The Growing Use of Sensors and the Challenges of Always-on Sensor Processing

Carmelo Sansone
NXP Semiconductors

ARM TechCon
November 11, 2015
Agenda

• Sensor basics
  • Target applications
  • Sensor processor architectures

• Low power MCUs for always-on sensor processing

• Sensor processing use cases

• Challenges of including sensors in your applications

• Sensor framework and sensor fusion

• Power optimization consideration

• Demos
Sensor target applications

**Mobile**
- indoor navigation
- context awareness
- mobile gestures

**In products such as:**
- mobile handsets
- tablets

**Health & Fitness**
- biometric data monitoring and communication

**In products used for:**
- portable fitness
- health monitoring

**Gaming / Entertainment**
- console orientation
- user motion

**In products such as:**
- 3D mouse
- head-worn glasses/terminals
- gloves with sensors

**Industrial**
- environment monitoring
- position
- positional accuracy, stability or balance
- dead reckoning
- intelligent sensing
- building automation
- fleet management
- asset tracking
- robotics & drones
- assembly line robots

**In products used for**
<table>
<thead>
<tr>
<th>Sensor</th>
<th>Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerometer</td>
<td>(3-axis) Acceleration. Measure change in velocity</td>
</tr>
<tr>
<td>Gyroscope</td>
<td>(3-axis) Angular velocity</td>
</tr>
<tr>
<td>Magnetometer</td>
<td>(3-axis) Strength or direction of magnetic fields</td>
</tr>
<tr>
<td>Pressure</td>
<td>Environment air pressure, altitude</td>
</tr>
<tr>
<td>Humidity</td>
<td>Relative humidity in the air</td>
</tr>
<tr>
<td>Temperature</td>
<td>Environmental temperature</td>
</tr>
<tr>
<td>Heartbeat</td>
<td>Heart rate</td>
</tr>
<tr>
<td>Poison gas</td>
<td>Detect presence of poisonous gases (Ex. CO, smoke)</td>
</tr>
</tbody>
</table>

Sensor fusion software is used to integrate data from these 3 sensors (9-axis) and generate an accurate position in space.
## Target applications

<table>
<thead>
<tr>
<th>Product</th>
<th>Sensors</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Accelerometer</td>
<td>navigation, context awareness, altitude</td>
</tr>
<tr>
<td></td>
<td>Gyroscope</td>
<td></td>
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<tr>
<td></td>
<td>Magnetometer</td>
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<tr>
<td></td>
<td>Pressure</td>
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<td></td>
<td>Temperature</td>
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<td></td>
<td>Humidity</td>
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<tr>
<td></td>
<td>Proximity</td>
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<tr>
<td></td>
<td>Biometrics</td>
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<tr>
<td>Smartphone</td>
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<tr>
<td>Asset tracking</td>
<td>●</td>
<td>dead reckoning, fleet management, product location</td>
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<tr>
<td>IoT nodes</td>
<td>●</td>
<td>building automation</td>
</tr>
<tr>
<td>Robot &amp; unmanned vehicles</td>
<td>●</td>
<td>navigation, positioning, stability and control</td>
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<td>●</td>
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</tr>
<tr>
<td>Wearable sensors</td>
<td>●</td>
<td>pedestrian navigation, head worn terminal, smart glasses, patient monitoring</td>
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<td>●</td>
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<td>●</td>
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<tr>
<td>Gaming</td>
<td>●</td>
<td>enhanced user interface</td>
</tr>
<tr>
<td>Pointing devices</td>
<td>●</td>
<td>3D mouse, remote controls</td>
</tr>
<tr>
<td>Health and fitness</td>
<td>●</td>
<td>calorie counter, remote patient activity monitoring</td>
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</tbody>
</table>
Sensor processor architectures

### AP + sensor hub MCU:
1-3 days battery life, ASP $200

**Diagram:**
- Display
- Application Processor
- MCU
- NTAG
- BTLE
- Wi-Fi
- GPS

### Sensor hub MCU:
3-7+ days battery life, ASP $100-$150

**Diagram:**
- Display
- USB
- MCU
- NTAG
- BTLE
- Wi-Fi
- GPS

**Devices:**
- LG G Watch R
- Qualcomm Toq
- Apple Watch
- Shine (Misfit)
- Nike+ FuelBand
- Fitbit
- Jawbone

**Phones:**
- Apple iPhone 5s
- Samsung Galaxy S5
LOW-POWER MCUS FOR ALWAYS-ON SENSOR-PROCESSING
NXP LPC5410x MCUs: Ultra-low power for always-on sensor-processing applications

