TI Designs: Benchmark
AM437x Single Chip Motor Control Benchmark

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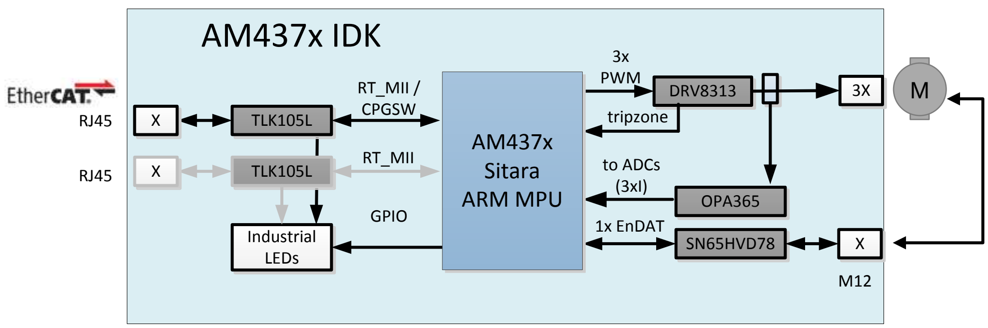
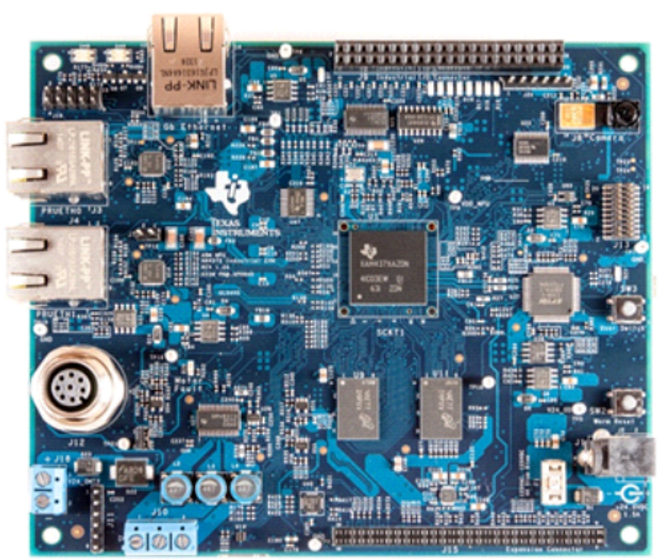
Circuit Description

The AM437x motor control benchmark demonstrates the performance of the advanced processing, communications, and control features of the AM437x and the industrial software development kit in an industrial application. The benchmark is an implementation of a single permanent magnet synchronous motor (PMSM) sensored 3-phase field oriented control (FOC) with an EnDat position feedback and current measurement with the onboard analog-to-digital converters (ADCs).





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1 Overview

The Sitara™ AM437x family a single consolidated MCU and MPU that can perform both motor and motion control and real-time industrial ethernet communications. The AM437x family is composed of a Cortex-A9 plus a powerful set of programmable and fixed function peripherals for Industrial communications, measurement, and control. This permits a single AM437x to replace multiple devices with an easy to use, compact, low power and cost efficient solution. The AM437x is a high performance Cortex-A9 family (up to 1 GHz) with NEON and VFP for floating point acceleration of control loop and motion control software.

A key feature is the quad-core programmable real-time unit (PRU) industrial communication subsystem (ICSS) that enables the AM437x family to provide concurrent industrial Ethernet protocol and control functions. The ICSS system supports Profinet, Ethernet for control automation technology (EtherCAT), PROFIBUS, Ethernet/IP, Powerlink, and Sercos3 protocols. The motor control functions include:

- Motor control algorithm (FOC)
- 3-channel EnDat2.2 master per PRU
- 9-channel Sigma-Delta Sinc^3 filter per PRU core
- PWM function

The AM437x also includes a number of integrated subsystems to support industrial applications including a real-time clock, Pulse Width Modulators (PWM), Quadrature Encoder Pulse (QEP) Drivers, ADCs, a dual camera interface, dual CANs, dual Gigabit Ethernet interfaces, and extensive peripheral interfaces.

