WHITE PAPER

ARM Cortex-M7 Processor in Sensor Fusion

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Introduction

Embedding sensor technology into products has been a very strong trend in recent years. From smartphones, fitness bands, gaming controllers, smartwatches, head mounted displays the list of consumer devices with sensors is rapidly expanding. Traditionally we have seen sensors used to track location and movement (e.g. GPS, accelerometers, gyroscopes, and magnetometers) but this too is quickly shifting to a raft of new advanced sensors such as bio-medical, audio and visual.

The more sensors we embed, the more data that is correspondingly generated. This data is useful and drives applications such as fitness and health tracking as well as the recent advances in virtual reality headsets. As we generate more data, we also consume more energy making 'sense of sensors' in more and more sophisticated applications. This is where sensor fusion comes in. Sensor fusion is the smart combining and interpretation of disparate sensor feeds thus giving the application a far greater insight into a user's behaviour or movement.

The ARM® Cortex®-M processor family is widely used in sensor fusion applications and can be found in many applications today. From the ultra-low power Cortex-M0+ core through to the high performance Cortex-M7 core, the Cortex-M family of processors offers a wide range of performance points to suit varied applications.

Hillcrest Labs is the leading provider of software solutions for sensor-enabled products. More than a decade of research and development has led to a portfolio of unique IP, which transforms sensor data into contextual information for use in a variety of consumer electronic devices and applications. Hillcrest's sensor fusion and processing technology used by many of the world's leading CE brands are in millions of consumers' homes, offices, pockets, and hands around the world.

This paper sets out to explain the background of sensor fusion processing and to present to the reader the advances in device capability that will be enabled as a result of Cortex-M7 processor. As well as explaining the benefits of the Cortex-M7 architecture in sensor fusion, this paper also goes on to present two application examples, the first showing how sensor fusion on a Cortex-M7 processor can be used as an offload engine to save energy in a high-end head mounted display application. In contrast, the second application example takes the reader through the benefits of using a Cortex-M7 core in a standalone configuration to run both the sensor fusion software as well as the main application software in a smartwatch application.

An Introduction to the ARM Cortex-M7 Processor

The Cortex-M7 processor is the latest member of the energy-efficient Cortex-M family of processors, which deliver 32-bit performance, together with very fast, deterministic handling of interrupts. This combination makes the family ideal for use in embedded applications requiring high performance and real-time response.

The Cortex-M7 processor has the same Cortex-M programmers' model as the Cortex-M3 and Cortex-M4 (code which runs on Cortex-M3 and Cortex-M4 will run unchanged on Cortex-M7), but it introduces many new optional features in terms of memory and system interfaces and has a powerful new microarchitecture.

The relationship between the instruction sets of the Cortex-M processor family is shown in the diagram below:

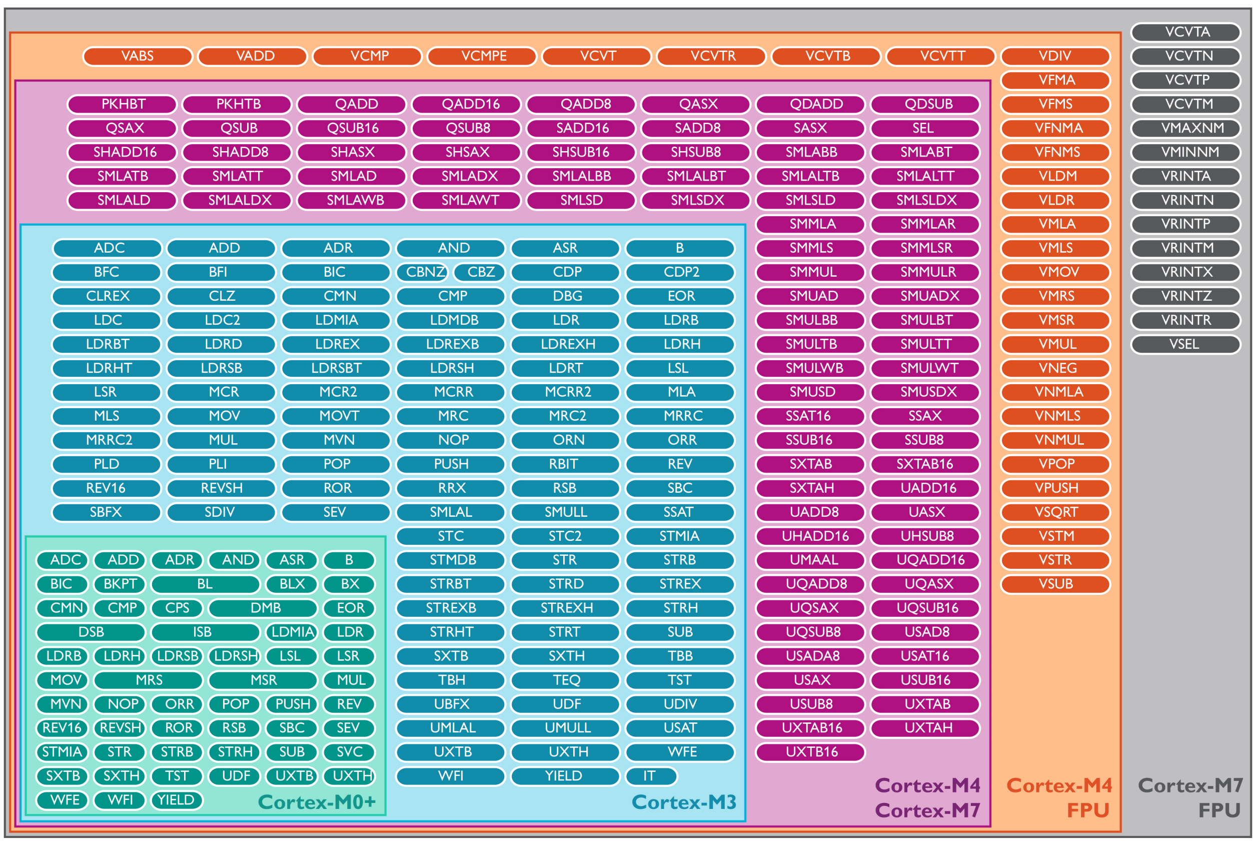

Figure 1 - Cortex-M Family of Processors Instruction Set

The key characteristics of the Cortex-M7 processor include:

- High performance six stage superscalar pipeline, with branch prediction
- Powerful instruction set with SIMD, saturating arithmetic, single cycle MAC for efficient DSP
- Optional 64-bit Instruction Tightly Coupled Memory (I-TCM), and optional 2x32-bit Data TCM (D-TCM), with support for custom Error Correction Code (ECC) implementation for each of the TCM interfaces
- 64-bit AMBA® 4 AXI bus interface for access to memory and slower or more complex peripherals
- Optional instruction cache (from 4kB to 64kB) and data cache (from 4kB to 64kB), with optional ECC support for each of the cache memories
- Optional low-latency AHB peripheral bus interface (referred to as AHBP)
- AHB slave interface (AHBS) to allow DMA access to the TCMs
- Integrated Nested Vectored Interrupt Controller (NVIC) with 1 to 240 interrupts, with 3 to 8-bit programmable priority level registers
- Optional Memory Protection Unit (MPU) with 8 or 16 regions
- Optional Floating Point Unit (FPU) with support for single- and double-precision IEEE-754 floating point instructions
- Powerful debug features, with optional full instruction and data trace

