WHITE PAPER

Sangmin Chon,
Director of C2000 marketing
Texas Instruments

TEXAS INSTRUMENTS

What it Takes to do Efficient and Cost-Effective Real-Time Control with a Single Microcontroller: The C2000™ Advantage

Overview

Performance, efficiency, flexibility and protection – these are the attributes paramount to power electronics technologies, such as motor control, digital power, renewable energies, lighting, and electrical vehicles. Backed by 15 years of working with customers developing these real-time control applications, TI's TMS320C2000™ microcontroller (MCU) platform enables developers to cost-efficiently meet all of the key criteria while also differentiating their designs.

C2000™ MCUs are based on a unique architecture that is optimized not only for accurate sampling of signals, accelerated control algorithm processing, and precise updating of PWMs, but also allows for simultaneous processing of math-intensive communications algorithms (e.g,. power line modem).

This paper provides an overview of what it takes to do real-time control, also highlighting why some MCUs on the market fall short.

"Real-Time Control" Defined

The questions of "What is real-time control?" and "What does it take to do a real-time control application?" are often raised. Real-time control is used in this paper in the context of a closed-loop embedded control system. It helps to put real-time control in context versus standard control processing where standard control refers to an open loop system, where the control process runs at a particular speed with no deadline. With a standard control system, if one wants to increase the performance, then he/she just needs to increase the speed (MHz) of the processor.

Real-time control systems are closed-loop control systems where one has a tight time window to gather data, process that data, and update the system. If the time window is missed, then the stability of the system is degraded. This reduced control can be catastrophic to some applications, such as power conversion and advanced motor control.

Many semiconductor companies are claiming their MCUs have the ability to support real-time control applications, but what does it really take to do real-time control? To answer this question one needs to take the entire system (Figure 1 on the following page) into account. In summary this entails:

- **The Input.** The ADC reads in information such as voltage and current and converts that information from the analog domain to the digital domain and then passes this information to the math engine. The ADC needs to have high resolution and needs to be able to convert an analog signal to a digital signal as fast a possible. One important feature is dual sample and hold, where both voltage and current can be sampled at the exact same time. In products such as inverters, dual sample and hold is important so that multiple voltages/multiple currents can be sampled.
- **The Math Engine.** This is the brain of the system that needs to precisely compute control law algorithms such a PID, 2P2Z, or 3P3Z. These algorithms are extremely math intensive and can be executed with far greater efficiency on a DSP core. After the processing of the control law has been completed, the math engine will then need to update the output.

