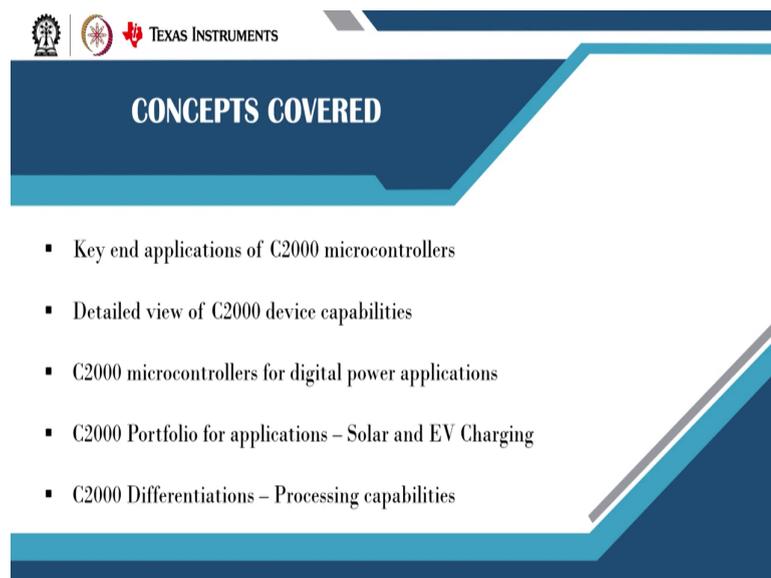


Digital Control in Switched Mode Power Converters and FPGA-based Prototyping
Prof. Santanu Kapat
Department of Electrical Engineering
Indian Institute of Technology, Kharagpur

Module - 09
Digital Control Implementation using Microcontroller
Lecture - 86
Texas Instruments C2000 Real-time Microcontroller Devices

Hello everybody. Welcome to NPTEL online certification course on Digital Control in SMPCs and FPGA based prototypic. My name is Aravindhan K. I am from Texas Instruments. I am going to cover Module 9 Digital Control Implementation using Microcontrollers. Specifically, I am going to talk about the Texas Instrument C2000 real-time microcontroller devices.

(Refer Slide Time: 00:51)



The slide features a dark blue header with the Texas Instruments logo and the text 'CONCEPTS COVERED'. Below the header is a list of five bullet points. The slide has a modern, angular design with light blue and dark blue geometric shapes.

- Key end applications of C2000 microcontrollers
- Detailed view of C2000 device capabilities
- C2000 microcontrollers for digital power applications
- C2000 Portfolio for applications – Solar and EV Charging
- C2000 Differentiations – Processing capabilities

So, we are going to cover in this lecture, the key end applications of C2000 microcontrollers. We are going to look at a detailed view of the device's capabilities. We are going to look at microcontrollers for digital power applications. Then we will look at the portfolio recommended by Texas Instruments C2000 for solar and EV charging. And finally, we will look at key C2000 differentiation from the processing capabilities in C2000 devices.

(Refer Slide Time: 01:20)



So, where are the places where the C2000 is used in real-time control? The C2000 devices are used in multiple-end applications, as you can see that we play a critical role in energy delivery primarily in charging infrastructure, and solar and wind power. We play a critical role in digital power, primarily in telecom server AC-DC rectifiers, and uninterruptible power supplies DC-DC converters.

Also, we have applications that are spanning across the motor control end application as well like appliances drones, E-bikes, and also in industrial drives like automation robotics. Also, in the automotive world, we are involved in many charging station-based applications HV DC-DC onboard charging, lighting, and also in traction drive. So, the C2000 real-time control is used across multiple end applications and it spans both digital power and motor control.

(Refer Slide Time: 02:21)

The slide is titled "C2000 Real-Time MCU Identity" and features the Texas Instruments logo in the top right corner. It is divided into three main columns, each with an icon and text:

- Broadest Real-Time Control Platform:** Accompanied by a bar chart icon. Text includes: "SW compatible low/mid/high at various price points", "Future-proof performance", and "Delivering high quality products".
- Innovation for the future of power conversion:** Accompanied by a lightbulb icon. Text includes: "Industry's fastest real-time signal chain Sense-Compute-Control" and "Enables GaN/ SiC today".
- Expertise for faster and easier development:** Accompanied by a speedometer icon. Text includes: "25 years of experience in digital control" and "Numerous Reference Designs HW/ SW to accelerate development".

Below these columns is a summary box with four bullet points:

- ✓ **Million** units shipped in Automotive & Industrial
- ✓ **Thousands of** customers worldwide
- ✓ **High quality**
- ✓ **Multi-source** FAB strategy for safe supply and future expansion

The bottom of the slide features the NPTEL logo on the left, the text "NPTEL Online Certification Course IIT Kharagpur" in the center, and the Texas Instruments logo on the right.

What is the key identity of C2000 real-time MCU? The device primarily has been one of the broadest real-time control platforms. Because, our software is compatible across low, mid, and high at various price points; that means, all the software that we create for low-cost devices, low-power, low-performance devices to high power devices, and high-performance devices are completely compatible.

So, that provides you with future-proof performance and we also deliver high-quality products. We also have a lot of innovation embedded inside our C2000 microcontroller. We are the industry's fastest real-time signal chain sense compute control processor. We also enable fast-switching GaN and SiC today. We also have been in this market for 25 years we have a lot of experience in digital control and we also have numerous reference designs hardware, and software to accelerate development.

So, far millions of units have been shifted in automotive and industrial applications already. We have thousands of customers worldwide; our devices are of high quality. And, we also have a multi-source FAB strategy to make sure that we have a safe supply and future expansion.

(Refer Slide Time: 03:35)

The slide is titled "C2000™ Real-Time Microcontrollers Overview". It features a central 2x2 grid with the following quadrants: "Sense" (top-left), "Process" (top-right), "Control" (bottom-left), and "Interface" (bottom-right). The central intersection of the grid is labeled "25 years expertise in real-time control systems" and "Functional Safety Compliant".

Highly accurate sensing:

- 12/16-bit ADCs, up to 24 channels
- Full analog comparators with built-in DACs
- Quadrature Encoder and Capture Logic

Highly flexible, High-resolution PWMs:

- Up to 32 outputs
- Tightly coupled with Sensing domain for fast response time
- Buffered Output DACs

Expertise and support:

Software libraries, reference designs, and functional safety-compliant devices.

Functional Safety:

All Safety integrity levels for Automotive and Industrial

High performance processing:

Floating-point DSP C28x™ core + parallel multi-core architecture + instructions set optimized for control math, up to 925 MIPS

Integrated communications:

CAN, CAN-FD, LIN, UART, SPI, I2C, PMBus, USB, 10/100 Ethernet MAC, EtherCAT™, XEMIF

Leading innovation:

Configurable Logic Block for peripheral customization, Fast Serial Interface for high-speed communication, ERAD for enhanced diagnostics and profiling

Functional Safety Support:

Built-in HW features for safety SW library and device drivers Safety certification documentation

Scalable, ultra-low latency real-time controller platform designed for efficiency in power electronics, such as high power density, high switching frequencies, GaN and SiC technologies

Specifications:

- 1.2-V core, 3.3-V I/O design
- Up to 2.5-MB Flash, 256-kB RAM (ECC protected)
- QFN, QFP, BGA packages
- 40 to 125°C temperature range
- Q100 automotive qualified options

Over 1 billion units shipped for industrial and automotive applications with compatible software

Logos for NPTEL and IIT Kharagpur are visible at the bottom.