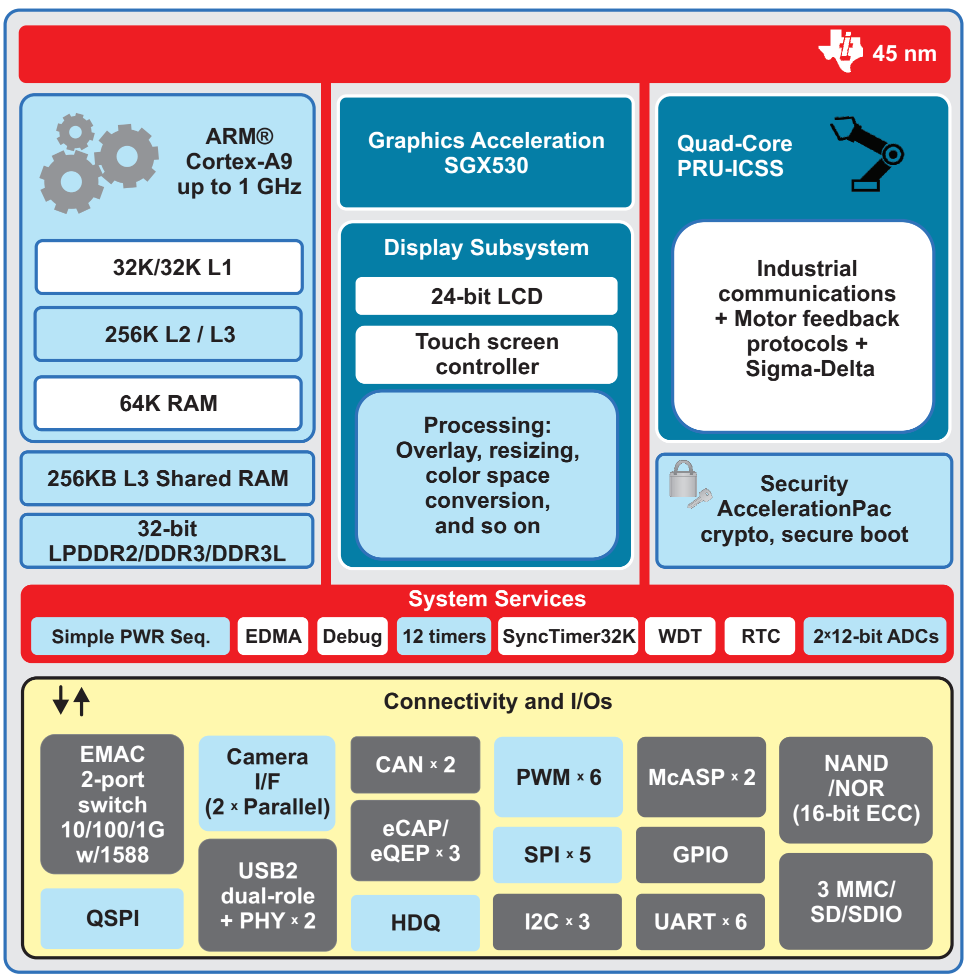

Figure 1. AM437x Overview

The Sitara AM437x portal page, which has additional information on the AM437x family, is available at http://processors.wiki.ti.com/index.php/Sitara_AM437x_Portal.

The AM437x family is well suited for applications such as:

- Industrial drives and connected drives
- Industrial HMI and PLC
- Industrial gateway
- Industrial protocol converter
- Barcode scanners
- Test and measurement equipment
- Patient monitoring
- Navigation equipment
- Portable data terminals
- Point of service

This system provides the high performance communications and control functions that are necessary for ultra-low latency response, deterministic, real-time processing, and high speed I/O.

2 AM437x Industrial Development Kit

The AM437x Industrial Development Kit (IDK) is an application development platform for evaluating the industrial communication and control capabilities of Sitara™ AM4379 and AM4377 processors for industrial applications. The benchmark is performed on the AM437x IDK. This platform provides a flexible development system supporting a wide variety of communications and control system configurations. An overview of the AM437 IDK board and hardware configuration is shown in Figure 2.