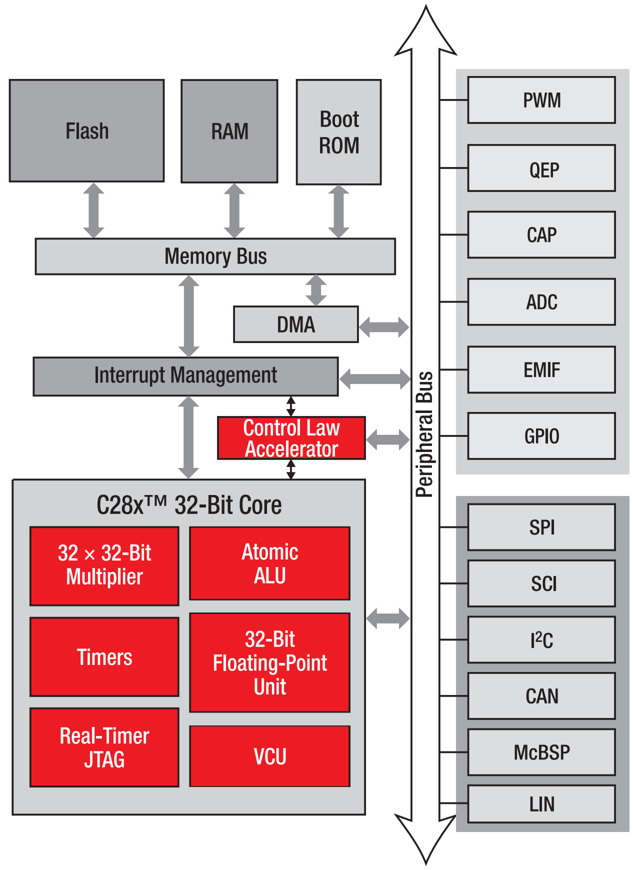

Figure 1. The innovative C2000™ architecture is ideal for real-time control applications. By streamlining performance and throughput, C2000-based microcontrollers are the first devices capable of dual-motor control with variable-speed drives that employ advanced algorithms such as field-oriented control (FOC) with power factor correction (PFC) and power line communications, all on a single microcontroller.

- **The Output.** The PWMs (Pulse Width Modulation channels) of the system need to be both flexible and high resolution. The PWMs in most cases control the output voltage or current in the embedded application. PWM flexibility is important in order to support a wide range of power topologies that enable different efficiencies, and support for high resolution is important in order to enable higher switching frequencies, which reduces the size/cost of the board magnetics

Again real-time requirements are extremely important from sampling on the input A/D, to control law calculations on the math engine, to updating the output via the PWMs – all of this needs to be completed within the control-loop time window in order to keep the system stable.

And while with traditional control applications, the microcontroller performs two main functions: system-level management and power conversion control, the landscape of real-time control is undergoing another important change. With the rise of initiatives like the Smart Grid and Green Electronics, there is more emphasis on system intelligence with communications which will place a major load on system resources.

While many MCU suppliers claim that they have all the necessary components like a fast ADC, a core that supports DSP extensions, and PWMs, their solution can fall significantly short of meeting a real-time control application's needs. This is, in part, because these MCUs lack the design of a finely tuned control architecture that integrates these components in such a way that allows for the lowest latency from sample to output delay, that provides the "small hooks" required by multiple power topologies, and finally allows for having mechanisms in the digital controller to protect for over current and over voltage conditions.

Latency, latency, latency: A need for a real-time control architecture

The overall performance of a system is measured by how well it regulates speed/position or voltage/current despite changing operating conditions. While complex control algorithms enable a system to reduce the effects of noise and error, maintaining accuracy requires more than just 32-bit math functionality, as timing and latency also play a key role in defining performance.

Ideally, a real-time control system will be designed for "Just-in-Time" execution. This means that the time between collecting feedback through an ADC measurement, computing the next speed or position required, and updating the PWM is as close to zero as possible. As these three stages spread in time, accuracy and efficiency suffer. Accurate real-time control reduces latency to a minimum by shrinking the window in which a real-time control system captures inputs, performs calculations, and outputs updates through the PWM.

TI's C2000™ microcontrollers achieve the highest accuracy and performance because their architecture is designed to accelerate the individual control loop stages. High-precision ADCs maintain accuracy through a variety of advanced features, including dual sampling and conversion sequencing. Real-time computations are handled either by the C28x™ core or by TI's innovative Control Law Accelerator (CLA). Finally, timely updates are made using high-resolution PWMs.

Each of these stages is implemented in distinct hardware and interconnected with timing triggers so that each can occur as soon as possible after the previous stage is complete (see Figure 2 below). For example, aligning sampling of the ADC with code execution on the CLA and updating of the PWM results in a substantially tighter control loop with minimal lag time and excellent transient response. The sample-to-output delay is further reduced through the CLA's ability to sample an ADC using early interrupt triggers. Even when a system encounters a major disturbance or step change, such as a large load being placed on the input, the