So, to just give you a brief overview of our real-time controllers, what are the key things that the C2000 devices have? The C2000 devices have highly accurate sensing capability; which means, we have good 12 16-bit ADCs which can operate up to 24 channels, we also have a quadrature encoder and capture logic. On the processing side, we have high-performance processing with the capability to do floating point operations, parallel multi-core architecture, instructions optimized to do math operations, and trigonometric operations, capable of delivering up to 925 MIPS.

Our PWMs are highly flexible and they can support up to 32 outputs. We also have the PWM tightly coupled with the sensing domain for fast response time. In addition to all these sense process control capabilities, we also have good integrated communication available on the device, we support CAN, CAN-FD, LIN, UART, SPI I square C, EtherNet, and EtherCAT.

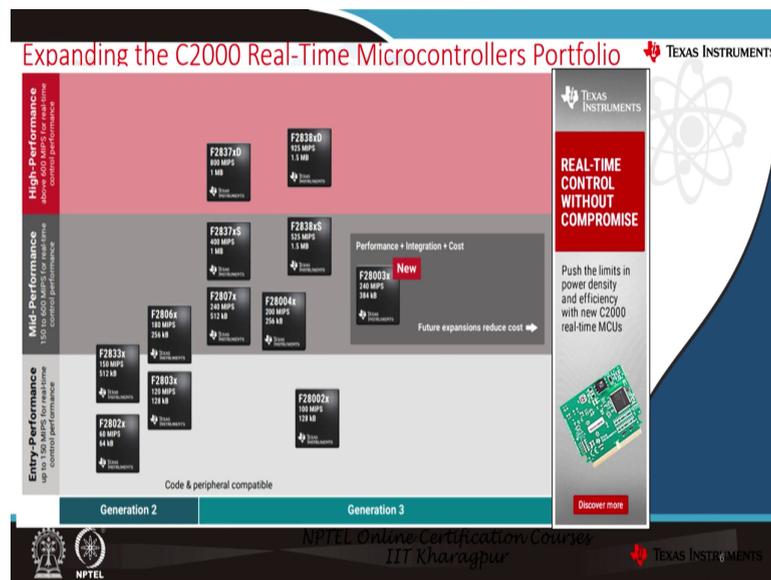
So, we provide all these integrated communications as well. So, these four pieces provide one of the best scalable ultra-low latency real-time controller platforms, that is highly efficient for high efficiency in power electronics and high switching frequency capabilities. A couple of other things that also are very unique to C2000 are that we have 25 years of experience in real-time control systems and we also support quite a lot of software that can help you to kick-start your development.

We have good software libraries and reference designs and also, and we make functionally safety-compliant devices that enable you to go and meet some of the automotive or industrial

safety needs. In addition to basic sense, process, control, and interface we also add a lot of innovation to our devices. For example, the configurable logic block for peripheral customization can replace many of the FPGA needs, when you need to customize your design.

We also have a fast serial interface, which is again a Texas Instruments proprietary for high-speed communication and ERAD for enhanced diagnostics and profiling capability.

(Refer Slide Time: 05:45)



So, if you look at our C2000 real-time microcontroller portfolio, we are currently classifying our devices into two types; Generation 2 and Generation 3. And, then based on the performance we are classifying the devices as entry performance, mid-performance, and high performance. The devices like F2802x, F28003x, and F2806x, these devices are classified as entry performance, because they have MIPS in the range of 150.

We the devices between 150 to 600 MIPS we classify them as mid-performance. In this category, we have F2837xS, we have F2838xS, then we have F28004x. And we also have the newly introduced F28003x. So, these devices give you performance in a range of 150 to 600 MIPS. Beyond 600 MIPS we have two devices, F2837xD and F2838xD which give you a performance of 800 MIPS and 925 MIPS which actually can be used for really high-end applications.

If you look at the memory sizes, the low-end variance has a smaller footprint of about 128 KB of flash whereas, the mid-range has flashes of up to 1.5 MB and the high-performance ones have flash memories of 1 MB and 1.5 MB. So, as you can see that the C2000 real-time microcontroller portfolio is very vast, ranging from very low-cost, low-MIPS parts to very highly advanced and highly MIPS-consuming parts which can span across multiple-end applications that you want to build.

Another key interesting aspect I want to highlight is that the core and the peripherals are compatible across these devices. This means that if you make software for let us say F2802x and you want to scale it to F2838x. It is scalable because you can recompile your code with minimum change and you can get your software working. Similarly, you can scale your software from a high-end device to a low-end device including the capability to use the peripherals.

So, this compatibility gives customers a wide range of options to build applications using the C2000 microcontroller.

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C2000 Low-Mid End Options TEXAS INSTRUMENTS

Device	In production F28002x			In production F28004x			In production F28003x			
	CPU	C28x+FIDIV+NLPID			C28x+CLA+VCU			C28x+CLA+VCRC+FIDIV+NLPID		
MHz/MIPS	100/100			100/200			120/240			
Flash	128KB-ECC, 4WS			256KB-ECC, 4WS			384KB-ECC, 5WS			
SRAM	24KB			104KB			69KB-ECC			
Control IPs	PWM(14Ch)-HR(8), ECAP(3)-HR(1), EOEP(2), SDFM(8ch), CLB(2)			PWM(16Ch)-HR(16), ECAP(7)-HR(3), EOEP(2), SDFM(4ch), CLB(4)			PWM(16Ch)-HR(8), ECAP(3)-HR(1), EOEP(2), SDFM(8ch), CLB(4)			
Packages	80QFP	64QFP	48QFP	100QFP	64QFP	56QFN	100QFP	80QFP	64QFP	48QFP
GPIOs + Optional	39+4	26+4	14+4	35+5	21+5	20+5	51+4	39+4	26+4	14+4
Ana. Chs + AGPIO	16	16	14	21	14	12	23	18+2	16	14
ADC/DAC	ADC(2)			ADC(3), BUFDAC(2)			ADC(3), BUFDAC(2)			
CompSS	4			7			4			
PGA	-			7			-			
Communication IPs	DCAN(1), I2C(2), SPI(2), PMBUS(1), SCI(1), LIN(2), FSI(1)			DCAN(2), I2C(2), SPI(2), PMBUS(1), SCI(2), LIN(2), FSI(1)			DCAN(1), I2C(2), SPI(2), PMBUS(1), SCI(2), LIN(2), FSI(1), CAN-FD(1)			
Safety	HWBIST, SRAM-ECC, ROM-Parity, BGCRC			ASIL-B			ASIL-B, SIL-2 HWBIST, SRAM-ECC, ROM-Parity, BGCRC			
Security	DCSM			DCSM			DCSM, AES Secure Boot, JTAG Lock, Live Firmware Upgrade			
Features				Live Firmware Upgrade			Live Firmware Upgrade, EPG, H			

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Now, if you look at in detail the differences between these devices, this table will give you a good snapshot of how the devices vary. For example, if you start with F28002x it is a 100 MIPS part whereas, F28004x can do 200 MIPS because it has got a C28x and a CLA. A CLA is nothing but, another co-processor that gives you the same performance as C28x. If you go to F28003x it gives you a performance of up to 240 MIPS.