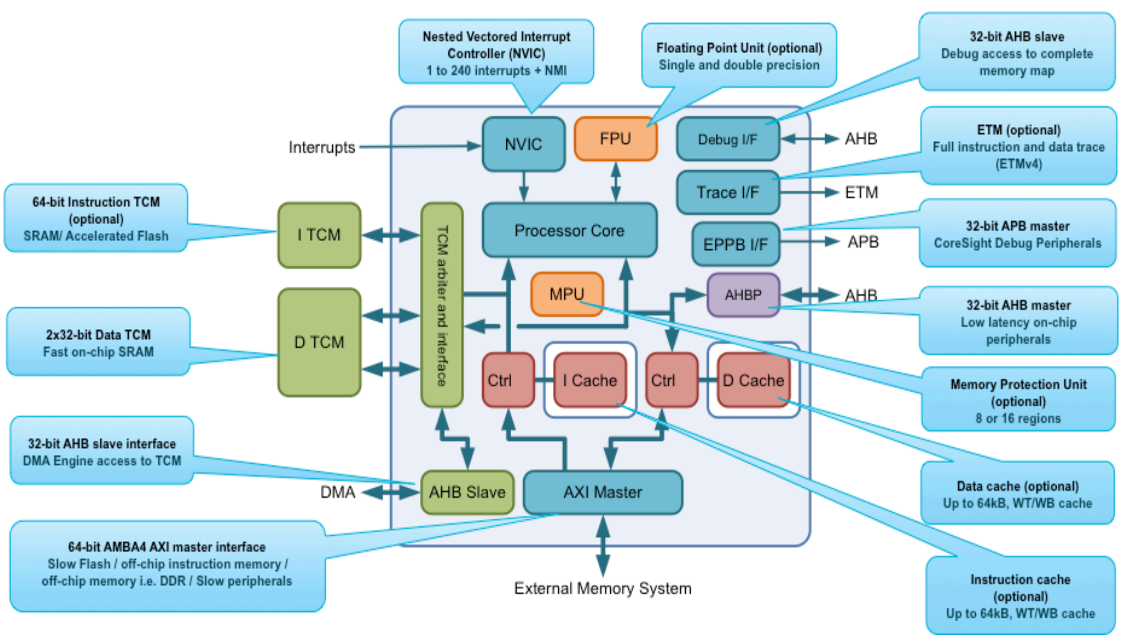

Figure 2 - Cortex-M7 Processor Block Diagram

An introduction to Sensor Fusion

Sensors are vital to the user experience in consumer electronics today. From your phone knowing which way you are facing on a map to your smartwatch auto-logging your activity and sleep 24/7, sensors are at the heart of how we interact with our devices. However, the quality of the user experience is largely driven not by sensors themselves but by the sensor fusion algorithms, which turn sensor data into useful, application-ready information.

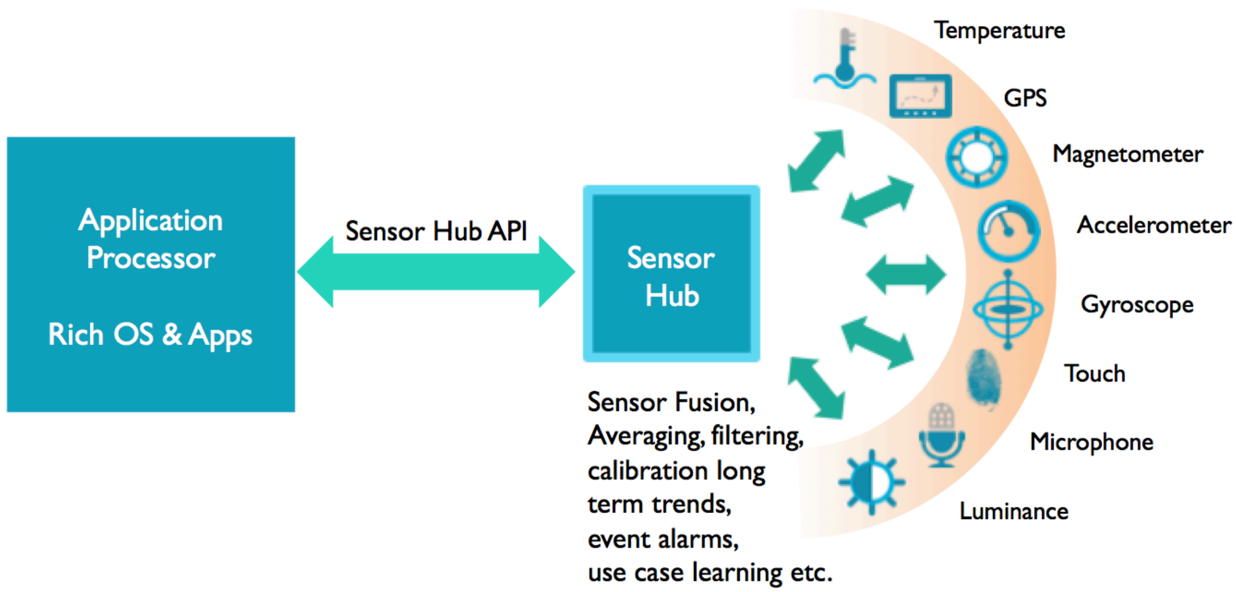

Figure 3 - Sensor Hub System Architecture

Sensors are small, noisy, and their signals are easily distorted and susceptible to interference; sensor fusion and processing software adds calibration, fusion, and much more to make the data more accurate, reliable and ready to be exposed to real-world applications. Sensor fusion itself is not simple, and can be compared to an iceberg – the 'visible' sensor fusion is a small, relatively simple set of algorithms. However, those algorithms rely on a hidden and complicated world of larger systems challenges, which must be addressed to provide high quality data to the fusion system. When good sensor fusion is integrated correctly into the sensor system, it can have dramatic impacts on the user experience.