- **Scalable power/performance**
  - 100 MHz Cortex-M0+ core: 55 µA/MHz for listening, data aggregation, management, and data communication
  - 100 MHz Cortex-M4F core: 100 µA/MHz for sensor fusion and other complex algorithms
- **Down to 3 µA for sensor listening** (power down mode with RAM retention)
- **Power-efficient ADC**: full spec performance (12-bit, 4.8 Msps), any voltage (1.62 to 3.6 V)
- **Tiny form factors** for space-constrained designs, down to 3.28 x 3.28 mm WLCSP
Example: 20% power savings in typical portable fitness device

<table>
<thead>
<tr>
<th>Task</th>
<th>LPC54102</th>
<th>Other MCU*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Listen (power down mode; no CPU processing)</td>
<td>3 µA</td>
<td>9 µA</td>
</tr>
<tr>
<td>Read (I²C &amp; ADC) (10 sps @ 12 MHz CPU)</td>
<td>55 µA/MHz (Cortex-M0+)</td>
<td>112 µA/MHz (Cortex-M4F)</td>
</tr>
<tr>
<td>Algorithm Processing (Once per sec @ 84 MHz CPU)</td>
<td>100 µA/MHz (Cortex-M4F)</td>
<td>112 µA/MHz (Cortex-M4F)</td>
</tr>
</tbody>
</table>

*LPC54102 is 20% more power efficient than closest competitor

*datasheet spec
Low-power peripherals

**Low-power analog**
- ADC: 4.8 Msps across entire operating spec
- 40% power savings by operating at lower voltage

![Diagram showing power comparison between 1.62 V and 3.6 V with 40% power savings at the same sampling rate](image)

**Low-power interfaces**
- Separate system clock
- Peripheral active in power down

![Diagram showing clock sources and peripheral power consumption](image)

Reduce peripherals power consumption impact

**4.8 Msps**
- LPC5410x
- MCU ‘S’

**1.62 V**
**3.6 V**

**40% power savings (at same sampling rate)**
- LPC5410x
- MCU ‘S’
SENSOR PROCESSING USE CASES
LPC5410x application
Mobile phones, tablets & laptops

• Saves power by offloading sensor processing from AP; wakes up AP only when required
  • Wake-up on SPI/I2C activities from AP
  • Hs-mode I2C (3.4 Mbps) Slave interface to AP

• Large RAM supports
  • Sensor data batching
  • More simultaneous use cases: context awareness, voice detection, indoor navigation

<table>
<thead>
<tr>
<th>Sensor data</th>
<th>Sample rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerometer</td>
<td>100 Hz</td>
</tr>
<tr>
<td>Magnetometer</td>
<td>25 Hz</td>
</tr>
<tr>
<td>Gyroscope</td>
<td>100 Hz</td>
</tr>
<tr>
<td>Rotation vector</td>
<td>50 Hz</td>
</tr>
</tbody>
</table>

Example of a batching data burst

<table>
<thead>
<tr>
<th>Acc</th>
<th>Mag</th>
<th>Acc</th>
<th>Lin. Acc.</th>
<th>Rotation</th>
</tr>
</thead>
</table>

AP interrupts f > 200Hz

Reduce AP interruptions, extend AP and sensor hub power down time reduce power consumption
LPC5410x application
Industrial asset monitoring & tracking

- Eliminates need for separate MCUs for listening and communication
  - Cortex-M4 with FPU for sensor processing and communication
  - 100 MHz Cortex-M0+ for sensor data aggregation
  - 12-bit, 4.8 Mbps ADC for high-precision analog sensor interface

- Free motion sensor fusion software

- 3.28 x 3.28 mm WLCSP package

POWER
3 µA low power mode with RAM retention for listening
Full-spec 4.8 Msps 12-bit ADC over full voltage range: 1.62 to 3.6V
LPC5410x application
Health & fitness / portable devices

- Extends battery run-time with full spec ADC down to 1.62V
  - ARM Cortex-M4 with FPU for sensor processing and communication
  - 100 MHz ARM Cortex-M0+ for sensor data aggregation
  - 12-bit, 4.8 Mbps ADC for high-precision analog sensor interface, full spec over voltage range: 1.62 to 3.6V

**POWER**
Low power mode with RAM retention
100 nA lowest power mode
Low voltage down to 1.62 V
CHALLENGES OF INCLUDING SENSORS IN YOUR APPLICATIONS
Challenges of including sensors in your applications

Need to add 6- or 9-axis motion to your application, integrating a sensor fusion library is too complex.

