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Xilinx Analog Mixed Signal Solutions

By: Anthony Collins

The introduction of the industry-leading 28 nm 7 series by Xilinx has greatly expanded the capabilities of the integrated analog subsystem over previous generations of FPGA families. The analog subsystem in the 7 series is called the XADC and includes dual, independent, 1 Megasample per second (MSPS), 12-bit Analog-to-Digital Converters (ADCs), and a 17-channel analog multiplexer frontend. By closely integrating the XADC with the device logic, Xilinx has been able to deliver the industry's most flexible analog mixed signal subsystem.

This white paper provides an introduction to the benefits and features of the XADC and analog mixed signal solution implemented with Spartan®-7, Artix®-7, Kintex®-7, and Virtex®-7 FPGA families, and Zynq®-7000 All Programmable SoCs.

Introduction

The tight coupling between the analog mixed signal subsystem and the programmable logic in the 7 series FPGAs and Zynq-7000 SoCs (based on the 7 series architecture) provides the system designer with the ultimate in versatility, enabling the integration of microprocessors and controllers, digital signal processing, control logic, and monitoring functions. Because of the broad capabilities of the ADC subsystem and programmable logic, designers have the ability to tune their designs to meet the exacting market requirements of their products, thus, enabling significant differentiation.

The XADC together with the programmable logic in the 7 series FPGAs and Zynq-7000 SoCs enables system designers to easily eliminate a wide range of mixed-signal devices from their systems, including "housekeeping" analog. The cost savings, board space savings, and I/O pin savings afforded by this analog mixed signal solution can be significant—especially for designs that have significant area and cost constraints or ship in high volumes. Additional benefits of the integrated solution include improvements in failure-in-time (FIT) rates, simplified inventory management, and elimination of potential end-of-life issues for mature mixed-signal devices.

Analog Demand

In the era of the "Digital Revolution," analog is still very much in demand. Most sensors used to measure real world information are, by definition, analog. Voltage, current, temperature, pressure, flows, and gravitational forces are continuous time-domain signals. Due to the high degree of accuracy and repeatability, digital techniques are commonly used to monitor and control these analog signals. Data converters, including ADC, Digital-to-Analog Converters (DAC), and analog multiplexers, provide the critical bridge between the digital and analog worlds.

The need to interface the analog world with the digital world continues to expand as analog sensor and digital control system markets each continue to grow. Market drivers for analog mixed signal technology include: smart grid technology, touch screens, industrial control safety systems, high availability systems, advanced motor controllers, and the need for increased security across a wide spectrum of equipment.

In 2005, with the introduction of the Virtex-5 family, Xilinx recognized the importance of supporting analog mixed signal functionality by integrating a subsystem called System Monitor. System Monitor enabled designers to monitor the vital statistics of the FPGA as well as the external environment. Adoption of System Monitor was readily embraced by customers, who employed this capability across a broad range of applications.

Two product generations later, Xilinx expands on the commitment to deliver analog mixed signal with the introduction of Spartan-7, Artix-7, Kintex-7, and Virtex-7 FPGAs and Zynq-7000 SoCs. Xilinx significantly increased the capabilities of the embedded analog subsystem by including two independent general purpose 1 MSPS 12-bit resolution ADCs. The capable analog subsystem is tightly coupled with the programmable logic, providing a powerful and flexible analog mixed signal platform.

Figure 1 is a block diagram of the ADC subsystem used in 7 series architecture. The ADC (XADC) subsystem includes:

- 17 differential analog inputs that support both unipolar and bipolar analog input signals
- On-chip and external reference options
- On-chip voltage and temperature sensors
- Sampling sequence controller
- Configurable threshold logic and associated alarms for on-chip sensors

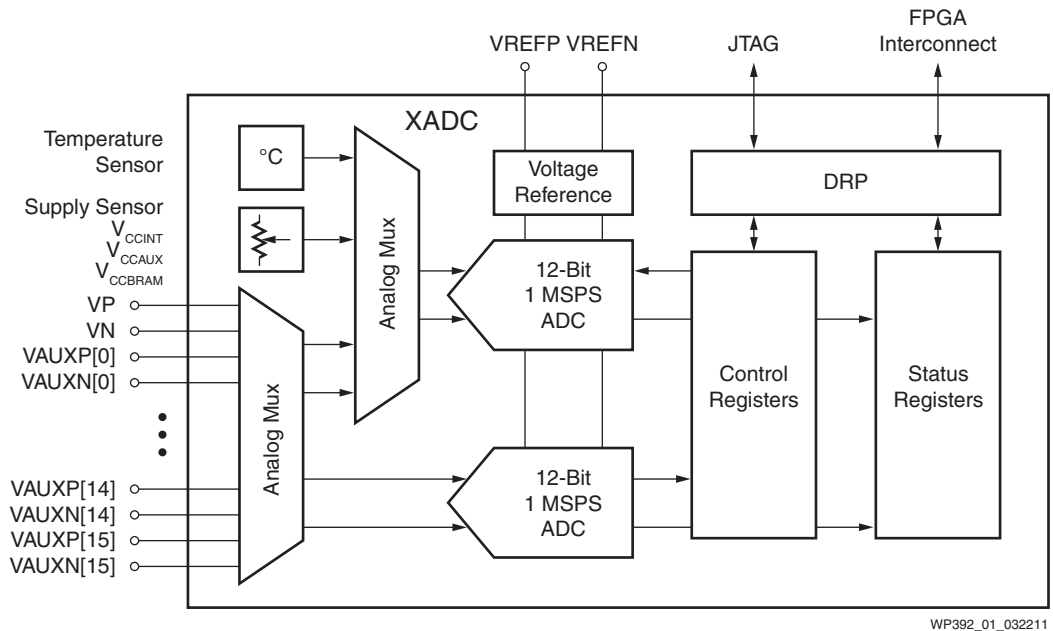Control and status registers provide a seamless interface to the digital programmable logic.