Because it can run at 120 megahertz and there are two processors; the C28x and CLA. Now, if you look at the control IPs you can see that there are 14 channels of PWM in F28002x, but it goes up to 16 channels in F28004x and F28003x. So, as you see these devices have small changes in their capability and they can span across multiple applications.

If you look at the ADCs, right, we have 2 ADCs in F28002x; whereas we have 3 ADCs in F28004x and F28003x. Some of the communication IPs also will vary across these devices with smaller changes between them to make sure that these are all fine-tuned for the specific end applications.

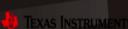
(Refer Slide Time: 09:15)

C2000 Mid-High End Options



Device	In production		
	F28003x	F2837x	F2838x
MIPS	240	800	925
CLA/TMU/FPU64	1/1/0	2/2/0	2/2/2
Flash/RAM	384KB/69KB	1MB/208KB	1.5MB/324KB
PWM/HR, ECAP/HR	16ch/8ch, 4/1	24ch/16ch, 7/2	32ch/16ch,
ADC/COMP/DAC	3/4/2	4/8/3	4/8/3
# ADC channel possible (Including AGPIO)	48 QFP:14 64 QFP: 16 80 QFP: 18 100 QFP: 23	100 QFP:14 176 QFP:20 337 BGA:24	176 QFP: 20 337 BGA: 24
EQEP/SDFM/CLB	2/ 8 ch / 4 tiles	3/ 8ch / 4 tiles	3/ 16ch / 8 tiles
FSI/CANFD/EtherCAT	Tx-Rx/ 1 / 1	0-0 / 0 / 0	2Tx-8Rx/ 1 /1
Special feature launch	LFU	16h ADC	CM & Ethernet
Safety	ASIL-B	ASIL-B	SIL-2/ASIL-B
Security	DCSM, Secure boot, ITAG lock, AES	DCSM	DCSM, Secure boot, ITAG lock, AES
Number of GPIO possible per package (Including AGPIO)	14/ 26/ 39/ 51	97/ 169	97/ 177
Packages	48QFP, 64QFP, 80QFP, 100QFP	100QFP, 176QFP, 337BGA	176QFP, 337BGA


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Now, if you look at the mid and high-end options, we have three devices in the mid to high-end options starting with the F28003x which is a 240 MIPS part, the F2837x is 800 MIPS part and F2838x is about 920 MIPS part. Now, if you look at what kind of architecture is there inside if you see the device F28003x, it has got 1 CLA; whereas F2837x has got 2 CLA; whereas F2838x also has 2 CLAs. The 3 7x and 3 8x have 2 CPUs of C28x and 2 CPUs of CLA which automatically gives you 800 MIPS.

Whereas, F2838x has in addition a communications manager that gives you another 125 Megahertz. So, overall F2838x gives you 905 MIPS, F2837x gives 800 MIPS and F283x gives you 240 MIPS. Again, if you look at the PWMs there are 16 channel PWMs in F28003x going up to 24 channels in F2837x going all the way up to 32 in the case of F2838x.

Similarly, ADCs as you can see as the performance of the device scales up, the number of ADCs on the chips also scales up.

So, this wide variety of capabilities and processing power helps you to build applications of varying requirements across all these devices.

(Refer Slide Time: 10:40)

C2000™ F28004x In production <http://www.ti.com/product/TMS320F280049C> **TEXAS INSTRUMENTS**

Differentiation

Optimized for power control applications

Streamlined performance and power

- 100MHz / 256 kb flash / 100 kb SRAM
- 200 MIPS DSP processing power
- Floating point and trigonometric math unit
- Next generation CLA; support for continuous background task
- 60% lower power consumption vs. F2806x + DC-DC option

Advanced actuation and design flexibility

- 4th gen ePWM enables implementation of the most advanced switching techniques for increased efficiency and power density
- Enhanced crossbars provide flexibility in combining inputs, outputs and internal resources for most advanced control and protection mechanisms

Integrated analog and protection

- 3 12-bit 3.45MSPS ADC with post processing and threshold actions
- 7 on-chip PGA(3/6/12/24) with post gain filtering and bypass option
- 7 Windowed Comparators + 2 12-bit output DACs
- 4 Sigma Delta Decimation Filters (with separate Data and Comparator filters)

Tools

F28004x experimenter's kit
Part number: TMS320CND280049C
<http://www.ti.com/tool/TMS320CND280049C>

F28004x LaunchPad
Part number: LAUNCHXL-F280049C
<http://www.ti.com/tool/launchxl-f280049c>

Software

C2000Ware™ software package

Application SDKs

Packages

Package	Footprint Dimensions
68-pin LQFP	21 x 7 mm
68-pin LQFP	12 x 12 mm
100-pin LQFP	18 x 18 mm

F28004x Specifications

Category	Item	Value
Sensing	ADC0: 11-bit, 3.45 MSPS, 6th	
	ADC1: 11-bit, 3.45 MSPS, 6th	
	ADC2: 11-bit, 3.45 MSPS, 6th	
	7x Windowed Comparator w/ Integrated 12-bit DAC	
Processing	C28x™ DSP core	100 MHz
	CLA core	100 MHz
Memory	256 kb Flash (total bank) + ECC	
	100 kb SRAM + ECC parity	
System Modules	3x 12-bit eQEPs Tracer	
	1M Watchdog Timer	
Configurable Logic Block	4 Traps	
	102 Internal PE	
Connectivity	2x UART, 1x LIN/UART	
	1x I2C, 1x PMBus	
Power & Clocking	2x 10 MHz 0-pin OSC	
	1.2V VREG	
Debug	2x 128-bit Security Engine	
	Embedded Real-Time Analyzer (eRTA)	

Now, let us look at the detailed block diagram of each of these devices. For example, let us start with F28004x. This device is optimized for power control applications. It has a 100 megahertz clock running at 100 megahertz, and it has got 200 MIPS DSP processing power because it has got 1 C28x core and 1 CLA core. It has got the floating point and trigonometric math unit which again accelerates your processing requirements.

We also have advanced actuation and design flexibility with the 4th generation PWM that generates one of the most advanced switching techniques for increased efficiency and power density. Similarly, if you look at our capability of us support, we support the devices in three different packages. We also have good software support for this device in terms of the C2000 software and application SDKs. We also provide the launch pattern experimental kit, to work on this device to build your end application.