The user experience benefits of good sensor fusion can broadly be assigned to two categories:

Enabling New Applications:

Sensor fusion and processing provide unique information on the device, user, and environment, which enables new applications and more personalized computing. Examples today include activity trackers, which monitor your steps and daily activity to encourage a healthier lifestyle, and gesture recognition which act as an interface to eliminate dozens of screen taps. Soon sensor fusion will enable your phone to guide you to an indoor platform at the train station without satellites, and track head movement to power virtual reality headsets. Beyond these application examples, contextual computing can enable your phone or wearable to deliver useful information before you even ask for it.

Saving Power:

Sensor fusion and processing can also help conserve power based on device context. As an example, if the phone is sitting on a desk in your office and has not moved in several hours, the phone does not have to sample the GPS or otherwise calculate location. Similar techniques can be used to automatically manage phone functions while you are in cars or on public transport. While these may seem like small steps, the associated power savings can really add up.

To enable these user experience benefits we need the sensors to be 'always-on' and gathering data regardless of whether the device is actively being used. That means we need to have a way of gathering, filtering, and analyzing the data from sensors without consuming significant amounts of the phone's battery or processing resources. This has led to the rise of a type of processor known as a "Sensor Hub". A sensor hub is a dedicated processor, typically based on the ARM Cortex-M processor series architecture, which handles sensor processing. By optimizing the processor, sensor fusion and processing software, we can enable the benefits of always-on processing with minimal impact on device battery life.

The Cortex-M7 Processor 'High Resolution Sensor Fusion'

The Cortex-M7 processor brings a number of architectural enhancements that benefit sensor fusion algorithms. The unique characteristics of the Cortex-M7 core allow a more efficient execution of sensor fusion algorithms. This in turn results in improved latency and overall lower system power (thereby extending battery life).

Specific architectural features of the Cortex-M7 processor that lend themselves to sensor fusion include:

- A superscalar architecture enabling an increase in performance
- Single cycle MACs, resulting in fewer instructions to do more math processing
- SIMD capability, to speed up the complex calculations required in sensor fusion (e.g. quaternion multiplications)
- Efficient access to on-chip RAM helps with context classifiers and chaining of multiple classifiers for better context. Local on-chip RAM access also saves energy vs. off-chip DDR accesses and as such increases overall battery efficiency
- When integrating the sensor hub into a wider SOC, the use of a cache allows efficient sharing of memories and minimizes off-chip accesses, hence saves energy and increases overall performance

