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Next Generation of Smart Sensors

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6.1 Introduction

IEEE STD 1451.0 (IEEE, 2005) defines standard interfaces in support of plug and play operation of smart
sensors and actuators on a network. Key components of the standard include

- A format for transducer electronic data sheet (TEDS)
- Transducer interface modules (TIMs)
- Network capable applications processor (NDAP)

The standard is optimized for network-based sensors and trade-off complexity and overall system power
for interoperability. It is not optimized for sensor subsystems deeply embedded in portable consumer
electronics. A new generation of smart sensors is evolving to meet the needs of this market. These
include the following features (Gervais-Ducouret, 2011):

- Competitive in terms of cost, area, and power.
- Virtual sensors can be created by fusing data from multiple physical transducers.
- Ability to detect events.
- Ability to determine current context (both spatial and activity).
- Sensor subsystems must be easy to integrate by product designers.

Nine- and ten-axis sensor subsystems will be used as the basis for discussions to follow. They include
the following components:

- 3 axes (XYZ) of acceleration (A) data
- 3 axes (XYZ) of magnetic field (M) data
- 3 axes (XYZ) of angular velocity (G) data
- 1 axis of air pressure (P) data
Next-generation devices will incorporate combinations of these and other sensors, as well as the ability to abstract the measured data to make it more useful to the user.

6.2 Need for Sensor Fusion

Each of the sensors in the sensor subsystem outlined in the previous section comes with its own set of strengths and weaknesses. As an example, let us consider the case of an accelerometer and a magnetometer at rest. Both provide the magnitude and direction, in the sensor’s frame of reference, for physical quantities being measured. In this case, these are gravity and earth magnetic field, respectively. Both sensor types are unable to detect rotation about the vector in question when one of X, Y, or Z sensor axes is aligned with that vector. Since the earth’s magnetic and gravity vectors are guaranteed to be non-colinear,* we can combine the two sets of measurements to provide a complete description of the device orientation in space. The ability to extract knowledge from the sum of multiple sensor outputs that could not be determined from any individual sensor is a key feature of sensor fusion.

Table 6.1 expands on this theme to outline key strengths and weaknesses of the various sensors contained in our representative sensor subsystem. The sensors shown represent only a small (but important) fraction of device types that might be included in specific products.

Figure 6.1 summarizes basic market requirements for sensor fusion at the time of writing. They include the following outputs:

1. “Corrected” sensor outputs in which sensor errors have been minimized
2. Current device orientation, which can be expressed in several ways
   a. Rotation matrix to take the device from a defined reference orientation to the current device orientation
   b. A quaternion representation of the same rotation
   c. Euler angle representation of the same rotation (φ, θ, and ψ)
3. Tilt-compensated compass heading

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerometer</td>
<td>Inexpensive, Extremely low power, Very linear, Very low noise</td>
<td>Measures the difference of gravity and acceleration</td>
</tr>
<tr>
<td>Magnetometer</td>
<td>The only sensor that can orient itself with regard to “north” Insensitive to linear acceleration</td>
<td>Subject to magnetic interference Not constant with location within specific environments</td>
</tr>
<tr>
<td>Gyroscope</td>
<td>Relatively independent of linear acceleration Can be used to “gyro-compensate” the magnetometer</td>
<td>Power hog Long start-up time Zero rate of set drift over time</td>
</tr>
<tr>
<td>Pressure sensor</td>
<td>The only stand-alone sensor that can give an indication of altitude</td>
<td>A “relative” measurement Subject to many interferences/environmental factors</td>
</tr>
</tbody>
</table>

* Except at the north and south magnetic poles. Since the human population of both is nominally zero, we can discount this case.
The outputs of Figure 6.1 represent a basic set of foundation functions upon which higher levels of software abstraction are layered. These would include:

- Pedometry
- Gesture recognition
- Head tracking
- Motion capture
- Fall detection
- VR tracking
- Augmented reality
- Navigation

6.3 Use Cases

The sensor subsystem outlined in the previous sections can support a variety of features, applications, and use cases. Table 6.2 presents a variety of features and applications versus the minimum set of sensors required for implementation. In almost every case, inclusion of additional sensor types over the minimum shown will improve accuracy.