Figure 1:   **XADC Block**

Analog Mixed Signal Functionality

The 7 series FPGAs and Zynq-7000 SoCs can be programmed to address a wide range of functionality including:

- Complex control and management through microcontroller or microprocessor functionality
- Digital signal processing (DSP) functionality: Filter, transform, data correlation, and sensor linearization
- General monitoring and control: Supervisory logic, threshold detection, and state machine controls

The flexibility that the programmable logic offers enables designers to tailor an analog solution that meets the exact needs of their system.

Applications and Uses

The flexibility and capabilities of the high-quality XADC and All Programmable devices allow for simplified board design, reduced cost, and improved reliability of systems through integration of multiple stand-alone devices.

Table 1 provides a list of markets and applications that can be addressed using an analog mixed signal solution.

Table 1: **Typical Applications Addressed by Analog Mixed Signal Solution**

Market	Application	Analog Mixed Signal Solution
Industrial, Scientific, Medical	Programmable Logic Controllers (PLCs), Power Conversion, Motor Control, Test and Measurement, Human-Machine Interface	Integrated safety monitoring technology Self test functionality Control of power devices Touch-based interfaces Remote sensors monitoring Autonomous Motor Controllers Enhanced support for IEC 65108
Communications	Wired and Wireless	System management: Monitor temperatures and power supplies Security: Anti-tamper counter measures
Aerospace and Defense	Secure Communications and Munitions	Monitor on-chip temperature and supplies for enhanced reliability Motor Control Security: Anti-tamper counter measures
Consumer	Multi-Function Printer, Digital SLR Camera, Broadband Access	Sensors monitoring: Humidity, temperature, power, light, and accelerometer Touch-based sensors and motor drivers
Automotive	Infotainment, Instrument Clusters	Monitor voltage and current Stepper motors Touch-based sensors

Benefits of Analog Mixed Signal

The benefits from the integration of the XADC with Xilinx FPGAs and SoCs are numerous and fall under many categories:

- Cost savings
- System integration and flexibility
- System security (tamper detection)
- Improved safety for industrial applications
- Higher reliability
- Autonomous processing
- Inventory management
- System debug capabilities

Cost Savings through System-Level Integration

Cost savings are realized by eliminating typical analog "housekeeping" devices. With the analog mixed signal solution, the designer can eliminate system monitoring devices (thermal and voltage), various discrete ADCs, touch sense devices, etc. This results in a smaller footprint and reduced bill of materials (BOM) cost.

Further cost savings can be achieved by integrating a discrete microprocessor into the FPGA, by utilizing one of the three MicroBlaze™ soft processor configurations:

- Microcontroller: For basic control applications
- Real-time Processor: Suitable for applications using an RTOS
- Applications Processor: Supporting embedded Linux applications

For a Zynq-7000 SoC that integrates one or more ARM Cortex-A9 processors, increased real-time responsiveness can be achieved by utilizing a MicroBlaze real-time processor in the programmable logic to offload iterative, time-critical functions.

For more information on reducing BOM cost, see WP460, Reducing System BOM Cost with Xilinx's Cost-Optimized Portfolio.

Higher Reliability

The analog mixed signal solution contributes to higher reliability because using fewer devices translates into an improved FIT rate; the built-in self test functionality can include power supply testing and monitoring; and thermal management ensures equipment maintains operation within thermal limits.

Autonomous Processing

Autonomous processing enables an "intelligent" analog subsystem that encapsulates functionality and helps to control and manage analog chores, thereby freeing processing cycles and ensuring quicker response times. It also enables the integration of DSP as needed and eases design, test, and maintenance activities. And because it eliminates the need to use a higher performance processor, it also contributes to lower system cost.

System Security - Tamper Detection

With the expansion of programmable logic use beyond commercial markets to avionic and military applications, system security and tamper detection include the additional aspects of safety and national security. The integrated voltage, current, and temperature sensors of the XADC block provide the highest level of confidence to detect attempted device tampering. And once detected, appropriate measures can be taken as defined by the system designer.

Inventory Management

Since the analog mixed signal solution allows the integration of a wide range of discrete devices, it minimizes the reliance upon multiple vendors with uncertain inventories. Fewer vendors means that there is less chance of constrained supply shutting down product manufacturing. Additionally, the analog mixed signal solution reduces the risk associated with end-of-life obsolescence of mixed-signal devices.