(Refer Slide Time: 11:40)

The image is a screenshot of the Texas Instruments website for the C2000 F28003x microcontroller. The page is titled "C2000™ F28003x In production. Other variants to follow" with a link to <http://www.ti.com/product/TMS320F280039C>. The main content is divided into several sections:

- Differentiation:** Building on F28002x for High-Performance Power Control Applications. It lists features like improved performance (120 MHz with CLA option, 240 MIPS DSP, more flash and RAM, better ADC), advanced actuation and design flexibility (premium Type 4 ePWM), premium analog (8 Sigma Delta Decimation Filters, 2* buffered DAC), rich digital options (CAN-FD, CLB tiles), safety (ASIL-B/SIL-2), security (AES, JTAG Lock), and perfect portfolio (pin compatibility).
- Tools:** Includes an Experimenter's Kit (Part Number: TMS320C280039C), a LaunchPad (Part Number: LAUNCHXL-F280039C), and Application SDKs.
- Software:** C2000Ware™ Software Package and Application SDKs.
- Packages:** A table showing four package options: 48-pin QFP, 64-pin QFP, 80-pin QFP, and 100-pin LQFP, with their respective footprints and temperatures.
- Specifications:** A detailed table for the F28003x/F28003x-Q1, categorized into Sensing, Processing (C28x™ DSP core, CLA core), Memory, Configurable Logic Block, System Modules, Temperatures, Actuation, Connectivity, Power & Clocking, and Debug.

The bottom of the slide features the NPTEL logo and the text "NPTEL Online Certification Courses IIT Kharagpur" along with the Texas Instruments logo.

The next device I want to highlight is F28003x. This is another interesting part because it has got high performance for power control applications. This is again a 240 MIPS part. It is got 1 C28x at 120 megahertz. And, a CLA core at 120 megahertz. This can do a lot more arithmetic operations because this has got fast integer division, has got a floating-point unit, it has got a trigonometric math unit, and it also can support a non-linear PID through additional instructions that we have added to the trigonometric math unit.

It also has rich digital options. For example, it can support CAN-FD, and also it has got what is known as the CLB 2-CLB tiles which helps you to build some custom logic for your application. This device also comes in multiple packages as you can see we support four different packages, with good support for software through our SDKs and C2000 wear.

(Refer Slide Time: 12:42)

The slide features a central graphic of a tree where the branches are composed of various technology-related icons such as gears, a smartphone, a laptop, and a network symbol. The text 'HIGH-PERFORMANCE' is prominently displayed in the center. In the bottom right corner, there is a video inset of a man in a yellow shirt. The slide is branded with the Texas Instruments logo in the top right and the NPTEL logo in the bottom left. The footer text reads 'NPTEL Online Certification Course IIT Kharagpur'.

(Refer Slide Time: 12:44)

This slide is a detailed product page for the C2000™ F2838xD microcontroller. It includes a URL at the top: <http://www.ti.com/product/TMS320F28388D>. The page is organized into several sections:

- Differentiation:**
 - High performance C2000 enhanced with rich connectivity:**
 - Real-time Connectivity:**
 - Arm® Cortex-M4: 125MHz / 512 KB FLASH / 96 KB RAM
 - Dedicated, fully programmable communications sub-system
 - EtherCAT Industrial fieldbus or 10/100 Ethernet MAC
 - CAN-FD, CAN, USB, 200 Mbps FSJ, multiple serial ports
 - Real-time control:**
 - 800 MIPS DSP performance with extended 64-bit FPU and faster divide
 - Most flexible and advanced timers and PWMs
 - System flexibility:**
 - Premium A/D converters, comparators, and Sigma Delta filters
 - CLB for FPGA-like customization and absolute encoder support
 - Safety and Security:**
 - Extension of TUV-certified ASIL-B F2837xD
 - Security: AES-128 Accelerator, ITAG lock
 - Tools:**
 - F2838x Experimenters' Kit (Part Number: TMS320C28388D)
 - Software:**
 - C2000Ware™ Software Package
 - Application SDKs
 - Packages:**
 - Package: 176-pin QFP, 28 x 28 mm
 - Package: 337-pin MFBGA, 18 x 18 mm
 - Technical Specifications (F2838xD):**
 - Connectivity:**
 - Connectivity Manager (CM) Access: C28x Access
 - 10/100 Ethernet: 10/ 2x 1x, 8x 1x
 - CAN-FD: 2x 1MBit/s
 - UART: 4x UART
 - SSI: 4x SPI
 - DC: 1x I2C, 1x 1MHz
 - EtherCAT: USB MAC & PHY, 2x CAN 2.0B
 - System Modules:**
 - 2x 32-MHz CPU (1 core per C28x CPU)
 - 192 Interrupts per C28x CPU
 - Watchdog Timer
 - Memory Check Detection
 - Power & Clocking:**
 - 2x 10-MHz OSC
 - Ext. OSC Input
 - Processing:**
 - C28x™ DSP core: 200 MHz
 - CLA core: 200 MHz
 - PPU: 200 MHz
 - 6-ch DMA
 - Memory:**
 - 512-KB Flash-EECC
 - 64-KB SRAM-EECC
 - 128-KB RAM shared equally
 - 28-KB RAM shared by IPC
 - ICM
 - 2x Security Zones
 - 2x EMIF
 - Temperatures:**
 - 15°C
 - 15°C-0100
 - Actuation:**
 - 16x ePWM Modules (Type II)
 - 32x Outputs (16x High-Park)
 - Fail-Trip Zones: 3x 12-bit DAC
 - Sensing:**
 - 4x Analog-to-Digital Converters: 16-bit Mode, 1.1-MSPS
 - 12 differential or 24 single-ended channels
 - 17-bit ADCs: 3.5-MSPS
 - 24 single-ended channels
 - 6x Windowed Comparators w/ Integrated 12-bit DAC
 - 8x Digital Output Channels (2.8-MHz per bit)
 - Temperature Sensor
 - 3x eCEP
 - 1x eCAP (2x HRCMS)
 - Debug:**
 - Real-time JTAG
 - Real-time Analysis (Diagnose and Fix)
 - Configurable Logic Block:** 6 Files
 - Functional Safety Compliant Product:**
 - Target Systematic Capability: ASIL-D/SIL-3
 - Target Diagnostic Coverage: ASIL-B/SIL-2

Now, let us move on to high-performance devices. The first high-performance device that I want to cover is F2838xd. This device is a very high-performance device with rich connectivity. Compared to the previous devices, you can see that this device has a communications manager which can help you with real-time connectivity. Primarily, what is the connectivity it can support EtherCAT, and EtherNet?

And it can also have support for CAN-FD can USB and so on. This 125 megahertz communication manager gives you the additional 125 MIPS on top of 2 C28x codes which

are running each at 200 megahertz and 2 CLA which are running at 200 megahertz. So, overall, this device gives you 925 MIPS of performance with a good connectivity capability like EtherCAT, and EtherNet as well, and also this device also has functional safety compliance.

So, it can meet ASIL-D and SIL-3 capabilities. This is one of the leading and high-performance devices that we have and this can scale into many many end applications that need significant MIPS for processing.