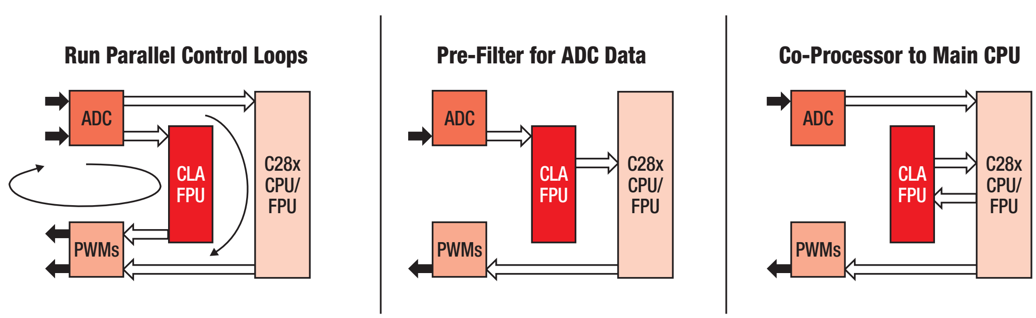

Figure 2. By implementing each control stage in hardware with interconnected timing triggers, sampling can be aligned with code execution on the Control Law Accelerator (CLA) and updates on the PWM to tighten the control loop with minimal lag time and excellent transient response.

C2000™ MCU's efficient ADC-CLA-PWM signal chain ensures fast responsiveness, consistent accuracy, and steady control.

Minimizing sampling latency at the input (ADC)

The first stage of an accurate control system is the ability to capture samples with as little latency as possible. To tighten the control loop, TI has integrated high-performance ADCs on its microcontrollers. This not only ensures fast, precise measurements but also lowers system cost. C2000 microcontrollers have as many as 16 ADC inputs, and developers can select which pins they want the ADCs to sample. Special ADC features include:

- **Reduced sampling latency:** C2000 microcontrollers employ a Peripheral Interrupt Expansion (PIE) architecture which streamlines interrupt handling for better responsiveness when sampling. In addition, the CLA supports early interrupt triggering to further minimize sampling latency.
- **Dual sample and hold:** With dual sampling, ADCs can take multiple samples simultaneously. For example, a system can capture voltage and current measurements at the same time. Without dual sampling, voltage and current have to be captured separately, each at a different time and introducing an error into subsequent calculations.
- **Conversion sequence flexibility:** When an ADC is triggered, rather than taking a single sample, the ADC can be configured to make a sequence of measurements. Developers can set three parameters to define a sequence: trigger source, sampling window size, and channel selection.

Don't underestimate the math engine

The impact of increasing system complexity can be seen by comparing the two common types of contemporary microcontrollers: general-purpose processors with math enhancements integrated into the architecture and those based on a DSP architecture. For system-level control tasks, the first type performs better than the second, operating at perhaps 25 percent greater efficiency. However, DSP-based architectures are on the order of three times as efficient when evaluating math-intensive algorithms. As CPU load increases from complex control algorithms, and while more and more performance is being demanded from the CPU (ex: power factor correction and self-diagnostic functions), the inherent mathematical capabilities of DSP-based microcontrollers provide a distinct overall performance advantage for real-time control applications.

The C2000 MCU platform is based on TI's 25+ years of DSP leadership, fulfilling the need for DSP processing since its inception in order to drive complex control systems. Evolving to meet market demand, TI continues to optimize the C2000 math engine which:

- **Is based on a true DSP foundation:** TI's microcontrollers offer high performance and power efficiency through their dual memory access, single-cycle instructions, parallel bus architecture, and unified memory map. C2000 devices also have deep execution pipelines which allow the controller to be clocked much faster than other microcontrollers, allowing developers to call upon up to 300 MHz.

- **Includes low cost floating point:** The obvious benefit of floating point is ease of use because it eliminates saturation and scaling required on most fixed point processors and it better supports meta-language tools. However, floating point can also offer a significant performance boost on typical math functions found in control algorithms and on overall control law algorithm performance.
- **Provides control algorithm acceleration:** The Control Law Accelerator (CLA) option on C2000™ MCUs offloads algorithmic processing to increase throughput and accuracy. The CLA is a co-processor to the main C28x™ core. It ties directly to the ADC and PWMs and can run 2× more efficient control loops.
- **Adds a more specialized math instruction set on top of DSP instructions:** The latest addition to the C2000 architecture, the Viterbi Complex Math Unit (VCU), accelerates communication operations for power line modem up to 7×. With 75 specialized math instructions, the VCU can increase performance on math-intensive algorithms from complex filters, FFTs, and Viterbi decoding.