System Debug

The XADC block allows designers to evaluate the PCB's power distribution system (PDS) and thermal management solution. The incorporated system debugging tools monitor voltage drop, on-chip temperature, and external sensors if required. The designer can also use the system debugging tools with the Xilinx ChipScope™ analyzer to correlate PDS performance and the vital statistics of the programmable device.

# Analog Mixed Signal Application Examples

The analog mixed signal subsystem provides a wide range of benefits across a broad range of applications.

Replacement of Analog "Housekeeping" Discrete Devices

The analog mixed signal subsystem is optimal for replacing a wide range of discrete analog circuits responsible for system-level "housekeeping" functions, including:

- Power monitoring and management
- Supervisors, voltage monitors, and sequencers
- Thermal management
- System monitor and control
- Single and multichannel ADCs
- Touch sensors

A broad portfolio of the "housekeeping" functions is available from multiple analog mixed signal vendors in the form of discrete small-scale to medium-scale integrated devices. These devices come in hundreds of configurations, covering a wide range of possible combinations and needs. An analog mixed signal solution in Spartan-7 or Artix-7 FPGAs and Zynq-7000 SoCs can readily replace the functionality found in the majority of devices, providing cost and board area savings. Figure 2 illustrates a simple controller board that includes a 4-channel ADC, small microcontroller, and an FPGA. The discrete ADC and the small microcontroller can be integrated into a Spartan-7 or an Artix-7 FPGA, creating a single device solution.
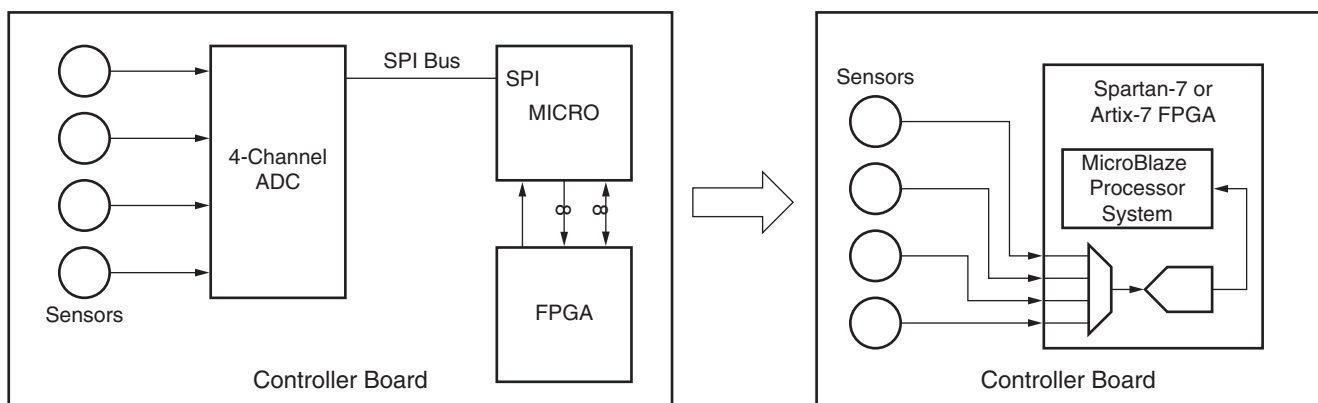
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Figure 2:   **Replacing Analog "Housekeeping" Device in a Simple Controller Board**

The single device solution provides BOM cost savings (typically, $2–5) board area, pin savings, FIT improvement, and better inventory management.

Multi-Function Printer

As another example of some of the benefits of the 7 series analog mixed signal solution, Figure 3 shows the analog housekeeping and control functions typically found in a multi-function printer. In this case, the analog circuits measure temperature, humidity, ink levels, touch screen sensors, and scanner sensors. Precision motor control is required for both scanning and paper handling. A single Artix-7 or Zynq-7000 device using the MicroBlaze real-time processor preset can accomplish all of these tasks, including the integration of the microprocessor that can be used for communications and overall control.