I do not want to pay for 3rd party license fees. Most of these vendors will not support me anyway.

Low power system optimization as well as tools to measure power consumption all in one place.
LPC54201 Sensor Processing/Motion Solution

- **Includes**
  - LPCXpresso54102 development board
    - Built-in high-speed USB debug probe
    - Power measurement tool
  - **Sensor shield board** with
    - Bosch Sensortec sensors: magnetometer, accelerometer, gyroscope, pressure
    - Maxim ambient light and proximity sensor
    - ACKme Bluetooth LE module

- **Optimized for expansion**
  - Stackable hardware supports more sensors or adding plug-in modules
  - A large set of pinouts for measurement and prototyping
  - Choice of onboard or external debug probes
LPC54201 Sensor Processing/Motion Solution
Flexible board architecture

Sensor shield board

<table>
<thead>
<tr>
<th>Bosch</th>
<th>LPCXpresso54102</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMC150</td>
<td>Link2 debug probe</td>
</tr>
<tr>
<td>BMM150</td>
<td>current probe</td>
</tr>
<tr>
<td>BMI055</td>
<td>LPC54102</td>
</tr>
<tr>
<td>BMP280</td>
<td>USB</td>
</tr>
</tbody>
</table>

Expansion connector

UART, SPI, I^2C, GPIO, ADC inputs

User buttons
- Reset
- Wake
- ISP

Prototype Header

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LPC54201 Sensor Processing/Motion Solution
Integrated software & middleware

- **LPC sensor framework**
  - Modular and integrated sensor drivers and sensor fusion library to accelerate product time to market
  - Power management for low power operations

- **Bosch BSXLite sensor fusion library**
  - Combines sensor data to get more accurate sensor signal or derived sensory information
  - Supports 6-axis & 9-axis motion vectors
  - Quaternions, heading, pitch and roll data output
  - Android 4.x support
  - Commercial and development license included

- **Drivers**
  - Bosch sensors
  - LPCOpen driver library
Software Stack

BSXlite Library

Algorithm Adapter

Main()

Enter_PowerPLL/IRC-Mode()

Enter_PowerDownMode()

Timer/Power Management

Kernel Timer (WDT)

Power Manager

ROM Power Library

Host I/F Handler

Command Handler

Tx Ringbuffer Management

I²C/SPI Slave Driver

Chip_I2CM_...() / Chip_SPIM_...()

CHIP_SleepOk()

Sensor_SetDelay()

Data pending

init/read/activate/setDelay()

dev_i2c_write/read/delay()

getCurrentTime()

Sensor data ready pin interrupt

Sensor_Enable()

Sensor_Process()

Sensor_Process()

Sensor_Enable()

Sensor_Process()

Sensor_Process()

Sensor_Process()

hostif_CmdProcess()

hostif_StartTx()

Hostif_QueueBuffer()

Algorithm_Process()

Algorithm_EnableSensor()

Hostif_SleepOk()

LPCOpen Driver Library

Teapot PC App

Sensors

IRQ

I²C

IRQ

I²C
Challenges for implementing sensor fusion

- Quality of sensor fusion data depends on sensor calibration and sensor noise suppression
- Magnetic disturbances must be detected and carefully handled
- Sensor data fusion with Kalman filter is a very complicated process involving various rounds of data simulation

### Top quality traits when evaluating sensor fusion performance

- No magnetic distortion
- No delay after movement
- No Jitter
- Heading accuracy

---

Sensor Data Fusion with Kalman Filter

<table>
<thead>
<tr>
<th>Accelerometer</th>
<th>Gyroscope</th>
<th>Magnetometer</th>
</tr>
</thead>
</table>

9-axis quaternion and rotational vectors combination with improved estimation of measured variable

---

"The Kalman filter is a set of mathematical equations that provides an efficient computational (recursive) means to estimate the state of a process, in a way that minimizes the mean of the squared error. The filter is very powerful in several aspects: it supports estimations of past, present, and even future states, and it can do so even when the precise nature of the modeled system is unknown." (G. Welch and G. Bishop, 2004)
Sensor – generic interface

- A large set of motion and not type of sensors are supported
- The SensorMap array defines which type of virtual sensors are supported
- Data from enabled virtual sensors can be read using BSXlite library function calls
## BSXlite vs. BSX