It is common for combinations of the previously mentioned features to be executing concurrently on the same device. Some applications may continue to run even when the end user is not actively interacting with the device. Pedometry is a good example of this; you probably want to count steps all day, even when the smartphone on which it is running is not in “active use.”

6.4 Power Considerations

The time between battery charges is a primary figure of merit for any portable consumer device; hence, every milliwatt is precious. A properly designed sensor subsystem can enable major improvements in battery life.

Figure 6.2 illustrates the case where the main applications processor (AP) in a system is responsible for sensor fusion. Most commonly, the AP bus interface is comprised of one or more serial interfaces (I²C or SPI). Every sensor sample must be individually read across the bus interface by the AP, which is subject to a high interrupt rate.

APs are typically manufactured using state-of-the-art complementary metal-oxide-semiconductor (CMOS) processes. These are designed to minimize run mode currents for the AP; however, this is

<table>
<thead>
<tr>
<th>TABLE 6.2</th>
<th>Minimum Sensor Sets for Various Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feature/Application</td>
<td>Accelerometer</td>
</tr>
<tr>
<td>Portrait/landscape, tap detection, fall detection</td>
<td>X</td>
</tr>
<tr>
<td>Pedometry, vibration analysis</td>
<td>X</td>
</tr>
<tr>
<td>Electronic compass, pointing/remote control, augmented/virtual reality, gesture recognition</td>
<td>X</td>
</tr>
<tr>
<td>Virtual gyroscope</td>
<td>X</td>
</tr>
<tr>
<td>Gyro-compensated electronic compass</td>
<td>X</td>
</tr>
<tr>
<td>Activity monitors</td>
<td>X</td>
</tr>
<tr>
<td>Motion capture</td>
<td>X</td>
</tr>
<tr>
<td>3D mapping and localization</td>
<td>X</td>
</tr>
<tr>
<td>Image stabilization, gesture recognition</td>
<td>X</td>
</tr>
</tbody>
</table>

Note: X indicates that the indicated sensor type is a minimum requirement for the feature/application.
normally at the expense of increased start-up latency coupled with multiple modes of operation (each with their own power trade-offs). Deep pipelines for the AP result in substantial power wasted during context switching. If the AP is otherwise idle, additional power is burned during wake-up/sleep transitions.

Another problem with the system of Figure 6.2 is that the operating system running on the AP doesn’t normally support real-time operation. The AP may have, at best, a rough idea of exactly when each sensor sample was taken. This uncertainty in the time domain leads directly to errors in sensor fusion algorithms performed on the AP.

In contrast to the previous text, with the system of Figure 6.3, the sensor fusion is performed by a local compute engine residing on an intelligent sensor hub. The compute engine may be a microcontroller, dedicated fusion logic implemented in gates, or a combination of the two. Use of a dedicated microcontroller offers maximum flexibility for enhancing the fusion feature mix over time. Once specific algorithms have proved to be matured, they can be moved into gates. Logic-based solutions are almost guaranteed to have lower power than other architectures, but should only be used when algorithm maturity has been proven. We expect a mixture of both methods to be used for some years to come.

![Figure 6.2 Sensor fusion via AP.](image1)

![Figure 6.3 Sensor fusion via an intelligent sensor hub.](image2)
A number of advantages are obtained by moving sensor fusion out of the main AP:

- Sample times are tightly coordinated in time.
- MCU-based sensor hubs can utilize a real-time OS (RTOS) to manage external sensor inputs and algorithm timings.
- AP bus traffic can be orders of magnitude less than the system of Figure 6.2 because only processed and aggregated data need to be passed up to the AP.
- Because the local computer engine does not have the context/power mode switching overhead of the AP, milliwatt per computation is minimized.
- The AP can be completely asleep while the sensor hub continues to process sensor-related functions. Consider a smartphone equipped with a sensor hub: the application software for a pedometer can be executed completely on the sensor hub. Therefore, the AP can remain asleep, even while steps are counted.
- The sensor hub can use heuristic methods to manage power for the overall subsystem without any oversight from the AP. For the case shown in Figure 6.3, the magnetometer and gyroscope could be completely powered down until movement is detected via accelerometer inputs.