This translates into higher performance, increased throughput, and added intelligence. Additionally, it gives developers more options in how they implement their real-time control systems, and more available head-room to support self-diagnostic functions and adaptive algorithms to increase accuracy and power efficiency.

Accelerating control processing via the Control Law Accelerator (CLA)

Truly exploiting the efficiency of a fast ADC requires a microcontroller with an architecture that is highly responsive and can quickly process multiple samples taken within the same time window. In this way, updates can be fed back to the system faster for finer tuning of the control loop.

TI recognized the need for a streamlined control path and introduced the CLA to minimize processing latency (see Figure 3 below). The CLA was designed to execute time-critical control algorithms in parallel with the main CPU, effectively doubling system bandwidth and accelerating overall processing. Based on an independent, 32-bit floating-point math accelerator, the CLA is well-suited for managing low-level control loops with substantially higher cycle efficiency compared to the CPU. In one example, a control algorithm consuming 53 percent of a C28x™ processor's capacity requires only 17.5 percent when implemented using the CLA.

Enabling faster system response and improved support for multi-channel loops, the CLA is able to reduce sample-to-output delay through direct access to ADC and PWM peripherals that bypasses the CPU. Also, once a task is initiated on the CLA, it runs to completion without further involvement of the CPU. This frees the CPU to perform system-level tasks and even manage a second control loop.

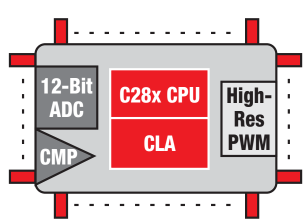

Figure 3: The CLA executes time-critical control algorithms in parallel with the main CPU, effectively doubling system bandwidth.

Part of the CLA's efficiency comes from the fact that the CLA does not use interrupts to synchronize with hardware. Rather, the CLA supports up to eight independent tasks, each of which is mapped to hardware events such as a timer or data being available on an ADC. The separate tasks also allow the CLA to support multiple control loops or phases at the same time. Eliminating interrupts also eliminates context-switching overhead. In addition, because the CLA is specifically designed to accelerate processing of control applications, it requires fewer transistors to perform the same operations on the CPU. The difference in power efficiency is significant, as one can move a dedicated control loop from running on the CPU to running on the CLA and can drop power consumption in half by powering down the Flash and executing from RAM.

Some systems achieve sufficient performance using hardware-based implementations. Such systems, however, are inherently inflexible, and any changes to the system can result in time-consuming and expensive redesigns. With the programmable nature of the CLA, developers are able to freely redefine control systems without impacting hardware design.

Because of the efficiency enabled by the CLA, developers can implement a complete motor control system on a single chip, including:

- Compute-intensive algorithms on the CLA, such as field-oriented control (FOC), which achieve greater efficiency for driving dual motors with power factor correction
- Sensorless feedback to eliminate the need for incremental encoders, thus lowering component and installation cost

The same efficiencies apply to power conversion systems which can support power conversion control loops. The system partitioning examples vary quite significantly across multiple end equipments from renewable energies, to lighting, to electrical vehicles. The math-intensive digital control loops (ex. 2P2Z or 3P3Z) can be performed completely by the CLA, leaving the CPU open for communications such as power line communications.

Fast, precise, and efficient control

The precision of power control stages can be lost if the system is unable to issue updates with low enough latency. To maintain precision and performance, C2000™ microcontrollers offer the industry's leading high-resolution PWM outputs. These PWMs provide:

- **Better accuracy:** With superior 150-picosecond resolution, a PWM can support higher switching frequencies, thereby increasing system responsiveness. This enables the PWM to most accurately reflect the ideal signal for tuning the control loop.
- **Higher efficiency:** The faster a power conversion system can operate, for example, the smaller the output ripple can be. This results in more efficient operation and greater power savings.