Application Example #1: Sensor Fusion Offload

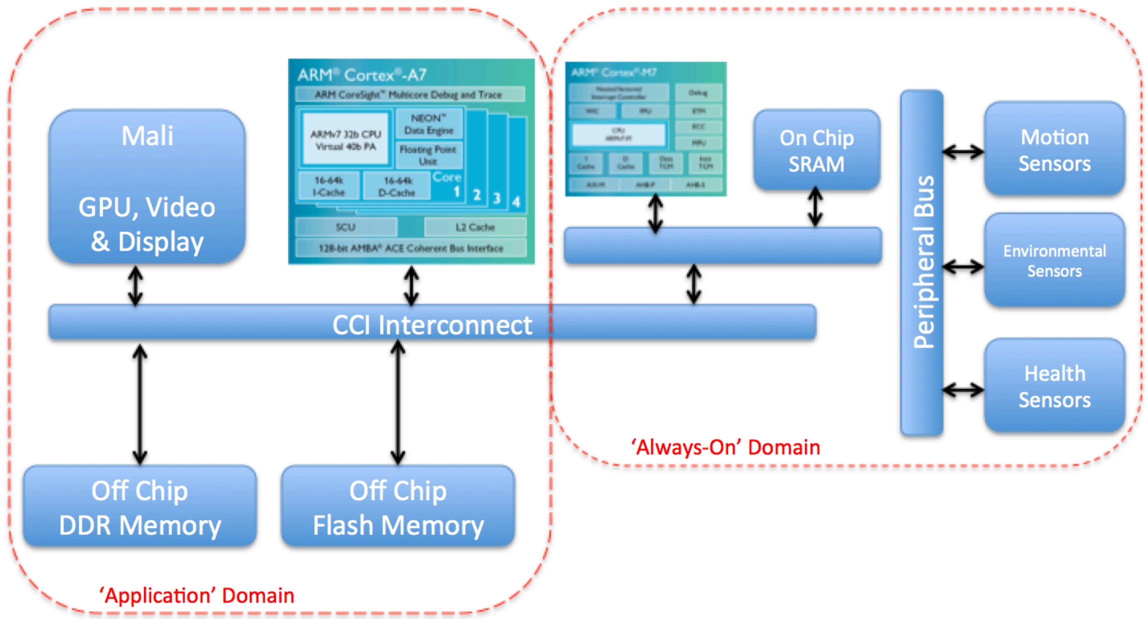

Figure 4 - High-end Wearable Example System Architecture

Virtual reality (VR) systems rely on tricking the brain into believing the virtual world is real. That means that it is vital for the system to translate real-world actions into the virtual world with the greatest precision and the lowest latency possible. A commonly used architecture of a modern wearable device uses a Cortex-A processor to run a rich OS providing a sophisticated user interface, while offloading the sensor fusion function, which requires deterministic real-time response, to a Cortex-M processor. As sensor data processing requirements grow, the Cortex-M7 is an ideal processor for this function. The processing power of the Cortex-M7 core provides the perfect foundation for the sensor fusion and processing to meet performance requirements of good head tracking solutions used in VR systems.

Take latency as an example, which is widely considered a primary cause of 'simulator sickness'. Latency is the time between head movement and the adjustment of the image, which corresponds to that movement. Many system factors contribute to latency, but gathering, processing, and delivering sensor data to the system is a notable one.

The Cortex-M7 processor enables high-resolution sensor sampling and sensor fusion including dynamic calibration of sensors. Typical sensor fusion output data rates (ODR) used in mainstream

head trackers today are in the order of a few 100Hz, but the extra processing capability of the Cortex-M7core allows that to scale upwards of 1kHz. Primarily this increased ODR means there is minimal delay when gathering data packets at an appropriate time for the graphics rendering, as the video frame rate is different to the sensor fusion-processing rate. Additionally, it enables a denser sample for more accurate predictive head tracking. By analyzing patterns and predicting future movement, latency can be reduced, but the density of data available over the course of a few milliseconds is vital to performance of head tracking. The further we have to look into the past to obtain an appropriate body of data to use in the predictions, the less reliable the estimate becomes. Higher ODR (1 kHz or more) increases the accuracy of the prediction and therefore the quality of the user experience.

The future of virtual reality is not only in the best head tracking possible, it is also in full body interactions, and controls with voice and other natural interaction methods. Even with high ODR sensor fusion processing, the Cortex-M7 processor would still have additional processing power to support these additional functions. For example, if additional sensors tracked movement of other parts of the body through a network of body-worn sensors, the Cortex-M7 processor could fuse that data together to track full-body orientation changes. Additionally, if voice controls and the recognition of specific command keywords were also added, the Cortex-M7 would have enough processing power for these additional applications.