6.5 Integration and Partitioning Issues

A variety of physical mechanisms can be used to measure the previously mentioned components. Microelectromechanical systems (MEMS) are commonly used to measure acceleration, angular velocity, and pressure for consumer-grade devices. Magnetic sensors can be fabricated using a number of different technologies, including tunneling magnetoresistance (TMR) and anisotropic magnetoresistance (AMR).

First-generation MEMS devices included only one or two measurement axes in a single packaged device. As time proceeds, the trend is to consolidate more axes into a single package. Three-axis sensors are now common, and 2012 has seen the introduction of 6 (X/Y/Z of both accelerometer and gyroscope) and 9 axes (X/Y/Z of accelerometer, magnetometer, and gyroscope) devices. There are a number of items that need to be taken into consideration Stanley (2012) when selecting components of this type:

- Equations of motion incorporating acceleration are simpler when the sensor is located in the center of mass of the device in question.
- Magnetic sensors are subject to interference from ferrous and magnetic materials within the unit. Typically, a magnetic sensor performs best when situated near the center of one edge of the device because the magnetic field will suffer less distortion in that area.
- First two bullets suggest different sensor placement on the PCB. If a single device incorporating both magnetic and acceleration transducers is used, the fusion algorithms need to include the ability to specify sensor set from center of mass.

From a physical perspective, the trend is clearly toward more and more integration into smaller and smaller packages. In 2010, discrete packages for accelerometer, gyrometer, and magnetometer were the norm. 3 x 3 x 1 mm packaged sensors were the state of the art. At the time of writing, 2 x 2 mm is standard for 3-axis accelerometers, and gyroscopes are at 4 x 4 mm and trending to 3 x 3 mm. Combinational devices are trending to 15–20 mm², including the sensor hub. Issues being managed by sensor providers are discussed in the following paragraphs.

6.5.1 Consolidation of MEMS Devices onto a Single Die

Stand-alone consumer accelerometers do not usually have their chambers evacuated. Gas molecules within the MEMS chamber provide a damping effect that is advantageous in shaping the transfer function of the accelerometer. Conversely gyroscopes work better when motion damping is not present.
The Coriolis effect leveraged by gyroscopes requires a proof mass that oscillates at high speeds. The same effect that is helpful for accelerometers increases power required for the gyro drive circuitry. To support higher levels of integration, MEMS structures will most likely be designed to operate at the same pressure. The accelerometer circuitry will need to be designed for force feedback (to ensure the accelerometer proof mass stays centered) if vacuum is used for both gyro- and accelerometer. Conversely, additional drive capabilities may be required if the gyroscope pressure is raised. Finding the right “sweet spot” will be even more complicated when we consider inclusion of a pressure sensor on the same die.

### 6.5.2 Magnetic Interference

By their very nature, magnetometers are sensitive to electronic currents. Placing them in close proximity to a microcontroller or logic core requires care. The Biot-Savart law can be used to estimate the effect of wire/trace currents on magnetic sensors. For long wires and traces, it can be simplified to

$$ |B| = \frac{\mu_0 I}{2\pi r} $$

where

- $B$ is the magnetic field strength in T (teslas)
- $\mu_0$ is the $4\pi \times 10^{-7}$ T mA
- $I$ is the current in amps
- $r$ is the distance from wire/trace to sensor in meters

This can be rearranged to yield

$$ I \leq \frac{5r |B|}{\mu_0} $$

where

- $B$ is the magnetic field strength in $\mu$T that you can afford to ignore
- $I$ is the current in milliamps
- $r$ is the distance from wire/trace to sensor in mm

As an example, if $B = 0.1 \mu$T and $r = 0.1$ mm, then $I$ must be roughly less than $50 \mu$A in order to not affect the accuracy of the result. While these numbers may sound small, they must be considered when designing within the context of an MCU-equipped smart sensor in a $3 \times 3 \times 1$ mm package.

