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Application of Texas Instruments Controllers for Electric Drives Control

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Abstract. This study presents Texas Instruments (TI) hardware, technology, and software for electric drives control based on the company's microcontroller families. The main characteristics and distinctive features of the company's solutions are considered through reference design kits. The Laboratory of the Technical University - Sofia, Branch Plovdiv for specialized electric drive control systems in robotics, built with the solutions of TI, is presented.

1. Introduction

The so-called DSC (Digital Signal Controllers) of the C2000 family of Texas Instruments (TI) are very popular worldwide in the field of digital control of electric drives. Its popularity is due to the high performance of the devices, the wide range of peripheral modules, and the fast response to external events, as well as the optimal functionality/price ratio. The relatively new Cortex-M3/R4F/M4F core microcontrollers, introduced by the TMS570/RM48L and LM3S/LM4F families, allow the creation of systems with reduced power consumption and with a wide range of communication capabilities, with increased reliability and with the ability to calculate complex algorithms for drive control. Despite the fact that the ARM core microcontrollers traditionally pertain to general-purpose control devices and control devices with specialized drive control peripherals, one of the advantages of such solutions is the familiar ARM architecture.

With the advent of dual-core microcontrollers (C28xx + Cortex M3), the capabilities of the developers expanded even more, as the algorithms for exchange with the control system and with motion control/coordinates have been divided into different cores.

The ARM Cortex-M belongs to the ARM architecture family and the to the set of 32-bit RISC ARM processor cores. These cores are recommended for low-energy and cost-efficient microcontrollers, which are implemented in large number of consumer devices. The cores consist of the Cortex M0, Cortex M0+, Cortex M1, Cortex M3, Cortex M4, Cortex M7, Cortex M23, Cortex M33, Cortex M35P, Cortex M55. The Cortex-M4/M7/M33/M35P/M55 cores have an option for hardware FPU, and being built in the silicon they are classified as "Cortex-MxF", or "Cortex-Mx with FPU", where 'x' is the core number.

2. Main types of electric motors

Currently, six main types of electric motors can be classified:

- brushed direct current motors (traditional - BDCM);
- brushless direct current motors (BrushLess Direct Current - BLDCM), based on the three-phase synchronous AC motors;
- stepper (SM) - special BLDC motors with toothed rotor/stator (the stator teeth form the "steps" which attract the winding or the corresponding teeth of the rotor);
- switched reluctance motors (SRM);
- three-phase induction/asynchronous (ACIM) and synchronous (PMSM) for alternating current;
- single-phase AC (eg. with split poles).

For each of the listed types of electric motors there are different algorithms for controlling their angular speed. Most of them can be divided into frequency algorithms (when the angular speed of the motor is controlled by modulating the frequency of the supply voltage) and pulse width modulation algorithms PWM, (when the motor speed is controlled by the pulse width of a signal with a constant frequency of modulation). Frequency control algorithms are currently used decreasingly due to the complexity and low efficiency of the control device. In its place PWM control is applied, which, in addition to providing speed control, allows easy control of torque. Practically, PWM timers are part of all modern microcontrollers (MCUs). Presently, the new MCUs are equipped with specialized multiphase synchronous PWM with complementary outputs, specially designed for motion control.

TI Corporation offers four main families of microcontrollers equipped with matching peripheral modules: C2000 real-time microcontrollers, specialized Hercules, standard Stellaris with Cortex M3/M4F cores, and instrumental (for measurement) MSP430. The various design kits offered by TI allow studying in detail the control algorithms and the circuit features of the control systems of the main motor types.

3. Microcontroller units for electric drive control systems

TI manifactures four families of microcontrollers, which are used to control the electric drives. Their main features are shown in Table 1.

Table 1. Features of TI MCUs in electric drive control systems.

Family	Features
C2000	Maximum performance of electric motors; industrial and automotive Q100 standard certified; medium level of safety; wide range.
Hercules TMS570/RM48L	Maximum level of safety (ASIL-D, SIL-3 certified); Q100 certified (TMS570); ARM; maximum flash memory.
Stellaris LM3S/LM4F	Budget ARM microcontrollers; a large number of interfaces for data transfer; initial level of safety (in the equipment).
MSP430	Minimal price; deep embedding.