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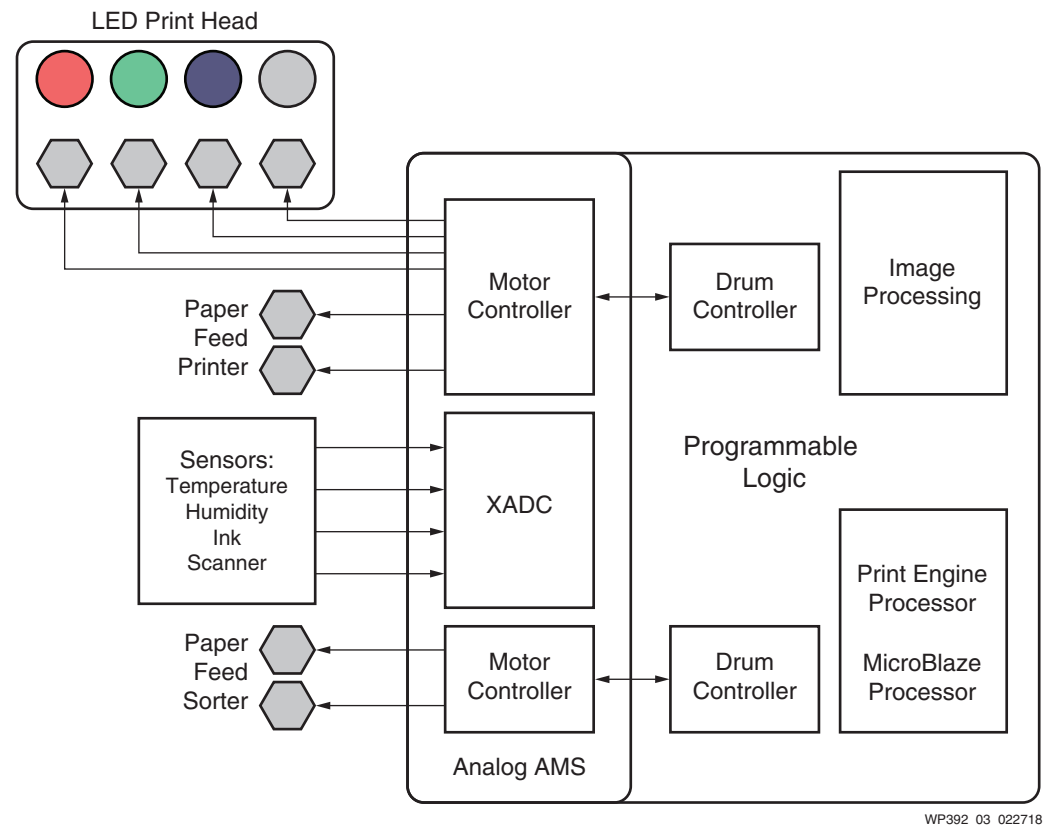
Figure 3: **Multi-Function Printer Implementation Using Artix-7 or Zynq-7000 Devices**

The resulting solution provides significant BOM cost savings (typically, $5–7), reduced board area, reduced IC count, reduced IC vendor count, reduced inventory management risk, and increased system reliability.

Resistive Sensing - Human Interface Devices

The popularity of touch-sensing interfaces has been rapidly increasing, especially with the emergence of smartphones and tablets. While there are multiple technologies used to manage touch sensing, one of the most popular methods is resistive touch.

Several manufacturers produce stand-alone devices designed specifically to address touch-screen interfacing. The majority of these devices are designed to communicate with an external microcontroller or processor. Figure 4 shows a simplified 8-wire resistive touch screen that has been implemented using a Spartan-7 or Artix-7 FPGA. In this example, the touch sensor and microprocessor are integrated using the MicroBlaze real-time processor preset, reducing device count and lowering overall system cost.
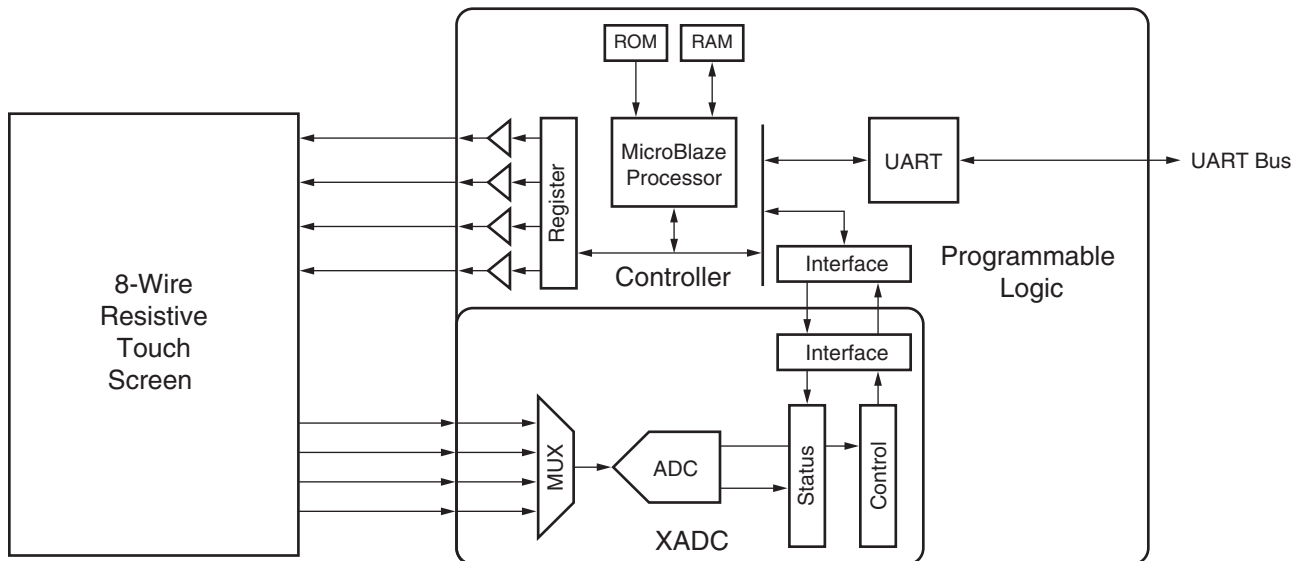
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Figure 4:   **Simplified 8-Wire Resistive Touch Screen Block Diagram**

Spartan-7 and Artix-7 FPGAs and Zynq-7000 SoCs are well suited for implementing both resistive and capacitive sensor interfaces. Using the XADC block, the Xilinx devices can directly measure sensor voltages. The device then processes the samples, compares the values to thresholds, and manages the touch or touches. In Figure 4, only a small amount of programmable logic resources are required, and even a 50k logic cell, low-cost Spartan-7 and Artix-7 devices have plenty of resources remaining for many additional functions.