Today, the magnetic sensor component of a composite device is commonly implemented as a separate die that is stacked on top of the controller Application Specific Integrated Circuit (ASIC). Depending upon the technology used, it should be possible to place the magnetic sensor on the same die as the compute engine. Ultimately, a 9-axis fused solution will probably only require two stacked dies.

Figure 6.4 illustrates this process of continuing integration. Notice that at any point in time, several alternative solutions may exist. These may be driven by both logistical (supply) and technical considerations. Typically, no one solution fits all problem spaces.

### 6.5.3 Soft Partitioning

A benefit of the sensor hub partitioning is that fusion algorithms can be packaged with the hub itself, simplifying hardware and software system design and integration. System integrators are increasingly looking for a single source capable of providing sensors, compute engine, and associated software. Microsoft Windows 8 is architected with this division in mind. Microsoft supports specific bus...
protocols for communications with sensor subsystems. These include HID* over Universal Serial Bus (USB) and HID over I2C. Microsoft requires vendors to meet all Windows 8 Hardware Certification Requirements (Microsoft, 2012c) before the vendor’s solution can be marketed as Microsoft-approved. Google has created the Android Compatibility Test Suite (CTS) for similar purposes (Android, 2012).

A high-level view of the Android software stack utilizing an intelligent hub is shown in Figure 6.5. By agreeing to a common communications protocol over I2C, SPI, or USB, sensor providers and system integrators can cleanly divide software development tasks. An alternate approach that is even more hardware/software agnostic could be based upon the Multicore Communications API (MCAPI, 2012). This standard message passing protocol could be used to completely abstract the smart sensor interface at the software level. Regardless of which approach wins out in the end, industry-wide definitions will enable the ability to swap out sensor subsystems with the substitution of a single component—with no impact to system software.

Physically, the systems of Figures 6.3 and 6.5 are the same. They support a clean division of efforts between sensor providers and system integrators and improved performance (both power and accuracy) over previous generations of devices. However, power can be improved even more by moving the compute engine onto the same die as the AP. This is shown in Figure 6.6.

The controller IC for the Figure 6.3 intelligent controller will be built upon CMOS processes that include support for flash memory. It allows fusion software to be stored directly in the sensor hub, simplifying distribution and integration of that software. The disadvantage is that flash-based technologies tend to “lag” the more advanced processes used for APs in terms of instructions/mW. In Figure 6.6, the secondary CPU can be designed for real-time operation with fast transitions to/from sleep mode. Improvements in power come from using the same advanced CMOS technology for the secondary CPU.

* HID, human interface device. See Microsoft (2012b).

FIGURE 6.4 Increasing levels of integration over time.
as for the main AP. The architecture of Figure 6.6 allows the system designer to choose best in class options for each individual sensor, providing a more “a la carte” option to the partitioning shown in Figure 6.3, which is more likely to be provided by a single vendor. This comes at the expense of additional traffic on the secondary bus and a tighter coupling between the sensor subsystem and the rest of the system from a software perspective. The latter may be reduced by implementing a software protocol such as MCAPI, which hides details of the physical transport mechanism from the application. Ultimately, the market will determine which of the two sensor hub approaches wins out.

Trade-offs between the systems of Figures 6.2, 6.3, and 6.6 are outlined in Table 6.3.
### 6.6 Trend and Market Segments

Improvements in sensor performance and intelligence are driven by new applications that are themselves enabled by the availability of affordable, small, and low-power sensors. An overview of some of the main trends of automotive, industrial, healthcare, and consumer markets is provided as follows.

#### 6.6.1 Automotive

The automotive market segment has used sensors for many years for monitoring and controlling engine performance. The explosion of sensor usage in this market has been driven by the need for increased safety, starting with airbags (which utilize accelerometers for triggering purposes) and tire pressure monitoring systems (TPMSs). The current trend is to further improve automotive security by adding active safety features to the existing passive safety feature set. Electronic stability control (ESC) can prevent some crashes due to loss of control by actively managing the braking of each wheel. ESC uses a combination of a gyroscope (1–3 axes) and accelerometer (2–3 axes) in a common package with an ASIC to efficiently monitor yaw, pitch, and rollover. The trend is clearly driving further integration of sensors and sensor fusion for proactive safety. Adoption of 6-axis sensors (3-axis gyroscope and 3-axis accelerometer) and the fusion of these sensors should increase in this market.