- **Improved control loop stability:** Higher resolution PWM helps to avoid limit cycle oscillation in high frequency switching systems.
- **Tighter system integration:** Developers have complete control over all aspects of the signal generation process, including duty cycle, frequency, and phase. Such fully-configurable PWMs enable tight integration with the control system, allowing compensation for faults and more efficient triggering of ADC start-of-conversions.
- **Lower system cost:** When systems can be controlled more tightly and consistently, developers can cost-reduce other system components without negatively impacting reliability. For example, a high-resolution PWM enables the use of smaller and less expensive magnetics.
- **Greater flexibility:** Power conversion systems, for example, are useful across a great many applications and can have a variety of topologies, including flyback converter, resonant LLC, DC/DC buck-boost, and DC/DC phase-shifted full bridge, to name a few. A PWM must offer flexible synching and phase delay to support these different topologies and allow developers to customize their waveforms to the highest degree for the particular application. C2000™ microcontrollers can be configured in hardware and will automatically sync as required.
- **Simplified design:** To further simplify design, these high-resolution PWMs support a variety of integrated features such as dead band generation.

Integrated communications at one-fourth the price

Reliable communication is an essential component for intelligent system management. For this reason, C2000 microcontrollers also offer a variety of peripheral options – including UART, SPI, I^2C, and CAN – to provide a fully-integrated solution for any real-time control system regardless of application. However, to capitalize upon the convergence of control and communications technologies to reliably network real-time systems and achieve higher operating efficiency, developers will need to turn to standards like power line communications.

Initial uses for intelligent power management have focused on smart metering to allow utility companies to track home and business power usage so that time-of-day rate incentives can be applied. A smart grid monitor with access to systems could also remotely manage hybrid car recharging. Instead of the power grid being put under a severe load as the majority of drivers plug in their electric cars after arriving home from work, cars can be charged in turn based on the currently available capacity of the grid. Similarly, the smart grid could manage home appliances, industrial systems, city lighting, and a host of other systems. Within a local network, solar inverters can transmit information to a smart grid monitor detailing actual power conversion performance. This data can then be used to dynamically adjust panels to optimally face the sun to maximize conversion rates.

One of the most compelling advantages of power line communications is that because it uses the existing power line infrastructure, systems can be connected without having to install any new wires. In this way, any system that is plugged in can be easily networked.

Today, power line communication (PLC) is typically added to a system through the use of an external PLC module. These modules are bulky and relatively expensive. With the introduction of the Viterbi Complex Math Unit (VCU), TI has taken a major step ahead of the competition by enabling developers to implement real-time communications without having to bring on a second processor or interfering with the microcontroller's ability to maintain reliable real-time control.

Using a C2000™ microcontroller with VCU, power line communications can be introduced to a system for 4× less cost than an external module, depending upon the application. Implementing power line communications onto the C2000 microcontroller also reduces system size and complexity by eliminating the need for an external module, connector, and interface. In addition, reducing the number of components reduces the number of points of failure and increases overall reliability.

The VCU is designed for the compute-intensive math that underlies communications that require heavy FFT processing, especially convolution and modulation techniques (see Figure 4). In addition to providing specific instructions for accelerating Viterbi decoding – including operating on multiple path metrics and performing trace back – the VCU also provides a variety of complex math functions well-suited for filters and FFT-based signal processing. These operations represent 80 percent of the processing for communication standards like power line communication and yield a performance increase of up to 7× compared to software-only implementations.

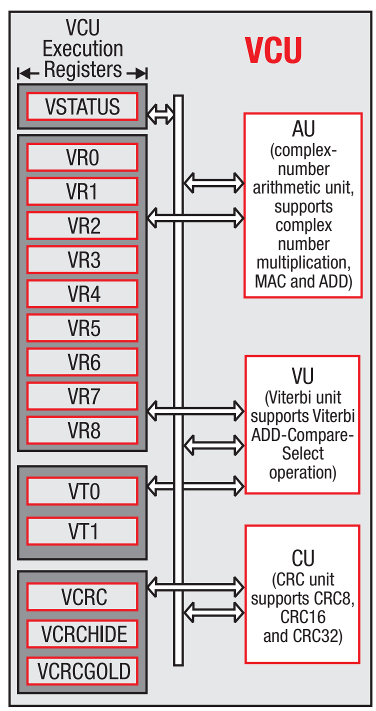

Figure 4. The Viterbi Complex Math Unit (VCU) is optimized for the compute-intensive math processing that underlies real-time communications, especially convolution and modulation techniques. Communication standards like power line communication implemented using the VCU yield a performance increase of up to 7× compared to software-only implementations.