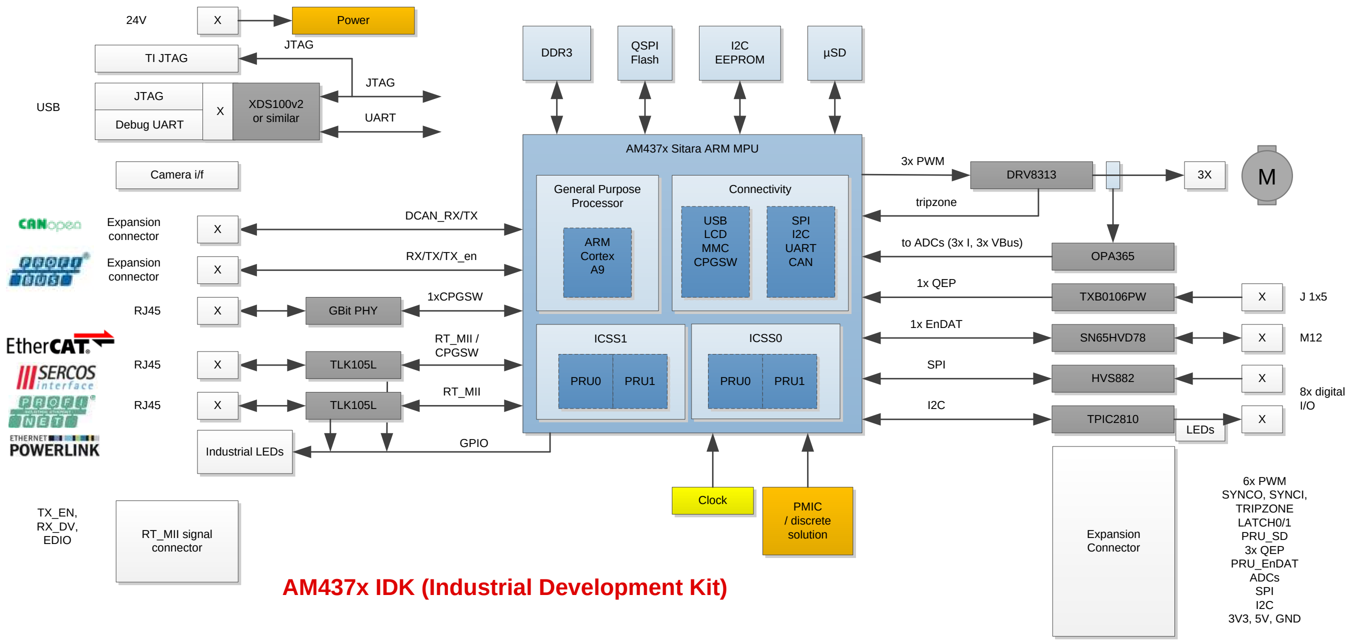

Figure 2. AM437x Industrial Development Kit Overview

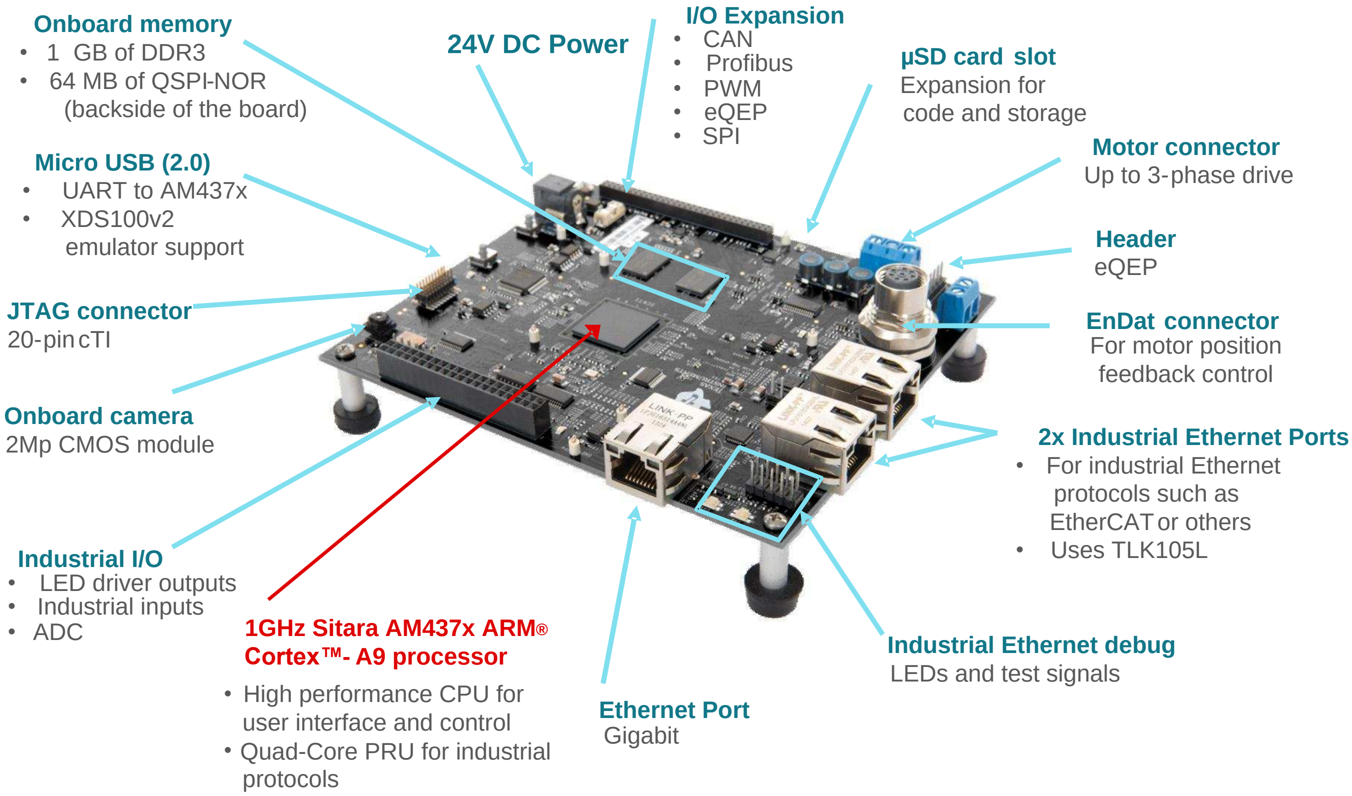

Figure 3. AM437x IDK for Industrial Protocols and Motor Control

Find additional information on the AM437 IDK at http://processors.wiki.ti.com/index.php/AM437X_EVM_Boards.

2.1 AM437x Industrial Communications Software Development Kit

Industrial applications and **application** development are supported by the AM SYSBIOS-based software development kit (SDK) for industrial communications. This SDK is designed for the Sitara AM437x ARM Cortex-A9 microprocessor family to enable customers add real-time industrial communications easily and quickly to their system. The industrial communications SDK is a comprehensive package that provides all of the basic system software components to quickly enable application code development. This package is optimized to support realtime industrial communications protocols such as EtherCAT, Profibus, Profinet, Ethernet/IP and many others. The SDK includes a real-time, low-footprint SYSBIOS kernel with boot loader and sample industrial applications to get started quickly.