#### 6.6.2 Industrial

The industrial market also benefits from smart sensors. Usage of sensors is as diverse as the industrial applications themselves. For instance, physical tamper detection, utilizing extremely low-power 3-axis accelerometers running for years on battery power, can now be seen in smart meters and other devices. Accelerometers are also used for vibration monitoring to detect machine defects and trigger maintenance prior to a real failure. Associating sensors with low-power wireless transceivers may enable the most pervasive technology for industrial: building and home automation. The main benefits are energy saving (heater, light, HVAC, etc.), cost saving (manpower, cables, maintenance, etc.), and security (alarm, detection of fire and gas, malfunction of devices, etc.). Smart sensors are crucial for such applications since power consumption is critical: 10 years is the minimum battery life for building automation sensors. Dedicated processing at the sensor level is one of the solutions used to minimize data flow and communication and therefore power consumption. Association of smart sensors together with very low-power wireless transceivers, such as ZigBee Smart Energy (Zigbee, 2012) and even energy harvesting (using differential temperature or vibration), will dramatically increase the spread of wireless sensor networks for better management of our energy.

#### 6.6.3 Healthcare

Health monitoring applications benefit from smart sensor’s low-power and quality of data. For instance, seamless monitoring of blood pressure, physical activity, and heart rate can be achieved using smart

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**TABLE 6.3 Trade-Offs Associated with Choice of Processor for Sensor Fusion**

<table>
<thead>
<tr>
<th>System Option</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 6.2: Fusion on the AP</td>
<td>Least expensive option</td>
<td>Higher power</td>
</tr>
<tr>
<td>Figure 6.3: Fusion within the smart sensor hub</td>
<td>Highest level of decoupling between top-level OS and sensor subsystem</td>
<td>Significantly improved power over 100% discrete option</td>
</tr>
<tr>
<td>Figure 6.6: Fusion on a secondary processor on the AP</td>
<td>Best power</td>
<td>Physical (and possibly software) partitioning between the main AP and secondary processor will tend to be different for each AP design</td>
</tr>
</tbody>
</table>
accelerometers and pressure sensors. Data can be recorded and displayed on any device acting as a health hub (e.g., smartphone). Accurate and low-power monitoring is possible thanks to smart sensor features such as First-In-First-Out (FIFO) buffers, which allow the transmission of measured data in burst mode. This minimizes the number of context changes required by the main processor, again, minimizing overall system power consumption.

Smart sensors and resulting fused data will be increasingly used to enable seamless and more detailed health monitoring. Data can be used for sport activity monitoring and accident prevention. It can also be collected and analyzed on a continuous basis, opening the possibility of adapting medication regimens to each individual patient's daily routine.

6.6.4 Consumer

The consumer market benefits from smart sensors more than any other, since these devices enable high-volume applications such as gaming, intuitive user interfaces, augmented reality, localization, and context awareness. The 10-axis sensor system discussed in the introduction to this chapter forms the basis for many consumer applications.

Figure 6.7 breaks applications into three levels of complexity. Bottom tier applications are supported by a 3-axis accelerometer and 3-axis magnetometer. This tier includes basic gesture recognition such as tilt or tap detection. It also requires functions for soft and hard iron compensation, which must be performed prior to electronic compass calculations. The first level of smart sensor and sensor fusion provides improved sensor performance in terms of drift, calibration, and ease of use. It forms the foundation for applications in the upper levels.

The middle level in Figure 6.7 includes applications such as a high-performance pedometer (with an accelerometer to detect steps, a gyroscope to remove parasitic movement linked to the handling of the

![FIGURE 6.7 Sensor fusion complexity levels/indicates optical sensors.](image)

*Basic functions like tilt and tap are often implemented in dedicated CMOS logic today. As other algorithms increase in maturity, it will be natural that many of these functions also move into "hard logic."
device, and a pressure sensor to detect altitude), pointing device (used in remote controls to improve intuitive interface for smart TV), and Kalman filtering to get reliable and more accurate sensor data as described in earlier sections.