Extending system operating life

While intended for accelerating communications processing, the specialized instructions of the VCU can also be used for advanced diagnostic processing to increase motor control performance and/or accuracy. For example, the VCU can offload the FFT processing required for analyzing motor vibration noise. These results can be used to determine the impact of vibration on a system, estimate operating life, and calibrate the control loop to improve efficiency.

Since the VCU offloads this processing from the main CPU, diagnostic capabilities can be introduced in systems which otherwise have little processing headroom. While speed and accuracy are important factors in motor control, diagnostics play an important part in extending the lifetime of motors. Many motor control and power conversion applications are part of systems with long operating lives that can extend over more than a decade. Systems that can adapt to changing operating conditions can maintain efficiency while preventing unnecessary wear.

Consider a system using a control algorithm that is relatively fixed in its implementation. Typically such an algorithm offers excellent performance and high efficiency across a limited operating range. When a motor has to drive a heavier load or operate faster than normal, the performance and power efficiency of the system can deteriorate. In addition, operating with less than optimal efficiency puts extra strain on the motor.

By supporting an adaptive control algorithm, a system can provide both short-term and long-term efficiency. In the short-term, an adaptive algorithm can provide excellent performance and high efficiency across the entire operating range by adjusting itself as the load and other operating conditions change. In the long-term, adaptive algorithms minimize the stress placed on a system, leading to less wear and a longer operating life.

Developers also have the option of introducing diagnostic algorithms that can analyze a system and compensate for expected wear. Spectral analysis techniques are available that can measure the electrical noise, harmonics, and vibrations given off by a system. This “spectral signature” changes as the system deteriorates through use. By occasionally monitoring its signature over time, a system can alert operators to pending maintenance or failure, adapt the primary control algorithm to compensate for current wear, or even shut itself down to prevent system damage or operator injury.

Diagnostic capabilities can be extended when a system has an active communications link such as power line communication. For example, performance can be tracked across all deployed systems, and failures can be analyzed to provide early-warning metrics for use in other systems. These analysis functions can be run in the background when the power line communication link is not in use. Coupled together, diagnostics and communications enable systems to be more robust.

Flexible architecture, flexible implementation

TI’s C2000™ real-time control platform offers an extensive selection of microcontrollers with a wide range of capabilities to allow developers to choose a device with the optimal processing capacity, memory, and other peripherals for their application. Code- and pin-compatibility among devices enables developers to leverage application code across different MCUs within the low-cost Piccolo™ and high-performance Delfino™ families. In addition, with the introduction of the VCU, developers will be able to easily introduce communications to existing C2000-based designs.

Developers also have the option of choosing a fixed- or floating-point architecture in both the Piccolo™ and Delfino™ generations. Floating point significantly reduces time-to-market and design complexity by simplifying algorithm development. Floating point also gives systems a performance boost by maintaining precision during complex calculations. For example, state estimator algorithms for motor control can more accurately determine rotor position and achieve the highest torque possible. Likewise, functions such as Park and Clark transforms as used in field-oriented control (FOC) require fewer cycles to execute, allowing an AC motor to be controlled using DC values.

TI also provides the IQmath Virtual Floating-Point Library, a comprehensive collection of highly optimized and high-precision mathematical functions, for C/C++ programmers to seamless port floating-point algorithms into fixed-point code implementations. IQmath's ready-to-use routines optimize execution speed and accuracy and can significantly shorten application development time.

Accelerated application development

TI understands that developers are designing under tight deadlines and need to focus on developing the primary application, not core functions like updating a motor or managing a communications link. With software development comprising the majority of almost every system design, off-the-shelf software plays a major supporting role in any silicon solution.