The SYSBIOS Industrial SDK for AM437x combines all the software components and tools needed to begin development of SYSBIOS-based applications on the ARM. The key features of the SDK are:

- Open source SYSBIOS real-time operating system (RTOS)
- Bootloader for AM437x IDK with support to boot from various peripherals
- Library of peripheral drivers integrated with SYSBIOS supporting IDK
- Sample applications demonstrating peripheral use cases for IDK
- Code Composer Studio™ integrated development environment (IDE) v6
- Sample industrial I/O applications over communication protocols and evaluation versions of protocol stacks such as EtherCAT, EnDat, and others

Find additional information on the AM437x Industrial Communications SDK at http://processors.wiki.ti.com/index.php/Main_Page.

3 AM437x Motor Control Benchmark Overview

The AM437x motor control benchmark is a connected single-chip drive application demonstrating the performance of the AM437x supporting concurrent industrial communications and the drive application. For this benchmark, the EtherCAT and the EnDat 2.2 were chosen for the communications protocol and the position feedback interface; however, the measured performance represents any of the supported communications protocols and position feedback interface. The benchmark is an implementation of a single permanent magnet synchronous motor (PMSM) sensored 3-phase FOC with an EnDat 2.2 master interface and on-chip ADCs.

3.1 Field Oriented Control (FOC)

The FOC attempts to separately control the torque producing and magnetizing flux components of stator current. By decoupling control of the magnetization, the torque producing component of the stator flux becomes effectively an independent torque control. To decouple the torque and flux, engage several mathematical transforms. The FOC consists of controlling the stator currents represented by a vector. This control is based on projections that transforms a 3-phase time and speed dependent system into a two-coordinate (d and q coordinates) time invariant system. FOC machines need two constants as input references: the torque component (aligned with the q coordinate) and the flux component (aligned with d coordinate).

The first set of inputs to FOC is the motor phase currents. These measurements feed the Clarke transformation module. The outputs of this projection are designated Isα and Isβ. These two components of the current are the inputs of the Park transformation that gives the current in the (d,q) rotating reference frame. The Isd and Isq components are compared to the references Isd* (the flux reference) and Isq* (the torque reference). This control structure can be used to control either PMSM or HVPM machines by simply changing the flux reference and obtaining rotor flux position. When controlling a PMSM, Isd* is set to zero. The torque command Isq* is the output of the speed regulator. The outputs of the current regulators are Vsd* and Vsq*, the inputs to the inverse Park transformation. The outputs of this transformation are Vsα* and Vsβ*, which are the components of the stator vector voltage in the (α, β) stationary orthogonal reference frame. These are the inputs of the space vector PWM. The outputs of the space vector PWM block are the signals that drive the inverter.

Both Park and inverse Park transformations need the rotor flux position. In a synchronous machine, the rotor speed is equal to the rotor flux speed. This speed is calculated from the rotor position of the QEP encoder. The rotor flux position (θ) is directly measured by position sensor or by integration of rotor speed. The rotor position permits the variable transformation from a stationary reference frame to a synchronously rotating reference frame. As a result of this Park transformation, the q-axis current controls torque while d-axis current is forced to zero. The result is that the torque and flux are decoupled from each other. The overall block diagram of this project is shown in Figure 4.