Beyond the benefits of system-level integration, the high-performance programmable logic allows for fine-tuning of touch-screen processing algorithms, which can quickly exceed the processing capabilities of most stand-alone touch-screen devices. This expanded processing capability, in turn, can allow for a superior human-machine interface that is optimized to the application needs or the characteristics of the touch-screen materials.

Industrial Motor Control

Motors used for industrial applications are ubiquitous and account for more than 66% of the electrical power consumed in the industrial markets. As the cost of power continues to rise and the automation of factories increases, motor efficiency is becoming increasingly important. The advanced algorithms, which deliver greater energy efficiency, typically require DSP and computational capabilities, which cannot be met using traditional DSP and MCUs. Therefore, FPGAs and SoCs are increasingly being used in motor control applications, where historically, microprocessors had been programmed to provide motor control solutions. However, FPGAs and SoCs provide a number of advantages over microprocessors, including: higher performance, lower cost, robustness of solution, DSP capabilities, and solution customization.

The programmable logic together with the XADC block in 7 series architecture enables the designer to construct autonomous monitoring solutions that allow for offloading of the main processor. Offloading of a system processor can prove critical for applications that require real-time control—or can simply be used to reduce the overall system cost. The combination of an autonomous monitoring solution and a main processor can be more cost effective than scaling up to a higher performance system process.

As an example of the benefits of an autonomous processing subsystem, Figure 5 shows an integrated high-performance motor controller based on the XADC, a soft core MicroBlaze real-time processor preset, DSP blocks, and support logic functions, including pulse width

modulation (PWM), counter-timers, and serial communications channels. Using a simple application programming interface (API), a central control processor can issue high-level commands to configure and control the autonomous subsystem. The subsystem controls motor functions independent of the central microprocessor, and reports back status or issues interrupts as appropriate.
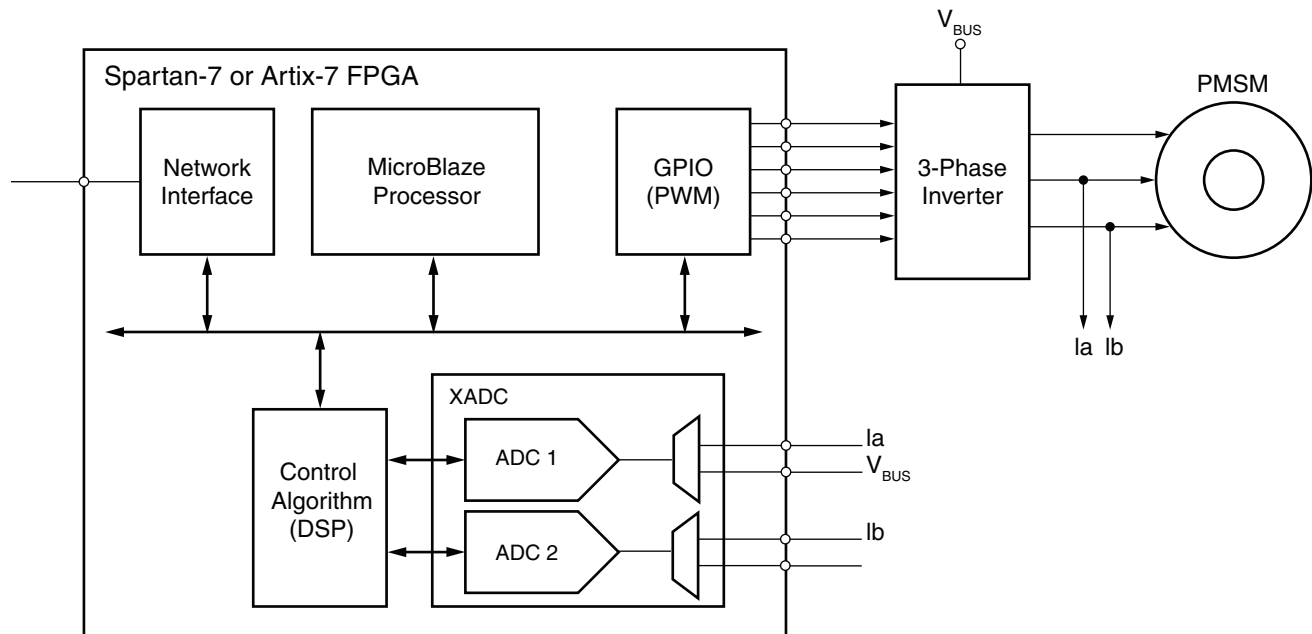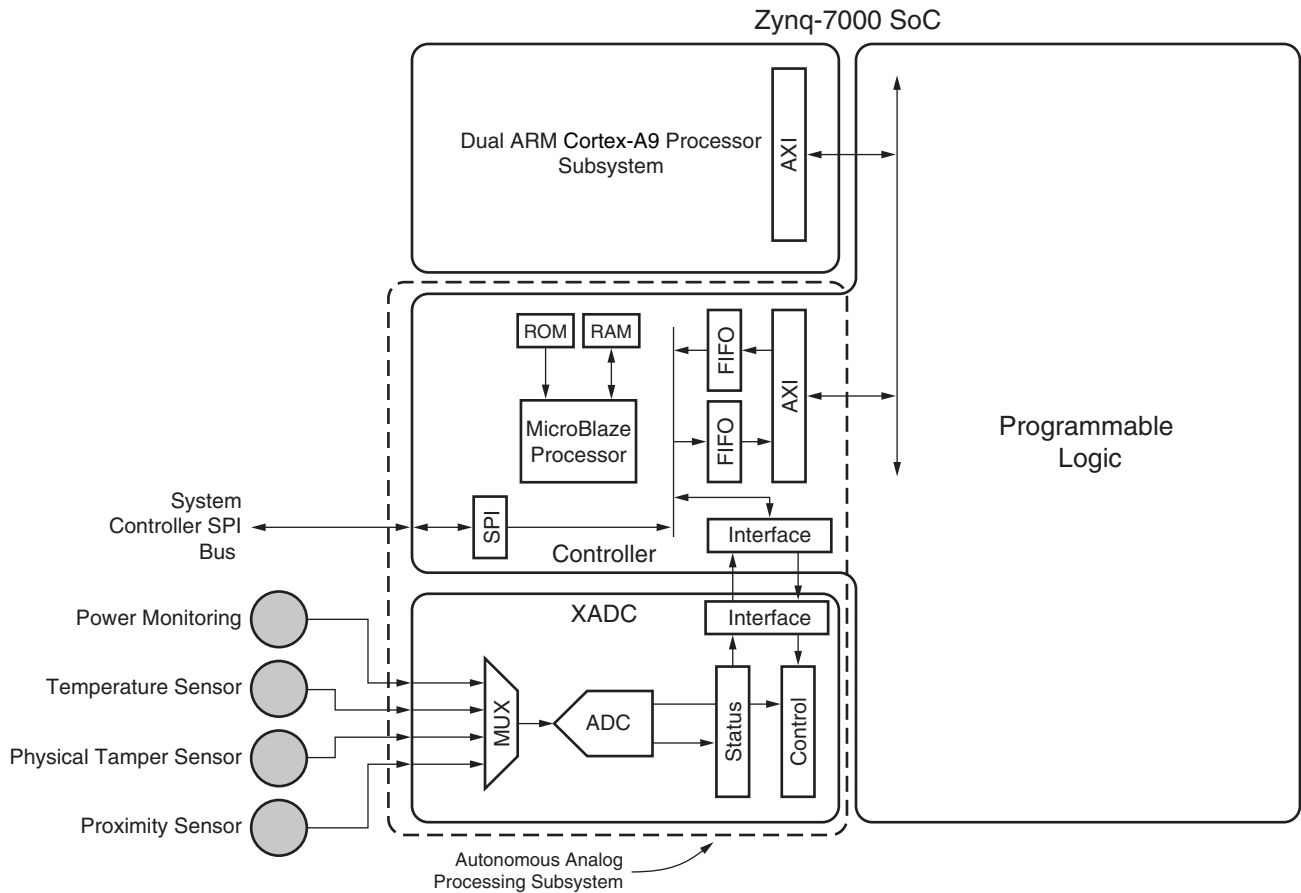