(Refer Slide Time: 13:53)

C2000™ F2837xD

In production: <http://www.ti.com/product/TMS320F28379D> TEXAS INSTRUMENTS

Differentiation

- Real-time performance of dual C28x core with dual CLA co-processors to run parallel control loops
- 800 MIPS DSP Processing Power
- 4 differential 16-bit ADC, 1MSPS each
- 3x 12-bit DAC (external outputs)
- Trigonometric Math Unit (TMU) - 1 to 3 cycle-SIN, COS, ARCTAN
- Direct memory access through dual EMIFs (16bit/32bit)
- 8x Windowed Comparators w/ 12b DAC
- 8 Sigma Delta Decimation Filters (with separate Data and Comparator filters)

Tools

- TMS320F2837xD LaunchPad
Part Number: LAUNCHXL-F28379D
- TMS320F2837xD Experimental Kit
Part Number: TMS500CK28379D or TMS500CKD28379D

Software

- C2000Ware™ Software Package
- Application SDKs

Packages

Package	Footprint Dimensions
100-pin HTQFP	16 x 16 mm
176-pin MLQFP	28 x 28 mm
337-pin MFBGA	16 x 16 mm

F2837xD

Temperatures	105C	125C	150C
Connectivity	4x EMIF	2x I2C (w/ Host PMBus)	3x SPI
Processing	2x C28x™ DSP core 200 MHz	2x C28x™ DSP core 200 MHz	2x CLA core 200 MHz
System Modules	3x 32-bit CPU Timers	NMI Watchdog Timer	2x 102 Internal FPE
Power & Clocking	2x 10-MHz CMDC	4-20 MHz Ext. CMDC Input	
Memory	Up to 512 KB Flash	36 KB SRAM	36 KB SRAM
Debug	128 KB SRAM Shared memory	IC2B	2x 128-bit Security Zones
Functional Safety Compliant Product			
Systematic Capability	ASIL-D/SIL-3		
Diagnostic Coverage (DC)	ASIL-B/SIL-2		

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The device F2837x is very similar to F2838x only difference is that the communication manager and the connectivity pieces are not there in this device. So, this device gives you 800 MIPS of performance. So, this is achieved through 2 C28x DSP each running at 200 megahertz, and 2 CLA cores each running at 200 megahertz, giving you 800 MIPS of performance.

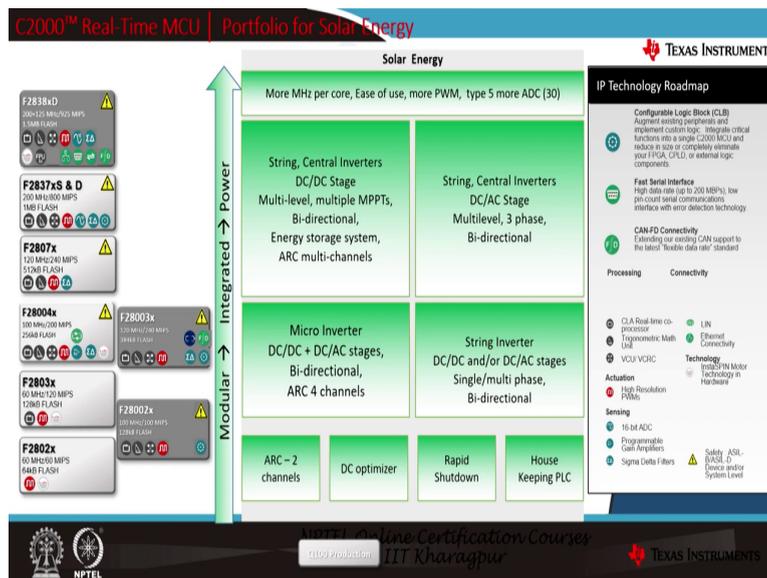
It has 4 differential 16-bit ADCs, 1 mega sample per second each, and then we also have 3x 12-bit DAC. It also has a trigonometric math unit, which also can accelerate trigonometric math operations. Again, this is also can meet function safety compliance of ASIL-D and SIL-3 and available in multiple packages, with good support in C2000 support software and application SDKs.

Now, if you just try to categorize these devices by flash size and performance. This is the kind of picture we will get. So, all the devices which I talked about which are of low MIPS, actually have fewer flash sizes up to 256 KB. The devices that we talked about in the range of 150 to 600 MIPS have flash up to almost up to about 1 MB and then devices beyond 600 MIPS have flash capability of 1 MB and 1.5 MB.

So, if you look at all our devices we can see that there are devices with a low-memory footprint, high-memory footprint, low MIPS, and high MIPS different capabilities of our peripherals. What this makes sure of is that, if you are trying to build an application ranging from something in solar to EV to any other application, you have a wide range portfolio of devices to pick up and as I had mentioned before, all these devices are software compatible.

That means you can build your software and scale and migrate seamlessly across all these devices.

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Now, let us look at the portfolio for solar energy. This is an example of showcasing which devices go into which kind of applications. So, if you look at our low-performance devices like F2802x-3x they can be used for ARC detection, DC optimization, rapid shutdown, and so on. For a microinverter or a string inverter kind of application, you have devices like F28003x or F28004x that need to meet the needs of these processing capabilities.

Suppose, you want to actually implement string or central inverters with multi-level, multiple MPPTs, bi-directional energy storage systems and also if you want to do multi-channel ARC detection, you have devices like F2838x and F2837x which has the power and the peripheral capability to meet this kind of end application. So, if you see that we have devices capable of covering the entire spectrum of applications needed for solar energy.

(Refer Slide Time: 17:27)

C2000 Proposal in Solar Energy TEXAS INSTRUMENTS

	Large Central & String Inverter	3p String Inverter (hybrid optional)	1p String Inverter (hybrid optional)	Micro Inverter	DC Optimizer	Arc Protection
Application	Large commercial & utility	Commercial rooftop	Residential	Residential	Residential	Residential/Commercial
Power Range	100kW – MWs	typ. <50KW	typ. <7KW	300W – 1.2kW	<1kW	/
Typ. DC-DC Topology	Interleaved multilevel boost	Interleaved multilevel boost Dual Active Bridge (hybrid)	Simple boost	Simple boost Flyback	Simple boost Flyback	/
# of MPPTs	typ. >= 10 MPPTs	typ. <= 6 MPPTs	typ. 1 - 2 MPPTs	typ. 1 - 4 MPPT	typ. 1 MPPTs	/
AC Output	3p	3p	1p	1p	/	/
Typ. DC-AC topology	3L NPC, ANPC & TNPC	3L NPC, ANPC & TNPC	2 L Half Bridge	2L Half Bridge	/	/
Decision Criteria	Lots of MPPTs and more complex interleaved power topologies require many PWMs, ADC chs and MIPS		Cost sensitive # of required PWMs, ADCs and MIPS can be supported by 1 C2000		Cost sensitive Only DC/DC stage	Standalone or integrated
C2000 Proposal	2x F2837x	1 ~ 2 C2000 chips F28075/F2837x (+ F280049/F280039) Roadmap device	F28075 F280039, F280049	F280039 F280049	F280025, Roadmap	F280039, F280025, Roadmap

NPTEL Online Certification Courses
IIT Kharagpur TEXAS INSTRUMENTS

So, this is an example of the C2000 proposal in solar energy. Suppose, you are building a large central and string inverter for a large commercial and utility kind of area. So, your power range will be 100 kilowatt to a few milliwatts, megawatts, sorry. So, in this case, you will have interleaved multi-level boost kind of topology. So, in this case, we recommend 2x of F2837x; that means, you need the 2 times F2837x device to support this kind of application.