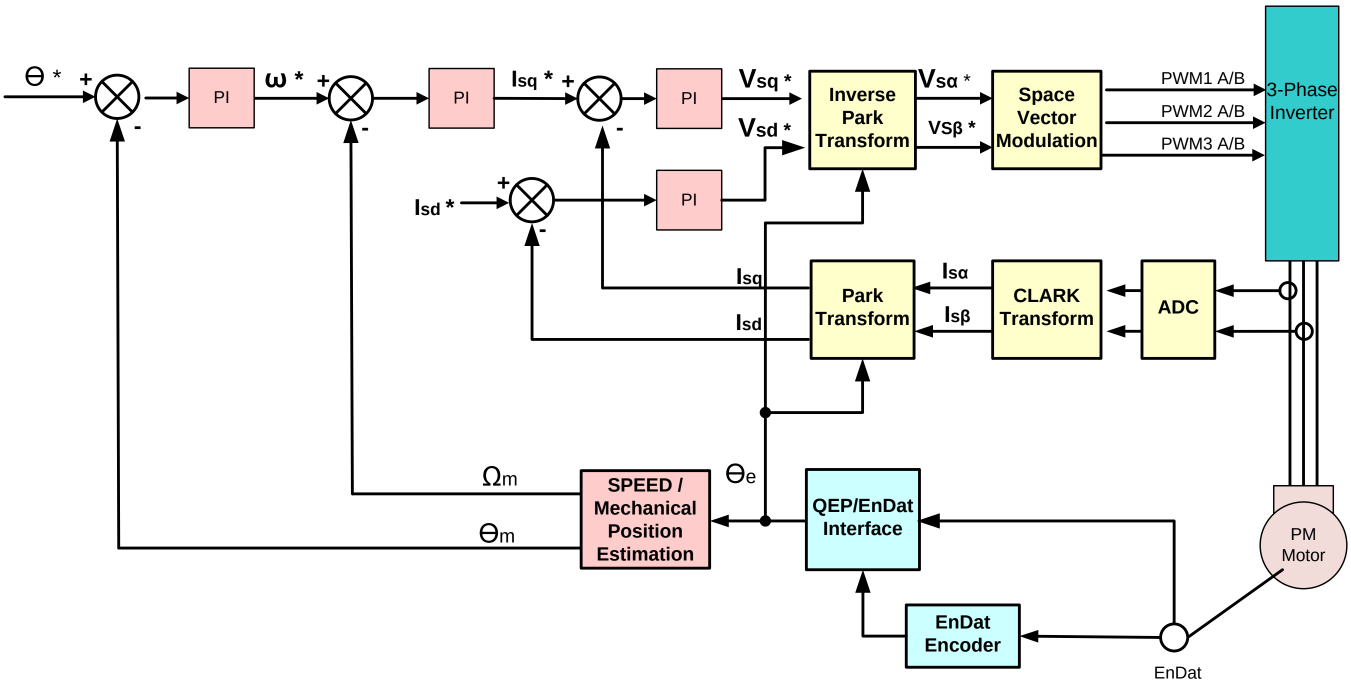

Figure 4. Block Diagram of Sensored FOC

3.1.1 Position and Speed Motor Control

A diagram of the speed and position FOC loop for a permanent magnet synchronous motor (PMSM) is shown in Figure 5. The AM437x family enables cost-effective integrated designs of communications system and intelligent controllers for three phase motors by reducing the system components and increasing efficiency. The FOC algorithm maintains efficiency across a wide range of speeds while compensating for the sinusoidal voltage waveform applied to the motor is created by using a space vector modulation technique. This algorithm maintains efficiency in a wide range of speeds and takes torque changes with transient phases into consideration by controlling the flux directly from the rotor coordinates. This in this benchmark implements the control for the sinusoidal PMSM. The sinusoidal voltage waveform applied to this motor is created by using the space vector modulation technique. This approach produces a minimum amount of torque ripple when driving a sinusoidal BEMF motor with sinusoidal currents.

In LEVEL4, the controlling variables are Isw and speed.

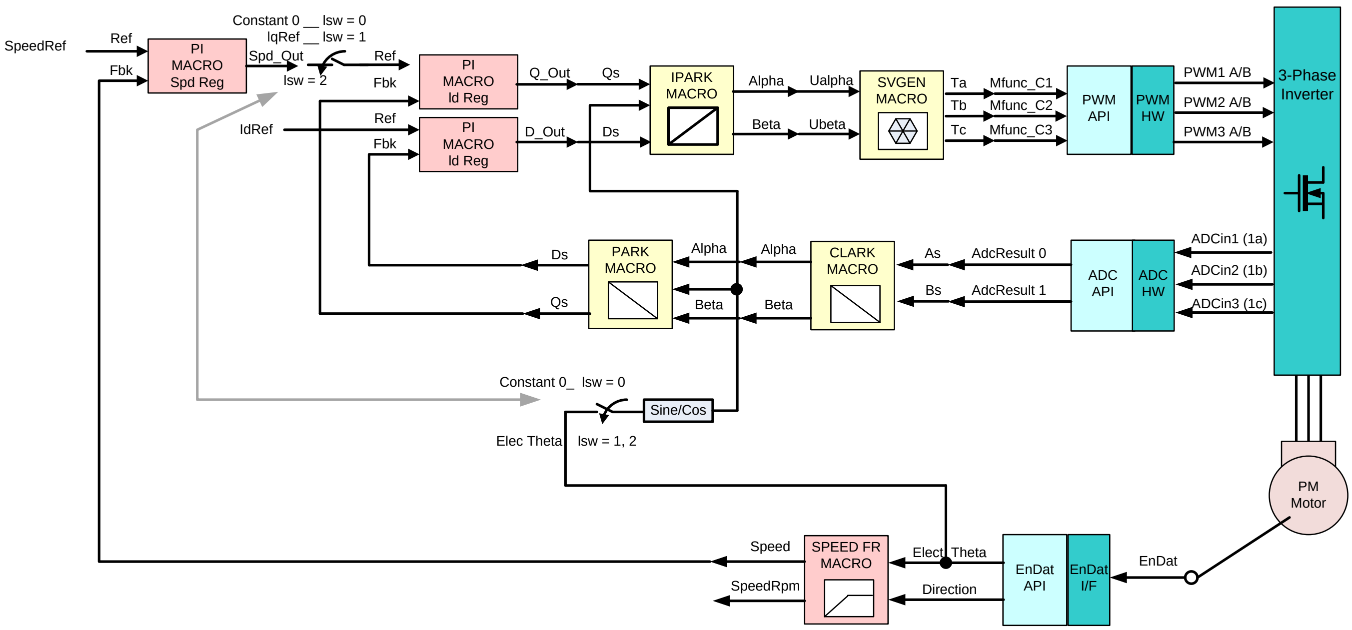

Figure 5. Level 4 — Speed Closed FOC Loop

In LEVEL5, the controlling variables are Isw and angle.