Application Example #2: Sensor Fusion Standalone

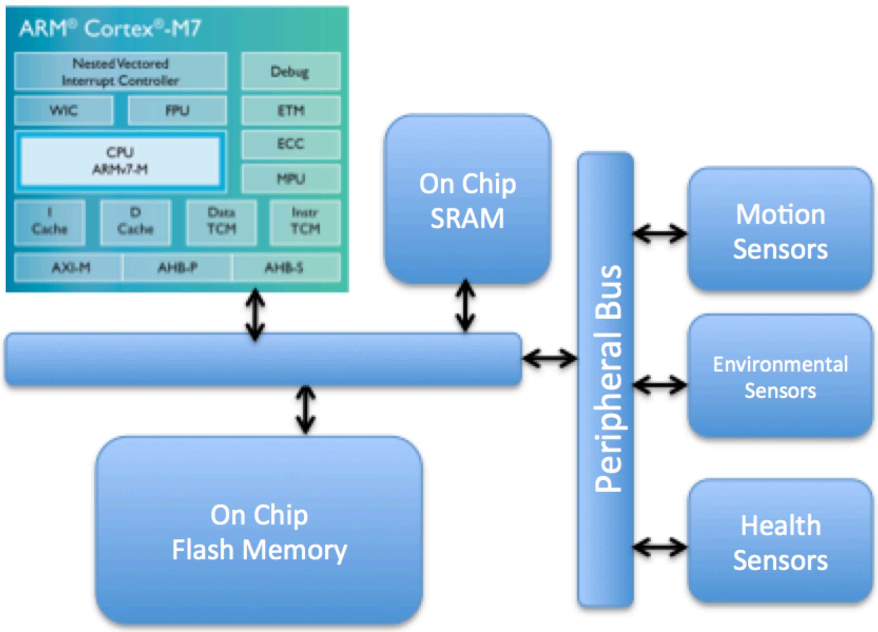

Figure 5 - Single Cortex-M7 Processor Example System

Wearables are a hotbed for sensor adoption. Nowhere is this more so than in wrist-worn wearables, where using sensors to track user activity have become commonplace. Current trends show more sophisticated, multipurpose devices such as smartwatches gaining market share at the expense of simpler devices such as activity tracking wristbands. These devices feature more sensors often incorporating pressure, heart rate, gyroscopes, and more to provide additional data to the user and to enable better user interfaces.

This trend is only going to continue as more sensors become available. Additional motion sensors including gyroscopes and magnetometers will help add richness and accuracy to personal context tracking. Environmental sensors, such as UV light, humidity, and temperature, will enable better user context and enhanced personal comfort. Biological sensors will measure hydration, blood oxygen and glucose saturation, skin temperature and sweat, and more to provide unique insights about the user's body and health.

Combining data from this expanding array of sensors will require a powerful yet power efficient processor. This will be particularly important for low-power context classification. Advanced context detection requires complex algorithms and these algorithms can take advantage of the advanced features of the Cortex-M7 processor to provide accurate yet low-power context detection for rich user applications.

Particularly useful here is the suitability of the Cortex-M7 core for audio processing. With limited interfaces, voice is a primary natural interaction method for wearables, so keyword recognition will be vital. In addition, a rich picture of context can be gathered from audio signatures. For example, detecting whether a user is in a car, on a bus or on a train can be difficult through motion and environmental sensors alone. However, distinctive audio signatures can greatly increase the context detection reliability.

Another application, which will make full use of the Cortex-M7 processor's features, is smartwatch-based pedestrian dead reckoning (PDR). With location-based services becoming more important, and sensors in smartwatches becoming more sophisticated, PDR will have an essential role in any low-power navigation application. However, PDR places a premium on the accuracy of sensor data, making the sample rate and efficient dynamic sensor calibration both vitally important. The Cortex-M7 processor is an ideal platform to support high sample rates and for a concurrent real-time calibration of several sensors to increase the accuracy of the PDR output.

A full navigation solution will fuse the accurate PDR output with external reference sources such as GNSS or Wi-Fi/beacons and map matching to increase the stability and accuracy of the navigation. The additional resources of the Cortex-M7 core make it uniquely able to unite these disparate data sources for complete and accurate navigation in a power-efficient manner.

Today most advanced wearables mimic the architecture of a smartphone, using a Cortex-M processor-based sensor hub in conjunction with a Cortex-A series application processor. However, the Cortex-M7 processor is suitably powerful so that in many cases, even after completing the processing of data from numerous sensors, as described above, it will still have remaining cycles for display management and the other important smartwatch functions. Therefore, for many wearable devices, the power of the Cortex-M7 processor will negate the need for a traditional application processor while extending battery life and time between charges, alleviating one of the primary design challenges surrounding smartwatches today.

Summary

The role of sensors is becoming ever important providing the ability to give unique insights into our lives and behaviours. From sports and fitness activity tracking to quantified self-medical tracking of parameters like heart rate and blood pressure, we see a constant need for more accurate and reliable sensor-based devices. In this paper, ARM and Hillcrest Labs have outlined the key areas of consideration to developers in designing sensor-based systems and in turn allowing more accurate and insightful applications to be built. The ARM Cortex-M7 represents a significant uplift in processing capability allowing more sophisticated sensor fusion algorithms to be deployed into advanced products whilst retaining the low power characteristics essential for todays advanced 'always-on, always aware' products.