<table>
<thead>
<tr>
<th></th>
<th>BSXlite</th>
<th>BSX (full library)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Release format</strong></td>
<td>Closed source code / compiled library</td>
<td>Closed source code / compiled library</td>
</tr>
<tr>
<td><strong>License</strong></td>
<td>Click-through on LPCWare.com</td>
<td>Contact Bosch Sensortec</td>
</tr>
<tr>
<td><strong>Support / Maintenance</strong></td>
<td>Limited (via LPCWare.com)</td>
<td>Full</td>
</tr>
<tr>
<td><strong>KEY FEATURES</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Offset correction</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Soft Iron Correction</td>
<td>✗ (can be implemented outside library)</td>
<td>✓</td>
</tr>
<tr>
<td>Accelerometer calibration</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>Magnetometer calibration</td>
<td>Classic: based on figure-of-eight motion</td>
<td>Classic and advanced (fast calibration)</td>
</tr>
<tr>
<td>Magnetic distortion check</td>
<td>Basic</td>
<td>Advanced</td>
</tr>
<tr>
<td>Gyroscope calibration</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>9-axis orientation processing</td>
<td>Basic (tilt compensation)</td>
<td>Advanced (adaptive filtering, tilt compensation)</td>
</tr>
<tr>
<td>Compass orientation processing</td>
<td>Basic (tilt compensation)</td>
<td>Advanced</td>
</tr>
<tr>
<td>Data fusion mode</td>
<td>9-axis</td>
<td>9-axis &amp; 6-axis (IMU, M4G, eCompass)</td>
</tr>
<tr>
<td><strong>SYSTEM REQUIREMENTS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ROM</td>
<td>52 K</td>
<td>67 K</td>
</tr>
<tr>
<td>RAM</td>
<td>2 K</td>
<td>7 K</td>
</tr>
</tbody>
</table>

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How to optimize power consumption

All peripherals that are not used throughout the runtime are clock-gated, and if possible, power gated.

Carefully select code sections that are executed at high CPU speed using the PLL as main clock source, and code sections are executed at low speed, using the 12 MHz IRC

Choosing the right low-power mode
- The low-power mode significantly reduces both the static and dynamic power
- The power manager has a single function ResMgr_EnterPowerDownMode() to enter a low-power state
- A Power API is used to configure the internal voltage regulator to its lowest setting
Optimize scalable power/performance profile

- **Power scaling**
  - Maximize time spent in low-power mode by decreasing the time spent in active mode
  - Optimize power consumption for any voltage/frequency, IO load
  - Dynamically scale frequency for each task
  - For all interrupts and housekeeping tasks, the CPU is clocked from the 12 MHz IRC
  - For the sensor fusion algorithm, the CPU is at 84 MHz

- Sensor fusion (~25 mW) at 84 MHz
- Sensor sampling (~5 mW) at 12 MHz
- Near-zero power is measured in power-down mode
- Average current is 1.29 mA
Five steps to get started with LPCXpresso

1. Open the NXP Sensorhub LPCOpen(v2.14.1sh), BSXLite Setup.
2. Accept the license agreement.
3. Import the project archive.
4. Unpack the directory.
5. Finish the import process.
Source-code directory structure

- LPCOpen board/chip libraries
- BSX library & BSX header files
- Sensor drivers
- Algorithm adapter for BSX
- Other (host I/F, DMA, main(), ...)

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LPC54102 SPM-S demo

- Connect the board to your PC
- Start ‘Teapot.exe’ on the PC
- On startup, teapot app sends commands to the LPC54102
- The LPC54102 sends back the ‘orientation vector’ of the board
- The teapot will rotate in 3D space when rotating the board
## More Information

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>Links</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPC54102 Sensor Processing/Motion Solution</td>
<td><a href="http://www.nxp.com/spm-solution">http://www.nxp.com/spm-solution</a></td>
</tr>
<tr>
<td>Board ordering information &amp; support (Forum based)</td>
<td><a href="http://www.nxp.com/demoboard/OM13078.html">www.nxp.com/demoboard/OM13078.html</a></td>
</tr>
<tr>
<td>Software download</td>
<td><a href="http://www.lpcware.com/content/devboard/lpc54102-sensor-processingmotion-solution-spm-s">http://www.lpcware.com/content/devboard/lpc54102-sensor-processingmotion-solution-spm-s</a></td>
</tr>
<tr>
<td>LPC5410x microcontrollers</td>
<td><a href="http://www.nxp.com/LPC54100">www.nxp.com/LPC54100</a></td>
</tr>
</tbody>
</table>