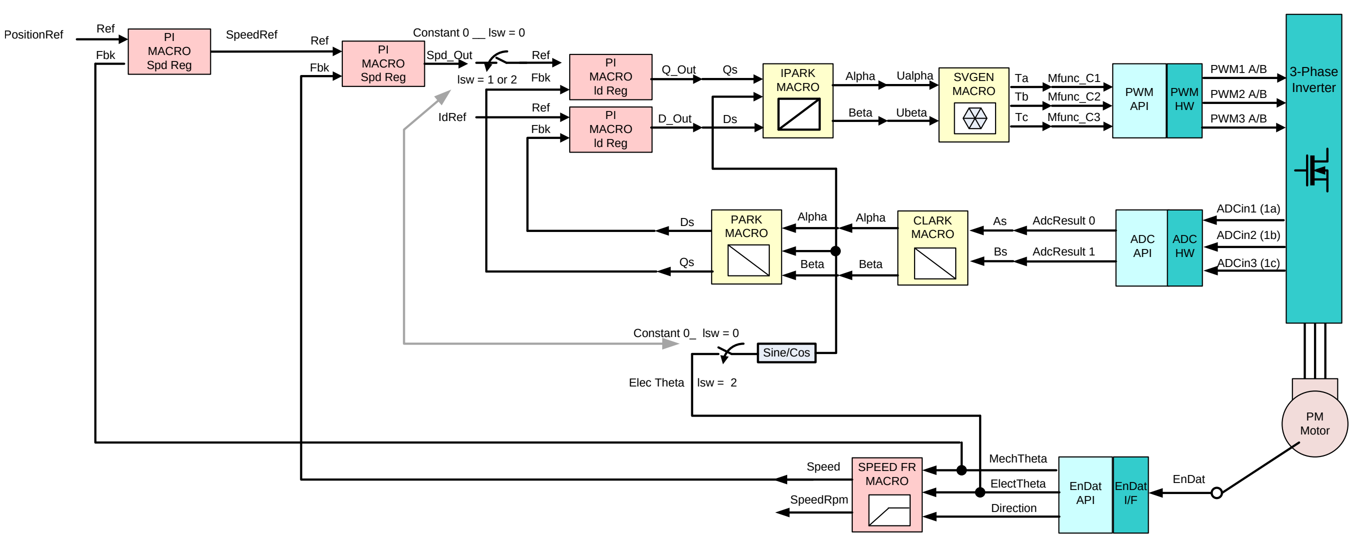

Figure 6. Level 5 — Position Closed FOC Loop

4 EtherCAT Overview

EtherCAT is a high performance Ethernet-based architecture developed by Beckoff that overcomes many of the limitations of fieldbus systems by means of "on-the-fly processing". This protocol is standardized in IEC61158. EtherCAT differs from other Ethernet solutions by providing parallel paths so that the slave devices will read data that is addressed to **them** while the frame is simultaneously passed through the nodes. The EtherCAT protocol avoids the delays that are incurred when an Ethernet packet or frame is received, interpreted, and copied as process data at each node. EtherCAT provides parallel paths which forward the received frame while the slave devices read the data that is addressed to them. In a similar fashion the slave devices input data as the frame passes through the node. As a result EtherCAT provides high speed low latency communications with cycle times of ≤ 100 µs.

In EtherCAT, each frame contains the send and receive direction data for multiple devices. This enables the EtherCAT protocol to achieve a usable data rate of over 90% of the network bandwidth. For example when using the full-duplex features of 100BASE-TX, an effective data rate of more than 100 Mb/s can be achieved (>90 % user data rate of 2 × 100 Mb/s).

The EtherCAT is an optimized protocol for process data. The data can be transmitted in an Ethernet frame or pack into UDP/IP datagrams. Ethernet frame transfer is used in when the EtherCAT components are in the same subnet as the controller. UDP/IP packing is used to support multiple EtherCAT segments in other subnets. The segments are accessed via routers. One or more EtherCAT telegrams are contained in an EtherCAT frame. Each telegram supports a memory segment of the logical process image. A telegram can be up to 4GB in size. The physical order of the EtherCAT Terminals in the network does not influence the communications order or addressing. EtherCAT supports broadcast, multicast, communication between masters and communication between slaves.

EtherNet Header			ECAT	EtherCAT Telegram				Ethernet	
Dest A	Source A	Type	Frame HDR	Datagram 1	Datagram 2	...	Datagram n	Pad	Frame Check Seq
6	6	2/4	2	10 +n + 2	10 +m + 2		10 +z + 2	0...32	4
Ethertype 88A4h									

Figure 7. EtherCAT in Ethernet Frame

EtherCAT also supports a powerful distributed clock mechanism which provides a network wide distributed time base with less than 1 µs of jitter. Texas Instruments Sitara industrial automation products support EtherCAT technology. Additional information on TI EtherCAT solutions can be found at EtherCAT® on Sitara™ Microprocessors.

Another important source of EtherCAT technology is available at the EtherCAT Technology Group website http://www.ethercat.org/default.htm.