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Figure 5: **Industrial Motor Control Example Using an Artix-7 FPGA**

Separating the motor controller operation through an autonomous solution encapsulates the solution, making the overall system easier to design, test, and maintain. This can also lead to lower cost and overall higher system-level performance.

System Health and Security

In a remote communications system, the health and security of the system is typically monitored by a series of different sensors, including: power monitoring, system temperature, and physical tampering. A simple soft core microprocessor, such as the MicroBlaze processor, can easily manage and monitor these signals using the XADC and report back status and alerts to a central location through a communications link.

Alternatively, an internal industry-standard data bus, AXI®, can be used to directly communicate with an on-chip processor subsystem, such as the MicroBlaze processor as well as the ARM® Cortex™-A9 cores in a Zynq-7000 device (see Figure 6). The autonomous operation of the analog subsystem functionality offloads the main processor and encapsulates the analog monitoring and control, providing known and predictable operation.

Figure 6: **Example Autonomous Analog Processing Subsystem**

System monitoring solutions continue to gain importance in high reliability systems. Typically, techniques based upon redundancy and environmental monitoring are employed to meet the stringent system requirements.

High Availability Systems

Communications systems must also meet high availability standards—working and available 99.999% of the time. To achieve these requirements, systems typically employ hardware redundancy and include system monitoring for early indication of potential failures, such as power supply drift or the presence of excessive temperatures. The XADC block found in the 7 series FPGAs and in the Zynq-7000 SoCs is ideal to address these needs.

Industrial Process Control

Industrial process control is concerned with maintaining the output of a specific process within a desired range. For example, a distillation process can require the temperature of a liquid to be maintained at a specific point within a narrow range. Programmable logic controllers (PLC) are often used in industry for managing these processes by continuously converting analog sensor outputs into digital values, analyzing the data, and then acting on the information based on a user defined program.