3.1. 32-bit real-time C2000 microcontrollers

The C2000 real-time microcontroller platform is an industry leader in the creation of digital motor control systems since the advent of the TMS320F24x generation in 1996. In 2002, the F281x series was introduced, based on the C28x DSP core, which became the first series with 32- bit architecture, specially designed for high-performance control systems using algorithms requiring intensive mathematical calculations. In order to meet the requirements of the application tasks in terms of performance, price, purpose of the pins and the presence of peripheral modules, a family of code-compatible chips is created on the basis of the C28x core (Fig. 1). MCU C2000 is used in many applications based on three-phase electric motors, including AC servo controls, precision motion control systems, compressors and hoods based on high-voltage AC motors, industrial pumps and household appliances, such as washing machines and compressors for refrigerators. The main feature of this family is the separation of the tasks of the C28 core related to the control object from the tasks of the M3 core related to the data exchange with the centralized control and monitoring systems. The new MCUs of the family (Fig. 2) introduce Parallel CPU Processing through a fast accelerated control loop - Control Law Accelerator (CLA) and a non-linear block for trigonometric operations (Trigonometric Non-Linear PID Math Unit (TMU)).

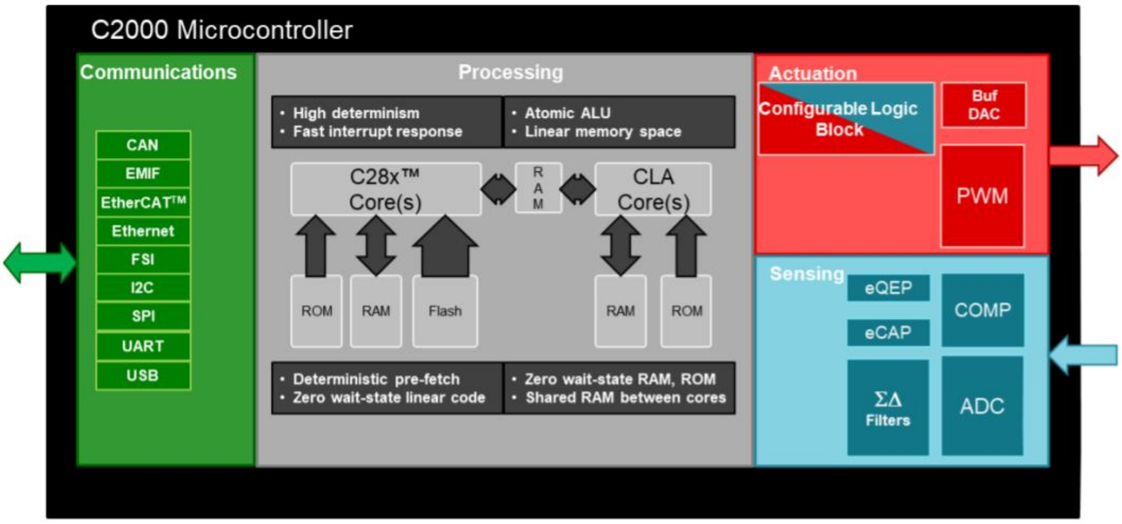

FIGURE 1. MCU C2000 architecture.

Currently, two families are popular - Piccolo and Delfino, which differ in price and calculation capabilities. Table 2 shows examples of reference kits based on MCUs of the C2000 family with an indication of the type of electric drive and control technology. This table also shows for which drive types there is a graphical user interface and file libraries in the controlSUITE software environment, which is described below.

Table 2. Application of Piccolo and Delfino microcontrollers in electric drive control systems.

Type of motor	Control technology	Hardware					
		Piccolo					Delfino
		Low voltage. Two axes+PFC	High voltage. One axis+PFC	Low voltage. small current	Low voltage. high current	Low voltage.	High voltage. One axis+PFC
		TMDS1MTRPFCKIT; TMDS2MTRPFCKIT	TMDSHVMTRPFCKIT	DRV8312-C2-KIT; DRV8332-C2-KIT	DRV8301-HC-C2-KIT; DRV8302-HC-C2-	DRV8412-C2-KIT; DRV8432-C2-KIT	TMDSHVMTRPFCKIT

					KIT		
BLDCM	Trapecoidal Sensored	controlSUITE	controlSUITE	controlSUITE	—	—	—
	Trapecoidal Sensorless				controlSUITE		
	Sinusoidal Sensored	SPRC922			—		
	Sinusoidal Sensorless	SPRC922 или controlSUITE					
PMSM SRM	FOC Sensored	controlSUITE	controlSUITE	controlSUITE	—	—	controlSUITE
	FOC Sensorless				controlSUITE		
	FOC PosSensored	—		—	—		—
ACIM	V/f Tacho/encoder	—	controlSUITE	—	—	—	—
	FOC Sensored						controlSUITE
	FOC Sensorless						controlSUITE
SM	Stepper	—	—	—	—	controlSUITE	—
BDCM	Servo						
FOC = Field Oriented Control							
PFC = Power Factor Correction							