5 EnDat Master

The AM437x supports EnDat 2.1 and EnDat 2.2 Master implementations. These implementations use the industrial communication subsystem (ICSS) to preserve ARM processing resources for other important functions. The implementations support communications on any of the three channels with clock rates from 100 kHz to 16MHz. The ICSS performs CRC verification and cable delay compensation on each channel. The EnDat master also supports continuous mode. The EnDat masters have a fast 200-MHz on-chip interface to the powerful ARM Cortex-A9 microprocessor. The AM437 EnDat master has been functionally tested with various makes and type of encoders.

Find additional Information on EnDAT 2.1 and 2.2 on the Heidenhain website at http://www.heidenhain.us/enews/stories_1012/main-el.php.

6 Motor Control Benchmark Configuration

This implementation is performed using an AM437x at 600 MHz under the AM437x SYSBIOS Industrial SDK 02.00.00.02 with the application operating on TI SYS/BIOS (TI-RTOS). Note that the FOC algorithm implementation uses standard floating point trigonometric and math functions from the gcc math lib. Optimizing these functions will improve performance.

The motor control benchmark configuration is composed of an EtherCAT slave communicating with PLC master continuously at a 100-µs cycle time. The EtherCAT distributed clocks provides a low jitter distributed clock suitable for a multi-axis servo usage case.

The EtherCAT communications module (on ICSS1) provides two interrupts (SYNC0 and PDI) to the ARM every 100 µs. The ARM Cortex-A9 implements a 33.3-kHz current or torque/speed/position FOC feedback loop using the advanced SIMD NEON extensions. The measurement inputs are provided by the on chip ADC 0 and 1 operating in simultaneous sampling mode.

ICSS0 IEP timer is synchronized to PWM timebase and PRU1 triggers ADC Start of Conversion (SoC) and EnDat position measurement. The ICSS0.PRU0 provides a 33.3-kHz bidirectional interface to an EnDat2.2 encoder, performs the CRC computation and bit endian conversion of the position value. ICSS0.PRU1 polls for ADC End of Conversion (EoC) event and processes and prepares the current samples and position data and indicates the same to Cortex-A9 through interrupt to GIC. GIC schedules the FOC algorithm loop on Cortex-A9 to compute the next PWM samples upon seeing an EoC interrupt.