Some controllers are shipped with example code that illustrates how to use the architecture but that must be substantially rewritten to be useful in a real-world context. To simplify design and accelerate time-to-market, TI offers comprehensive libraries with code that can be configured for a particular application and shipped with final product. TI's software libraries and development tools are based on years of direct industry experience and allow developers to implement robust control and communications applications with little or no prior design experience. Combined with versatile development kits, these powerful development tools minimize software development time, allowing developers to jumpstart product development from concept to a production system quickly and easily.

TI offers a wide range of tools designed specifically to assist in the development of real-time control systems:

- **Code Composer Studio™ IDE** is the industry's premier microcontroller development environment. Providing access to an extensive battery of debugging and analysis tools, Code Composer Studio IDE gives developers unparalleled access and visibility into real-time control systems with capabilities such as real-time debug.
- **controlSUITE™ software** is a single portal for all of C2000™ content and content management, giving developers access to a comprehensive library of free motor control and power conversion software for digital power, as well as information on C2000 kits, supporting documentation, project examples and more. For example, controlSUITE includes TI's Digital Power Library that provides modular software to enable flexible and efficient coding of digital power supply applications using both the C2000 CPU and CLA

across a variety of topologies. Other resources include Floating Point Math and IQmath libraries. Designed with a simple user interface, controlSUITE also allows developers to keep up-to-date with the latest software through automated alerts.

- **plcSUITE** provides developers with a black-box approach to communications design. After being configured for a particular application, plcSUITE supplies all of the appropriate drivers. Developers only need to access the APIs from their application to implement a robust power link in just minutes.
- **Real-World System Application Kits** provide developers a way to jump start their design with a developer's kit that is very close to their real-world design. For example, the C2000™ High Voltage Motor Control Kit can be directly connected to the AC mains and can provide a power-factor corrected rectified 400 V DC Bus to drive the IPM stage for controlling an ACI, PMSM, or BLDC motor.

C2000 microcontrollers provide the processing capacity and robustness required of today's complex real-time control systems. The control-optimized C2000 architecture and math engine, combined with high-performance ADCs and high-resolution PWMs enable developers to tighten the control of various stages of the control loop to minimize latency and maintain the highest precision. With the comprehensive development tools and software TI supplies, developers can also quickly develop production systems with reliable communications for integration with other systems.

The increasing capacity of microcontrollers continues to offer new opportunities for product differentiation in real-time control systems. By implementing more complex control algorithms, diagnostics, and communication interfaces like power line communications, developers can improve system performance and efficiency. With the optimized architecture of the C2000 platform, developers can design more cost-effective systems, all on a single microcontroller, without compromising reliability.

For more information, visit:

C2000 real-time control MCUs: **www.ti.com/c2000**

"Adding efficient communication via new VCU" whitepaper: **www.ti.com/lit/pdf/spry158**

controlSUITE software: **www.ti.com/controlsuite**

IMPORTANT NOTICE

Following are URLs where you can obtain information on other Texas Instruments products and application solutions:

Products		**Applications**	
Audio	www.ti.com/audio	Communications and Telecom	www.ti.com/communications
Amplifiers	amplifier.ti.com	Computers and Peripherals	www.ti.com/computers
Data Converters	dataconverter.ti.com	Consumer Electronics	www.ti.com/consumer-apps
DLP® Products	www.dlp.com	Energy and Lighting	www.ti.com/energy
DSP	dsp.ti.com	Industrial	www.ti.com/industrial
Clocks and Timers	www.ti.com/clocks	Medical	www.ti.com/medical
Interface	interface.ti.com	Security	www.ti.com/security
Logic	logic.ti.com	Space, Avionics and Defense	www.ti.com/space-avionics-defense
Power Mgmt	power.ti.com	Transportation and Automotive	www.ti.com/automotive
Microcontrollers	microcontroller.ti.com	Video and Imaging	www.ti.com/video
RFID	www.ti-rfid.com	Wireless	www.ti.com/wireless-apps
RF/IF and ZigBee® Solutions	www.ti.com/lprf		
	TI E2E Community Home Page		e2e.ti.com

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265