Level 3 applications leverage sensor and general data fusion. Navigation applications can use the outcome of sensor fusion to lower the power consumption of GPS by extrapolating the trajectory between two navigational fixes. However, the most dramatic improvements are for indoor localization. These systems utilize inertial/magnetic sensor fusion coupled with diverse techniques such as Wi-Fi positioning, cell IDs/triangulation, and soft maps to enable indoor navigation via smartphones. Going forward, they will also combine pressure readings with map/GPS data to estimate altitude.

Smart sensors play a key role in decreasing power consumption in these systems, since the power consumed by GPS/Wi-Fi is of two orders of magnitude higher than other sensors. They also help improve accuracy of position estimates. Today’s consumer sensors are not accurate enough to support purely inertial navigation equations. But by coupling pedometry techniques with orientation data provided by the same sensors, reasonable (linear) bounds can be placed on position estimates.

Another new trend is inclusion of context awareness. This involves gathering information from different sensors and data sources to characterize the user’s environment and activity within that environment. Examples might include entering/exiting an elevator, recognizing that user is at rest, eating, and walking. Indeed, understanding the context is as important as knowing the location of a person for location-based services (LBSs), contextual services, and menus. Knowing if a person is stressed, rushing about town, or just browsing in a shopping mall can be achieved by doing pattern analysis of sensor outputs—primarily accelerometers but also gyroscopes.

Modern operating systems include the ability to register software functions as event listeners. Think of these as callback functions that are invoked when something interesting has happened in the physical world. To enable innovative applications, the sensor fusion layer should provide ready to use data for pattern recognition, which then provides trigger events for application-level software to log context changes and/or perform event-triggered actions. The goal is to continually raise the level of data abstraction to make it easy for software developers to develop applications that interact in the world in natural and innovative ways. Hence, data fusion of smart and low-power sensors combined with wireless connectivity is enabling new applications for multiple markets. Indeed, since the role of smart sensors in context awareness, positioning, healthcare, and safety is essential, this technology is becoming pervasive for most of related IoT (Internet of Things) applications.

6.7 Summary and Conclusions

This chapter has examined trends in smart sensors using a basic 10-axis sensor subsystem as a basis for discussion. Clear trends include:

- Continued focus on reducing cost and power
- Continued improvement in raw sensor performance, as well as performance improvements resulting from intelligent sensor fusion
- Consolidation of more sensors into fewer dies within fewer packages, utilizing less board space
- Localized computation
- Standardizing interfaces to sensor subsystems
- Raising levels of data abstraction, including inclusion of higher-level functions like gesture recognition and context awareness
References


Partial List of Sensor Manufacturers

AKM, manufacturer of magnetometers and 6-axis combo eCompass.
Analog Devices, manufacturer of accelerometers, pressure sensors, gyroscopes, microphones, 6-axis combo sensors, sensor fusion, and inertial modules.
Bosch Sensortec, manufacturer of accelerometers, pressure sensors, magnetometers, microphones, sensor fusion, and 6-axis combo sensors.
Freescale Semiconductor, manufacturer of accelerometers, gyroscopes, pressure sensors, magnetometers, touch sensors, sensor fusion, 6-axis sensors, and intelligent sensor platform.
Infineon, manufacturer of magnetometers and pressure sensors.
Honeywell, manufacturer of magnetometers.
Invensense, manufacturer of gyroscopes and combo sensors of a gyroscope with an accelerometer and/or magnetometer and sensor fusion.
Kionix, manufacturer of smart sensors: accelerometers, gyroscopes, 6-axis combo sensors, and sensor fusion.
Knowles Electronic, manufacturer of MEMS microphones.
Memsic, manufacturer of accelerometers, magnetometers, and flow sensors.
Murata, manufacturer of accelerometers, pressure sensors, gyroscopes, 6-axis combo sensors, and sensor fusion.
Panasonic, manufacturer of accelerometers, gyroscopes, and RF MEMS.
STMicroelectronics, manufacturer of MEMS and smart sensors: accelerometers, pressure sensors, magnetometers, gyroscopes, microphones, 6-axis combo sensors, and inertial modules.

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