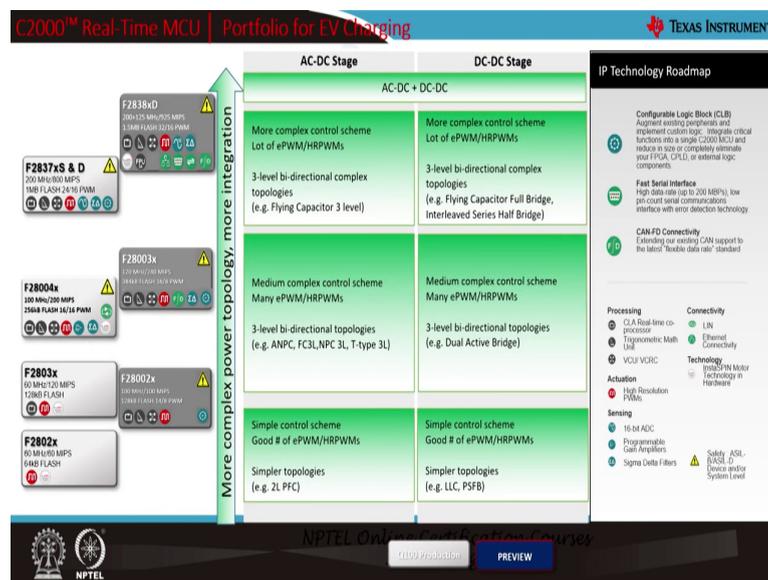
Suppose you are looking for a 3-phase string inverter which is for a commercial rooftop, typically less than 50 kilowatts in this case we recommend one or two devices like we recommend F2837x plus a combination of F28004x.

Suppose, you are interested in a single-phase string inverter for residential then the topology is very simple. So, you need a simple boost topology and in this case devices like F280039 or F280049 will be very useful. For a micro-inverter kind of application where it is for residential applications, then the requirements are still again low MIPS.

So, we can go with F280039 or F280049. For a DC optimizer again, devices like F280025 should be sufficient for the performance needs. Similarly, for ARC protection, we can use F280039 or F280025. If you see that, there are multiple devices that TI has designed to meet multiple-end applications, and the beauty of these devices is that as I said before, you can scale across in terms of performance and peripheral capability.

And you can build multiple of these applications, either using one device which is powerful or you can use multiple low-cost devices to meet some of these application needs.

(Refer Slide Time: 19:18)



Now, if you look at the portfolio for EV charging, again we have multiple ranges of devices. Again here, the ones that need simple control schemes which need low MIPS power like F2802x, and F2803x can be used for simple control schemes because they have a sufficient number of PWM and HPWM. If you need a medium or complex control scheme, where you need many ePWM and HRPWMs like three-level bi-directional topologies you have devices like F28003x and F28004x which can meet these end application needs.

Suppose you want to go for more complex control schemes, like three-level bi-directional complex topologies, then you can choose F2837x or F283xD devices. The peripheral mix of all these devices is also created in such a way that, they can fit into all of these end applications in a very cost-optimized manner.

(Refer Slide Time: 20:16)

Why C2000?

- Accurate current and voltage sensing with fast and precise ADCs
 - Separate 3.45MSPS ADCs, each supporting INL of 52 LSBs & 11bits of ENOB
 - Support for simultaneous sampling of two to four inputs
 - ADC Post Processing Block (PPB) helps remove DC-offsets from sensed voltage and current signals in hardware → significant cycle savings
- Built-in analog comparators against a 12bit DAC with 50ns pin-to-pin response time → enable real-time system protection against over-current & over-voltage events
- Trip any or all PWMs asynchronously to the system clock and independently from processing bandwidth
- Tight integration to ePWM module enabling peak-current mode control with blanking & ramp compensation
- Analog integration → reduce cost and decrease board area

Optimized C28x core, CLA and TMU enable fast execution of the control loop enabling greater voltage/current loop bandwidth

- FPUI unit built in → no more coding concern of scaling, overflow/underflow
- CLA, as a processing unit, enables execution of parallel tasks & higher control loop frequencies
- C2000 MCU with TMU can execute trigonometric & division operations, such as a "sine" instruction in 4 pipelined cycles. This compares with up to 41 cycles on an MCU without TMU → 10x performance improvement
- Enables higher PFC performance (THD & Po Factor)
- PLLs or software algorithms that use to benefit greatly from the TMU
- Fast interrupt response time with de-latency

- C2000 PWMs provide added flexibility to help implement the most advanced high-frequency switching techniques for increased efficiency and power density
- Software programmable HRPWMs with 150ps step size help control power FETs more precisely to avoid limit cycling (duty, phase, period)
- With up to 4 different compare events, ADC start of conversion point is very flexible & wide varieties of PWM schemes can be generated
- Advanced ePWM peripheral capabilities → control of multi-phase/complex topologies & ability to support light load improvement techniques, such as valley switching, without overburdening the processor

Now we have seen a wide range of C2000 devices and their capabilities. Now, the question arises, why do you need to choose C2000? So, there are three or four key aspects in terms of why C2000 is so powerful for a control application. The first and key part is that we have accurate current and voltage sensing with very fast and precise ADCs. As I mentioned before, we can do up to 3.4 mega samples per second ADCs.

We have the support of up to 3 to 4 ADCs in each of our devices. We also can do ADC post-processing; that means, we can do some processing post-taking ADC value which actually would help you in saving several cycles. Second is our device and the core, the C28x core is highly optimized for control applications. I talked about the control law accelerator and the TMU they help you to implement control algorithms in a much quicker manner.

So, your overall latency is much lesser; that means, once you sense and do the processing you can quickly get the result that you want to compute. We also can support a floating point unit, which has which can take care of your coding concern, off-scaling, overflow, and so on. The CLA is again an independent unit that runs in parallel with C28x which is highly optimized for control loop computation.

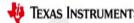
So, overall, these kinds of capabilities enable you with higher performance that you can need to compute for high-performance ph PFC and so on. Now, if you look at our PWMs, the PWMs have provided additional flexibility, because they can actually manage high-frequency

switching frequencies, are software programmable, and also they can manage to work up to four different compare events.

So, all these capabilities of PWM provide good switching capability and faster response to whatever we need to control on the output side. In addition to some of these things, we also have built-in analog comparators which help you faster response time. So, this capability can enable you with even 15 nanosecond pin-to-pin response time.

We also can trip any or all PWMs asynchronously to the system clock. We also have very capability to tightly integrate the PWM with ADCs. So, overall, whatever you are sensing, processing, and controlling the overall latency is very much reduced in using C2000. So, if you look at each of these peripherals they have been carefully designed and differentiated so that we can provide a faster response as well as lower latency time.

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C2000 – Processing Capabilities - Control Optimized 

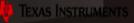
C2000 is enhanced for best possible performance in digital power control

Advantage of our C28x CPU systems :

- Added specialized instructions (usable by the compiler) -> significant overall performance advantage (with lowest latency) e.g. TMU operations, single cycle tasks, deterministic operation
- Normally ARM CPU system takes at least 2x to 3x the MHz to match the execute time of a C28 system
- Optimization in C28x CPU gives the best real-time control cycle efficiency and reduces the computation delay in a digital control loop

Enable designing high efficiency high power density power conversion systems

["Essential Guide for Developing with C2000™ Real-Time Microcontrollers"](#), Enhancing the Computational Performance of the C2000™ Microcontroller Family along with a white-paper explaining how C2000 and TI-GaN are partnering together can provide a glimpse of how C2000 can be optimized and bundled with complementary circuitry to achieve power-efficiency and density goals.