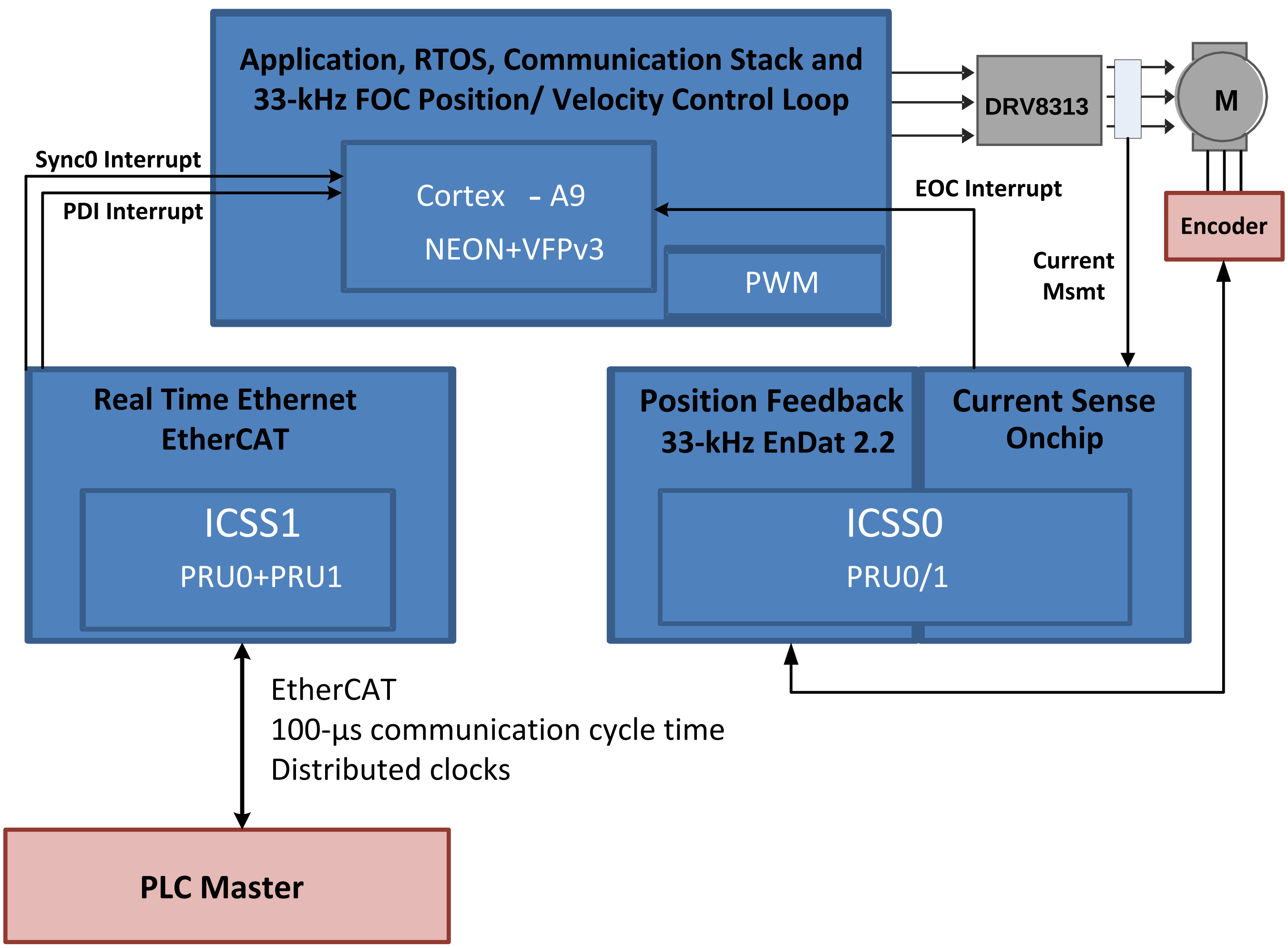

Figure 8. Motor Control Benchmark Configuration

7 Benchmark Results

Table 1. Benchmark Results

FUNCTION	PROCESSING TIME		UNIT
	LEVEL 4 (CLOSED SPEED LOOP)	LEVEL 5 (CLOSED POSITION LOOP)	
ADC sampling and conversion	1.33	1.33	µs
SYSBIOS interrupt latency	1.26	1.26	µs
FOC close current/torque loop to PWM update	5.79	5.83	µs
Elapsed time — Sample to PWM update	8.38	8.42	µs
25% head room	2.1	2.11	µs
Elapsed time +25 % headroom	10.48	10.53	µs
Maximum operational rate	47	47	kHz

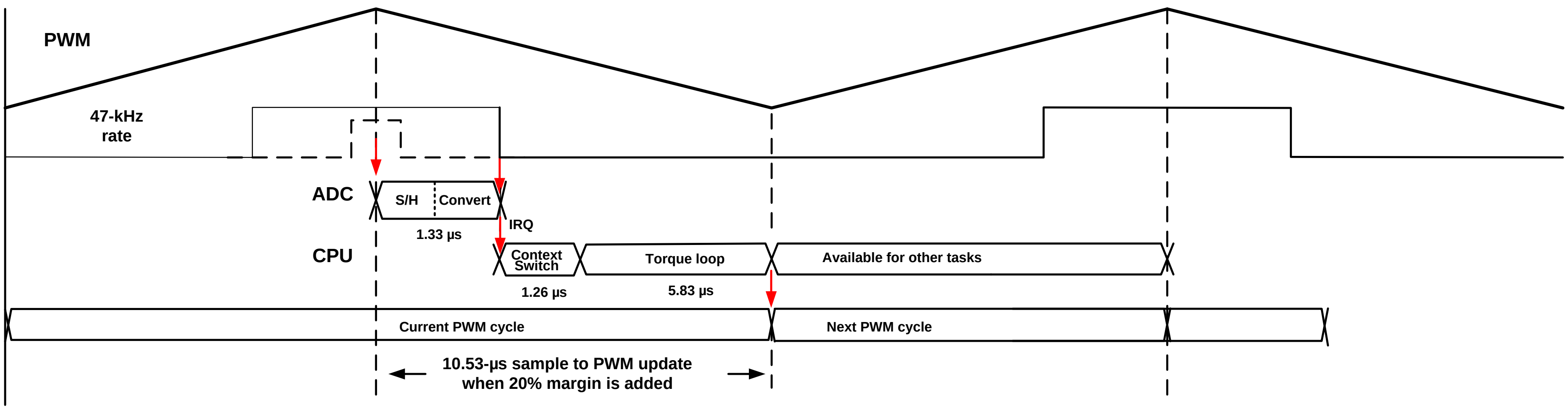

Figure 9. Benchmark Timing

8 Conclusion

This benchmark demonstrates that up to a control loop speed of 47 kHz is easily achievable (assuming 25% head room, without using special optimizations in math lib, RTOS, and so on), parallel with industrial Ethernet for connectivity at very low cycle times as 100 µs on AM437x, thanks to powerful PRU-ICSS subsystem integrated with Cortex-A9 (up to 1GHz) + NEON + VFP and other on-chip peripherals for control applications. This result clearly shows the scope for increased customer innovation using flexible architecture of AM437x, which enables multi-protocol industrial Ethernet and position and current feedback implementations.

9 Design Files

9.1 Schematics

To download the schematics, see the design files at TIDEP0025.

9.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDEP0025.

9.3 Layer Plots

To download the layer plots, see the design files at TIDEP0025.

9.4 Gerber Files

To download the Gerber files, see the design files at TIDEP0025.

9.5 Software Files

To download the software files, see the design files at TIDEP0025.

10 References

1. *Sensored Field Oriented Control of 3-Phase Induction Motors* (SPRABP8)
2. *AM335x and AM437x EtherCAT firmware API guide* (http://processors.wiki.ti.com/index.php/AM335x_EtherCAT_firmware_API_guide)

11 About the Authors

DAVID ZAUCHA is an applications engineer at Texas Instruments where he is responsible for supporting customer applications in Industrial Communications segment. David has been with TI since 1999 and has been involved in designing and supporting products in analog and embedded systems. David earned his BSEE at Univ. of Massachusetts and his MSEE at Univ. of Rochester.

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