Spartan-7, Artix-7, and Kintex-7 FPGAs and Zynq-7000 SoCs are ideal PLC components. With up to 17 analog inputs, the XADC block provides the ability to monitor multiple sensors using a single device. Programmable logic provides a powerful compute solution to monitor the

data, easily performing filtering, threshold comparison, and control operations. The PLC designer has the ability to integrate flexible high-performance DSP functions, microcontrollers, and logic functions and data processing capable of processing millions of data samples per second—far in excess of even some of the highest performance microprocessors.

The benefits of integrating the data conversion functionality include: lower system cost, higher product flexibility, higher system performance, and the extended product life cycle of the FPGA and SoC. One major benefit of integration is the reduction of the number of vendors on the BOM, resulting in lower issues with device inventory such parts shortages or obsolescence. FPGAs and SoCs are completely reconfigurable, enabling new functionality to be added or updated to products at any time over the lifetime of the product.

Industrial Safety - IEC 16508

Safety systems have always been a critical component of the typical manufacturing environment, responsible for monitoring the general health and operation of the manufacturing equipment, and shutting down a process when something operates outside of specification. Smart sensors and actuators with integrated safety features, such as diagnostics and test, continue to be introduced to market. These smart sensors typically integrate an analog sensor or multiple sensors with digital control logic to ensure that distributed control systems are continuously monitored for maximal safety.

IEC61508 is the leading Functional Safety Standard for systems containing electrical, electronic, and programmable systems. In its basic form, a functional safety system detects a potentially dangerous condition and causes corrective or preventive action to be taken. Detecting the dangerous situations is a function of the system under control and relies upon auditing data from a wide range of sources, including analog sensors, and determining when a particular specification is operating outside of a pre-defined tolerance level. These safety functions are typically implemented in a combination of analog and digital components and subsystems.

Spartan-7, Artix-7, and Kintex-7 FPGAs and Zynq-7000 SoCs offer an excellent fit for a wide range of industrial applications. Multiple external and on-chip analog sensors can simultaneously be measured by the XADC block and then processed using an embedded processor core or digital logic within the programmable logic. Inter-system communications using light-weight 3-wire protocols, such as SPI or I2C, or even more advanced industrial networking standards, including industrial Ethernet, EtherCat, etc., can be incorporated into the same FPGA or SoC. This allows for a highly integrated single device solution, which delivers the highest level of safety and reliability while also delivering lowest cost, smallest board space, and highest pin savings.

Anti-Tamper Detection

Military activity around the globe provides nearly daily discussion of the vulnerability of communications networks and the Internet to hostile attacks. And the trend towards the digitization of all media and the longer term trend towards monetary transactions via digital mediums, is driving an ever-increasing focus on security and anti-tamper in the public sector. Similarly, securing Intellectual Property in the form of soft IP for microcontrollers or FPGAs is increasingly becoming a high priority for high-technology equipment manufacturers and designers.

In military applications, in the U.S., anti-tamper security consumes the systems engineering activities intended to prevent and/or delay exploitation of critical technologies in weapons system. Although not intended to completely defeat hostile attempts, anti-tamper security significantly discourages exploitation or reverse engineering. There are four components of an anti-tamper system: tamper resistance, tamper detection, tamper evidence, and tamper response.

Tamper resistance functionality in Xilinx FPGAs and SoCs starts with the incorporation of the AES bitstream encryption capability with RAM-based key storage; this provides the first level of defense against possible reverse engineering and subsequent exploitation.

Tamper detection is typically addressed through the use of physical indicators. Encasing the secure electronics in a protective housing requires the potential attacker to pry off the casing, and hence, leaving visible evidence of tampering. However, attacks that are based upon electronic and thermal techniques can easily circumvent these forms of detection.

One common method of attack is to vary the voltage and temperature of the device with the intent of "confusing" the device into divulging the AES keys and rending the AES bitstream ineffective. An analog mixed signal solution plays a critical role in detecting and then subsequently responding to this type of attack. By configuring the integrated XADC to monitor the internal device temperature and voltage, the attack can be detected when the FPGA or SoC starts to operate outside of a pre-defined range. When the tampered state has been detected, the programmable logic can be used to clear the encryption keys, and report the attack to a central location or to another nonvolatile secure device, thus providing evidence of the attack. As such, the Xilinx 7 series scalable, optimized architecture provides some of the most comprehensive Anti-Tamper capabilities available.

Analog Mixed Signal Integration

The integration of the XADC has two primary usage models: JTAG interface and the XADC programmable logic interface.