 NPTEL Online Certification Courses IIT Kharagpur 

Now, let us look at the processing capabilities, what are the uniqueness that we have inside the device, right? So, in terms of first the C28x core. The C28x core has specialized instructions, that are used by the compiler to save cycles. For example, trigonometric math operations or you want to do multiplication, division all that is highly optimized using our core.

Normally the ARM CPU will take at least 2 to 3x the megahertz to match the execution time of a C28 system. So, the core itself the C28 CPU has good efficiency for the control cycle.

On top of this core, we have added additional differentiations that I will show next which is how it improves our processing capability.

(Refer Slide Time: 23:45)

C2000 – Processing Capabilities - Control Optimized

The C2000 family of microcontrollers (MCUs) from Texas Instruments addresses these challenges with an array of integrated on-chip hardware math enhancements that dramatically increase the performance of the MCU in many real-time applications. The five key enhancements are:

- Floating-Point Unit (FPU)
- Control Law Accelerator (CLA)
- Trigonometric Math Unit (TMU)
- Fast Integer Division Unit (FINTDIV)
- Viterbi, Complex Math, and CRC Unit (VCU)

Figure 1-1. System Block Diagram with Math Enhancements

At the center of each C2000 MCU lies a fast fixed-point central processing unit (CPU) that on its own provides excellent 32-bit processing capabilities. The FPU provides seamless integration of floating-point hardware into the CPU. To augment this further, the CLA provides an independent floating-point CPU operating at the full speed of the device and it is designed to perform control law computations with minimal latency. This effectively doubles the raw computing capabilities of the device. The TMU provides hardware support for common trigonometric math functions, while the FINTDIV enables fast integer division operations. The VCU adds hardware support for communications, complex math, and CRC calculations. This paper provides an overview of each of these math enhancements.

[Enhancing the Computational Performance of the C2000™ Microcontroller Family \(Rev. C\)](#)

So, if you look at some of the crossing elements that are there. So, on top of the C28 core we have a floating point unit, have control accelerator, a trigonometric math unit fast integer division, on and VCU which further enhances the instruction set so that the computations can be done much faster. So, these are called extended instruction set to the situ score, but they provide a dramatic improvement in processing capability.

(Refer Slide Time: 24:13)

C2000 – Processing Capabilities - Control Optimized

Enhancing Performance – FPU

- Addition of the FPU/ FPU32 to the C28x fixed-point CPU enables the C2000 MCUs to support hardware IEEE-754 single-precision floating-point format operations
- Devices with the C28x+FPU add an extended set of floating-point registers and instructions to the standard C28x architecture.
- Some C2000 MCUs are available with a FPU64 that provides hardware support for both IEEE-754 single-precision and double-precision floating-point operations.

Function	Type	FPU Cycles	FPU64 Cycles	Fixed Cycles	Improvements/Comments
Complex FFT	512 pt	24243	43935	63192	2.61x (FPU) / 1.44x (FPU64) vs Fixed-Point
	1024 pt	53219	98683	141037	2.65x (FPU) / 1.43x (FPU64) vs Fixed-Point
Real FFT	512 pt	13670	20219	34513	2.52x (FPU) / 1.71x (FPU64) vs Fixed-Point
	1024 pt	30352	45476	76262	2.51x (FPU) / 1.68x (FPU64) vs Fixed-Point
Square Root	Compiler intrinsic	22	22	64	2.91x (FPU/FPU64) vs Fixed-Point – both modes use 32-bit float-point arguments
Finite impulse response (FIR)	64 pts	119	280	111	0.93x (FPU) / 0.40x (FPU64) vs Fixed-Point – FIR algorithms using circular addressing mode

*example code in C2000ware(FFT, FIR, square root)

Now, let us look at the floating-point unit. The floating-point unit significantly improves our performance. For example, if you take a complex FFT, 1024 point complex FFT on our C28 core, we take about 141K cycles, whereas, on an FPU which is a single precision floating point takes only 53K. Whereas, FPU 64 is a double precision floating point unit that takes about 98K.

So, immediately you can see that by the addition of the FPU, we have improved the performance of FFT computation by 2.6x on FPU and 1.43x on FPU 64 which is double precision. So, by adding all the small floating-point units, we have improved the performance of the C28x core. The device that I talked about earlier the F2838x has the double-precision FPU which can further enhance your computational accuracy.

If you look at the real FFT again, you can see the almost 2.5x improvement we get with the addition of FPU and 1.68x improvement with FPU 64.

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C2000 – Processing Capabilities - Control Optimized Enhancing Performance - CLA

- Execute time-critical control loops **concurrently** with the main CPU and free it up to perform other required tasks.
- Independent access** to peripheral registers
- Designed for **math intensive computations**
- Minimal latency** -> where the time delay between sampling, processing, and outputting must fit within a tight time window in order to meet performance objectives.

Function	Implementation
Arc-Cosine	Exponential raised to a Ratio
Arc-Sine	Exponential (Base 10)
Arc-Tangent of a ratio	Inverse Square Root
Arc-Tangent of a Ratio per Unit	Natural Logarithm
Arc-Tangent	Logarithm(Base 10)
Cosine	Sine
Cosine Per-Unit	Sine Per-Unit
Divide	Square Root
Exponential	

Application	Number of Execution Cycles		Improvement
	CPU Min/Max	CLA Min/Max	
Motor AC Induction	888/952	639/694	1.39x (vs CPU)
Power CNTL 2p2z	48	39	1.23x (vs CPU)
Power CNTL 3p3z	68	52	1.31x (vs CPU)

* fully software programmable solution-> CLA Math lib -> C2000ware

Now, let us look at what is CLA. CLA is another co-processor that is in running concurrently with the main CPU, it can free up the performance of the C28x. The uniqueness of CLA is that it can access independently the peripheral registers. It can do math-intensive operations like cos, sin, division, exponential square root, and so on. And, it can also directly interface with PWM and ADC. What this drive is that the CLA can quickly take the data from ADC does the processing, and drive your PWM saving a lot of cycles and freeing up the bandwidth of C28x.

For example, a motor AC induction control which takes about 888 cycles in CPU is reduced to about 640 cycles in CLA. So, we can automatically see that there is a 1.4x improvement in performance. Similarly, a power-controlled 3 pole 3 0 like a CPU will take about 68 cycles, where whereas CLA takes about 52 cycles. So, whatever performance we get in C28x we can get a better performance with CLA and it can run in current with the C28x.

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The slide features a diagram of a System-on-Chip (SOCx) architecture. At the top, it lists the Texas Instruments logo and four bullet points describing the CLA's capabilities:

- CLA is able to read the ADC result register on the same cycle that the ADC sample conversion is completed
- Little to no delay in processing the data, typically caused by the context switching of the main C28x core
- The CLA has its own dedicated memory region for its code and shared memory for passing information between it and a C28x CPU in the system.
- CLA is constantly waiting in an idle state for an event, such as an ADC conversion, to process that data and actuate the system.

