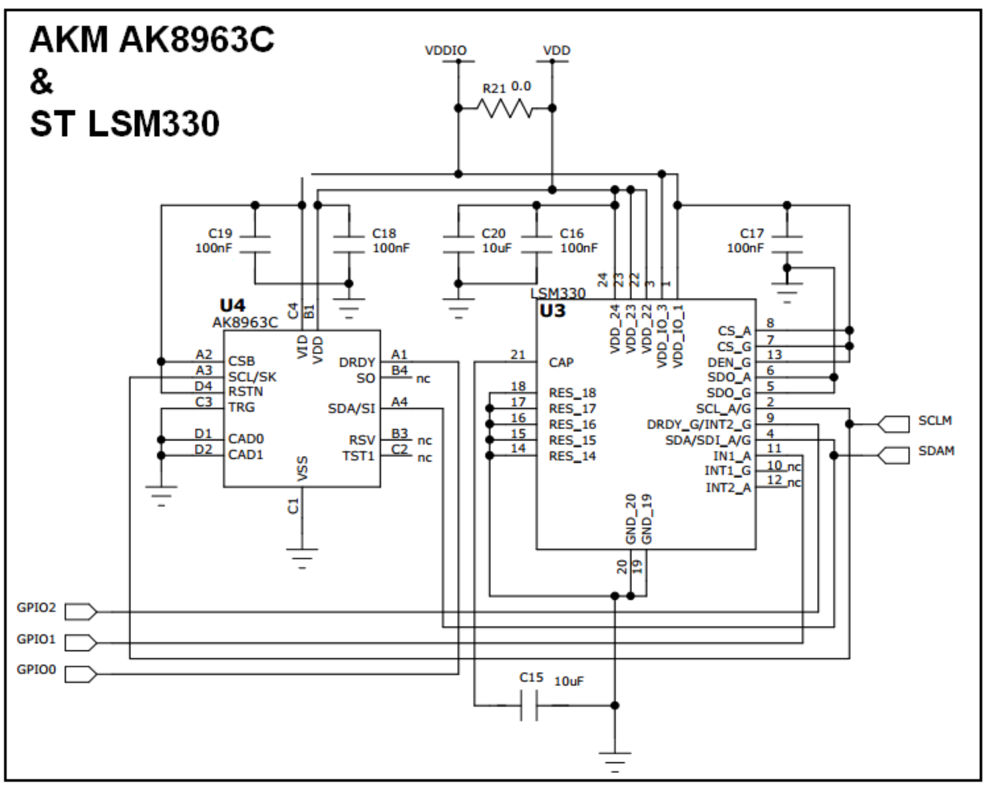

VDD
VDD
VBAT
C12
10uF
C6
100nF
C5
100nF
C4
100nF
L1
IND_CHIP_0201
C1
100nF
C2
1uF
R14 200
R15 200
R16 200
R17 200
R18 200
D1
D2
D3
D4
D5
U1
STM32L151UCY6D
H1
B2
B7
H7
VDD_1
VDD_2
VDD_3
VDDA
GPIO6
BATMON
BT_DRDY
BT_RSTN
SSN
SCK
MISO
MOSI
TXD
RXD
JTMS
JTCK
JTDI
E4 PA0-WKUP1
G5 PA1
H6 PA2
J7 PA3
J6 PA4
H4 PA5
G4 PA6
J5 PA7
E3 PA8
C1 PA9
D2 PA10
B1 PA11
D3 PA12
C2 PA13
C3 PA14
A2 PA15
PC0 E6 LED1 *1
PC1 E5 LED2 *1
PC2 G7 LED3 *1
PC3 G6 LED4 *1
PC4 F4 LED5 *1
PC5 J4
PC6 F1 *1 VSET
PC7 E1 *1 SPARE1
PC8 D1 *1 SPARE2
PC9 E2 *1 SPARE3
PC10 B3 *1 SPARE4
PC11 A3 *1 SPARE5
PC12 B4
PC13-WKUP2 D5 GPIO5
PC14-OSC32_IN D7
PC15-OSC32_OUT D6
Crystal clock traces; short as practical
Y1
37.768kHz
C26
8pF
C27
8pF
VDD
J5
BOOT1
R5 10K
J3 PB0
H3 PB1
G3 PB2
C4 PB3
D4 PB4
A5 PB5
B5 PB6
C5 PB7
B6 PB8
C6 PB9
J2 PB10
H2 PB11
G2 PB12
G1 PB13
F3 PB14
F2 PB15
JTDO
JNTRST
SCLS
SDAS
BATMEAS
PD2 A4
PH0-OSC_IN F6
PH1-OSC_OUT F7
BOOT0 A6
NRST E7
VLCD C7
R6 10K
J4
VDD
BOOT0
C25
100nF
VSS_1
VSS_2
VSS_3
VSSA
VSS
J1
A1
A7
F5
H5


VDD
VDD
C9
1uF
C7
1uF
C8
100nF
R1 4.7K
R2 4.7K
R3 4.7K
R4 4.7K
U5
SENTRAL
D3
D1
VREG
VDD
GPIO0 D4 GPIO0
GPIO1 C4 GPIO1
GPIO2 A3 GPIO2
GPIO3 A2 GPIO3
GPIO4 B2 GPIO4
GPIO5 B3 GPIO5
GPIO6 C1 GPIO6
SA0 C3
SCLS B1
SDAS A1
SCLM B4
SDAM A4
SCLS
SDAS
SCLM
SDAM
RES
GND
C2
D2
VDD
R7 1K


VDD
C29 100nF
C28 1uF
C30 100nF
C31 100nF
C36 100PF
C35 150nF
C39 100PF
C32 100nF
U6
BLUENRG
Y2 16MHz
Crystal clock traces; short as practical
C38 15pF
C37 15pF
Y3
37.768kHz
C41 22pF
C42 22pF
AUXADCN
AUXADCP
FXTAL1
FXTAL0
SXTAL1
SXTAL0
NO_SMPS
RESETN
TEST8
GND
VBAT3
VBAT2
VBAT1
VDD1V8
VDD1V2
RF1
RF0
SMPSFILT2
SMPSFILT1
SPI_CLK
SPI_CS
SPI_IRQ
SPI_MISO
SPI_MOSI
TEST10
TEST9
TEST7
TEST6
TEST5
TEST4
TEST3
TEST2
TEST1
NC
L2 10uH
SCK
SSN
BT_DRDY
MISO
MOSI
C34 100nF
C33 1uF
BT_RSTN
C44 56pF
BALUN & AND ANTENNA MATCHING NETWORK
L3 1nH
C45 1pF
C46 1.5pF
ANT1 TDK ANT8030
L6 1nH
C47 56pF
L4 2.7nH
L5 1.2nH
C48 0.8pF
C51 No Load
C50 No Load
C49 1pF

**There are 2 sensor layouts shown on this page.
Only one should be used, or the OEM may select
a different sensor set and generate their own layout.**





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Revision History

Rev.	E.C.N.	Pages	Date(m/d/y)	Resp.	Description
1.0		48	01/16/2014	M. Becvar	Updated to R1.0 PNI Sentral Datasheet