JTAG Interface

A unique capability of the XADC is that is can be accessed through the JTAG port without the need for programmable logic resources or for the programmable device to be configured. JTAG access supports both data and control, enabling the JTAG infrastructure to provide another level of functionality, system health monitoring. A central processor controlling the JTAG bus is capable of gathering remote power, temperature, and other analog data, and then performing system-wide system monitoring. For high-availability systems, the analog mixed signal solution provides a low-cost approach to monitoring the system, controlling redundant hardware, and reporting requirements. The ChipScope analyzer provides a convenient way to access the on-chip senors' information and configure XADC over JTAG. See Figure 7.
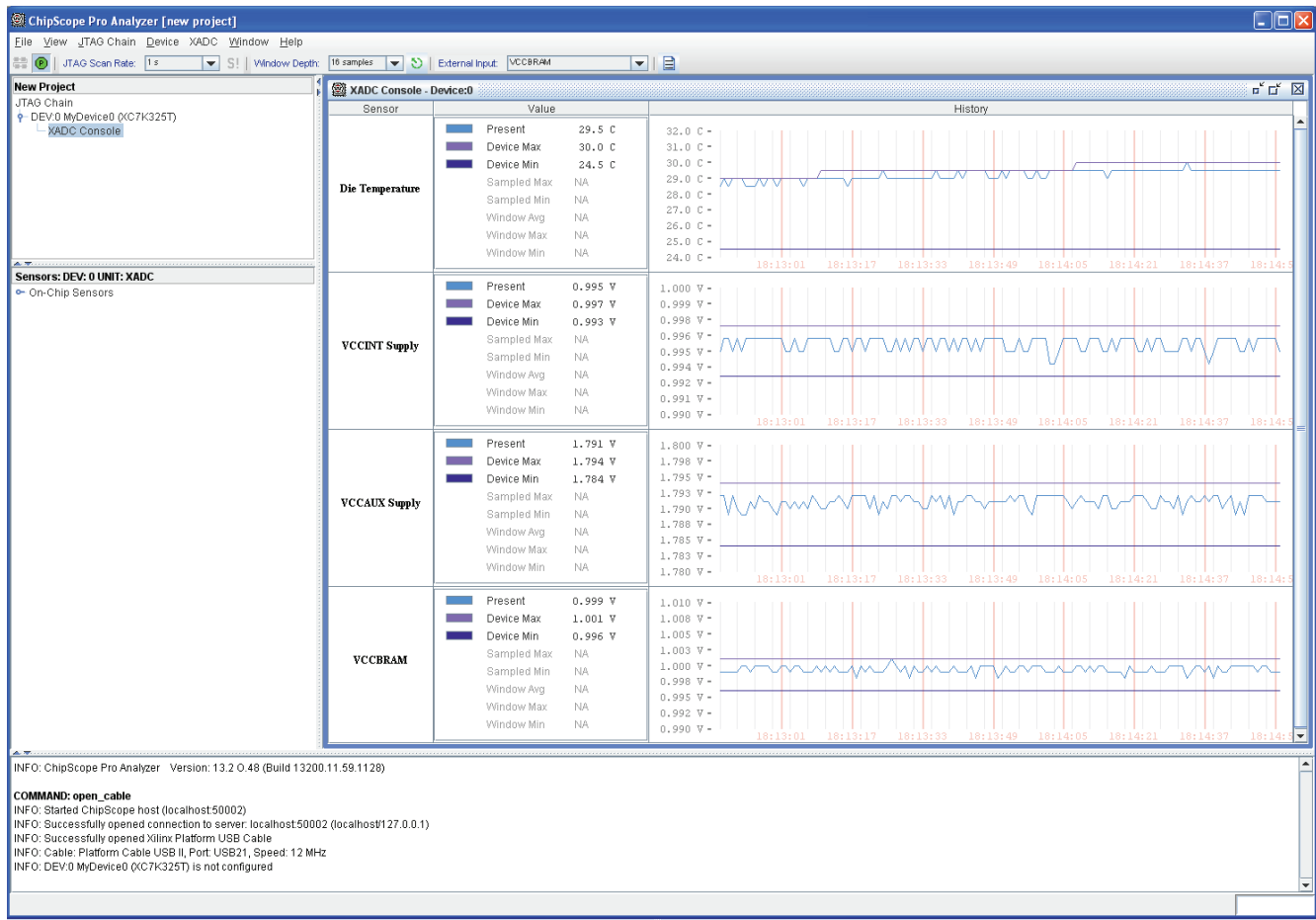
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Figure 7: **ChipScope Analyzer Output**

XADC Design Wizard

Implementing an analog mixed signal solution in a design is greatly simplified using the Xilinx XADC Design Wizard tool, which is available in the CORE Generator™ software. This interactive graphical user interface automatically creates an HDL instantiation module with all major features configured, including:

• ADC

• Programmable device temperature and voltage monitoring

• Alarm generation based on user defined thresholds

Once instantiated, the XADC can be further controlled through a bank of configuration registers.

Summary

The Xilinx commitment to XADC block solutions has been significantly extended with the introduction of the 7 series FPGAs and Zynq-7000 SoCs. The analog mixed signal subsystem found in the 7 series' scalable, optimized architecture combined with the programmable logic and MicroBlaze processor presets provides a powerful and flexible programmable mixed-signal platform. This capability enables designers to replace multiple discrete analog mixed signal ICs, which provides cost, board, and pin savings, and an improvement in FIT rates, while reducing inventory management burdens.

To learn more about the analog mixed signal capabilities of Xilinx products, go to:

https://www.xilinx.com/products/technology/analog-mixed-signal.html.

Revision History

The following table shows the revision history for this document:

Date	Version	Description of Revisions
03/24/11	1.0	Initial Xilinx release.
03/06/12	1.0.1	Minor typographical edits.
03/14/18	1.2	Updated title. Updated Spartan-7 FPGA, Zynq-7000 SoC, and MicroBlaze processor information throughout document.

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