 The diagram shows the following components and their interactions:

- SOCx**: The overall system architecture.
- ADC**: An Analog-to-Digital Converter that sends **ADC interrupt signals** to the **PIE**.
- CPU**: The main C28x core, which sends **ePWM interrupt signals** to the **PIE**.
- ePWM modules**: Connected to the CPU and sending **ePWM interrupt signals** to the **PIE**.
- PIE**: Peripheral Interrupt Expander, which routes interrupt signals to the **CLA**.
- CLA**: Control Law Accelerator, which can be triggered by the CPU and can fire interrupts to the CPU.
- Text boxes**: One states "CLA can run control loops independent of PIE and CPU", and another states "CLA can be triggered by the CPU and can fire interrupts to the CPU".

 The slide also includes the NPTEL Online Certification Courses logo for IIT Kharagpur and the Texas Instruments logo at the bottom. A small video inset shows a presenter in a yellow shirt.

How does this operate? The operation is very simple. The CLA can run controlled loops independent of the CPU. It has access to the ADC; it can read the ADC result register in the same cycle as the ADC sample is completed. There is little or no delay in processing the data because there is no such contest switching, it has its program and data memory. So, it can pass information between it and the CPU.

So, CLA also can be triggered by the CPU and can fire interrupts to the CPU. So, if you see the CLA has access to all the important control peripherals, it can do processing and it can independently run the control loop. So, when we have a device with C28x and CLA that is how we get, double the MIPS even though the processor is running at let us say 100 megahertz spot if you have C28x and CLA we can go up to 200 MIPS of processing capability.

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C2000 – Processing Capabilities - Control Optimized Enhancing Performance - TMU

- **TMU:** Many common mathematical techniques in real-time control rely on the use of trigonometric functions: sine, cosine, and arc tangent are all examples
- 85% improvement is possible on a simple Park Transform.
- Cycles taken for trigonometric operations are listed below.

Operation	C Equivalent Operation	C2x Pipeline Cycles
Multiply by 2π	$a = b * 2\pi$	2 cycles + Sine/Cosine function
Divide by 2π	$a = b / 2\pi$	2 cycles + Sine/Cosine function
Divide	$a = b / c$	5 cycles
Square Root	$a = \text{sqrt}(b)$	5 cycles
Sin Per Unit	$a = \text{sin}(b/2\pi)$	4 cycles
Cos Per Unit	$a = \text{cos}(b/2\pi)$	4 cycles
Arc Tangent Per Unit	$a = \text{atan}(b/2\pi)$	4 cycles
Arc Tangent 2 and Quadrant Operation	Operation to assist in calculating ATANPU2	5 cycles

Park Transform Example:

85% Improvement

CPU Cycles

With TMU: [Short bar]

Without TMU: [Long bar]

```
Equation in Floating-Point C: PARK Transform
#include "math.h"
#define TWO_PI 6.28318530717959
void park_calc(PARK *v)
{
    float cos_ang, sin_ang;
    sin_ang = sin(TWO_PI * v->ang);
    cos_ang = cos(TWO_PI * v->ang);
    v->da = (v->da * cos_ang) + (v->qa * sin_ang);
    v->dq = (v->dq * cos_ang) - (v->da * sin_ang);
}
```

The next interesting addition that we have done recently is the trigonometric math unit. The trigonometric math unit has been added to add additional instructions which can help you to compute sin, cos, and tan in a much faster way. We take only about 4 to 5 cycles to do all these trigonometric operations, whereas, in our C28x traditional CPU, this would have taken 10x times.

For example, the path transform, with devices which has TMU, now can be done with 85 percent improvement. So, this saves significant cycles from the processing point of view. Again, the TMU's additional instructions are added on top of the C28x, and enabling TMUs is much easier. If you are calling a sin or a cos function and if the device has TMU automatically the compiler will pick up the instructions and make sure that your sin and cos are highly optimized.

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C2000 – Processing Capabilities - Control Optimized Enhancing Performance – Fast Integer Division

The FINTDIV extended instruction set optimally supports fast division operations commonly found in adaptive control systems for scaling parameters based on a variable. All instructions execute in a single cycle and three types of integer division are supported (Truncated, Modulus, Euclidean) of varying data type sizes (16/16, 32/16, 32/32, 64/32, 64/64) in unsigned or signed formats. Truncated format is the traditional division performed in C language (where “/” is the integer, and “%” is the remainder); however, the integer value is non-linear around zero. Modulus and Euclidean formats are more appropriate for precise control applications because the integer value is linear around the zero point, and this avoids potential calculation hysteresis. Both the Modulus and Euclidean divisions are supported by C intrinsics, and the C28x compiler supports all three division formats for all data types. Since the FINTDIV uses the existing FPU register set to carry out the FINTDIV operations, there are no special considerations relating to interrupt context save and restore.

Table 5-1. FINTDIV Performance Improvements

Operation	Number of Execution Cycles		Improvement (vs CPU)
	CPU (C operator)	FINTDIV (intrinsics)	
+16/16 Truncated	52	16	3.2x
+16/16 Euclidean and Modulus	58	14	4.1x
+16/32	56	14	4.0x
+32/32 Truncated	59	13	4.5x
+32/32 Euclidean and Modulus	63	14	4.5x
+32/64 Truncated	37	14	2.6x
+32/64 Modulus	41	14	2.9x
+64/32	37	12	3.1x
+32/16 Truncated	60	18	3.3x
+32/16 Euclidean and Modulus	64	16	4.0x
+64/16	58	13	4.5x
64/64 Truncated ⁽¹⁾	78 – 2031	42	1.9x – 62.5x
64/64 Euclidean & Modulus ⁽¹⁾	82 – 2035	42	2.0x – 62.7x
64/64 Truncated ⁽²⁾	54 – 2025	42	1.3x – 62.0x
64/64 Euclidean & Modulus ⁽²⁾	58 – 2029	42	1.4x – 62.1x
64/64 ⁽³⁾	53 – 2048	42	1.3x – 60.7x

⁽¹⁾ Example code in C2000ware

⁽²⁾ Example code in C2000ware

⁽³⁾ Example code in C2000ware



The next one that we have added is the fast integer division. The fast integer division gives you support for many different types of divisions, for types like truncated, modulus, Euclidean, and of varying data sizes. So, you can do a 16-bit by 16-bit; 16-bit by 32 bit; 32-bit by 32-bit, and so on.

And typically, we have seen that with the addition of this fast integer division, we can reduce our cycle conservation for division almost by 3x. For example, typically our division takes about 60 cycles at C28x which has come down to 14 to 15 cycles using fast integer division.

Again, as I mentioned before, enabling fast integer division is much easier, because you can use this through compiler intrinsic, and automatically the code gets replaced with fast integer division instructions. So, all these added capabilities are also supported through examples in our software called C2000 ware.

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So, these unique additions that we have done to the CPU make the CPU much faster and reduce the overall latency. And this is one of the key capabilities of the C2000 device. So, overall, I think the device portfolio in this topic we have covered the device portfolio and the key processing capabilities of C2000. For any questions or any support that you need in the future, you can visit the C2000 TI E2E support forum for any questions related to any of the topics that we have covered here.

Thank you.