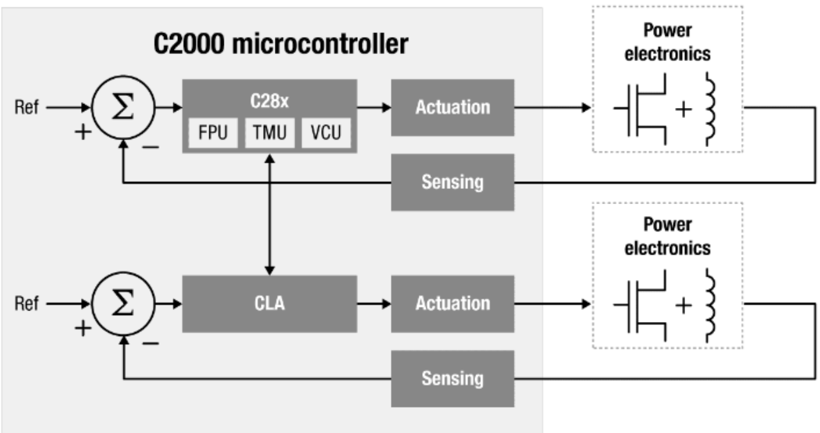

FIGURE 2. MCU C2000 with TMU and CLA

3.2. Stellaris, Hercules and MSP430 microcontrollers

Currently, Stellaris microcontrollers with a Cortex-M3/M4F core are standartly used in embedded applications. Their wide application is due to its 32-bit architecture, good price/performance ratio, determined response to interruptions, low energy consumption, presence of modes with reduced energy consumption. Cortex-M cores typically are implemented as specialized microcontroller chips, and built-in inside of SoC (System on a Chip) chips as I/O controllers, smart battery controllers, power management controllers, controllers of touch screens, system controllers, and sensor controllers. The popularity of TI's Cortex-M core microcontrollers in the Stellaris family is due to the large number of microcontrollers with different internal memory volumes (including built-in ROM with a library for peripheral modules) and various sets of peripheral modules, which allows to choose the most suitable microcontroller for a specific task. The growing popularity of the family is facilitated by the presence of a large number of powerful software tools for development and configuration, such as Keil, IAR, graphical user interfaces GUI (Fig. 3) and, of course, TI CodeComposerStudio, as well as a large number of modules for experimentation and evaluation and reference kits of finished products.

Hercules microcontrollers are of two classes – industrial (RM) and transport (TMS570) – and are high-performance Arm Cortex-R-based MCUs from 80 MHz up to 330 MHz with intelligent peripherals to offload the CPU. They are designed for use in railways, road transport, industry, battery, and alternative energy management. Hercules MCUs provide on-chip diagnostics coverage required by safety standards while leaving a smaller software footprint in a hardware optimized solution, which reduces safety system complexity.

The TI MSP series are microcontrollers with ultra-low-power consumption and consists of devices featuring different peripherals and targeted for various applications. The architecture, allows low-power modes, and typically is used to extend battery life in portable measurement applications. The device has a 16-bit registers, powerful 16-bit RISC CPU, and generators of constants that contribute to maximum code efficiency. The digitally controlled oscillator (DCO) allows the transitions between low-power modes and active mode in less than 5 µs. TI offers best-in class software development tools, GUIs and support for multiple IDEs for rapid development with MSP430 MCUs including TI-owned software libraries and IDEs as well as open source and third-party compilers and IDEs.

3.3. InstaSPIN technology for electric drive control

TI also created the latest electric drive control technology - InstaSPIN, using the appropriate software - Motor Ware and C2000Ware MotorControl SDK. Aimed at budget BLDC applications, it does not need sensors. InstaSPIN does not require mandatory knowledge of the operating parameters of the specific motor and it is necessary to specify only one parameter. The technology has developed in two directions - InstaSPIN-FOC™&FAST™ and InstaSPIN-MOTION™&SpinTAC™. The first direction is FOC speed control (Complete sensorless FOC solution provided by TI on-chip in ROM of selected devices - FAST observer, FOC, speed and current loops, effectively controlling the motor without the use of mechanical rotor sensors) using FAST – a uniform structure of magnetic Flux observer (F), flux Angle (A), motor shaft Speed (S) and Torque (T). The second direction is InstaSPIN-MOTION - a comprehensive sensorless or sensor FOC solution for controlling the current, speed, position and movement of the motor. This solution provides the robustness of the highest efficiency control system for motors operating in intensive dynamic modes of controlled coordinates. InstaSPIN-MOTION includes the integrated FAST monitoring software combined with the SpinTAC Motion Control Suite. The SpinTAC speed controller proactively estimates and compensates for system disturbances in real-time, improving overall product performance. The SpinTAC motion controller apples the idealy calculated reference signal (using forward compensator). SpinTAC supports the standard industry curves, and LineStream's proprietary "smooth trajectory" curve. The SpinTAC motion sequence planner allows the design of complex, user-defined motion sequences.

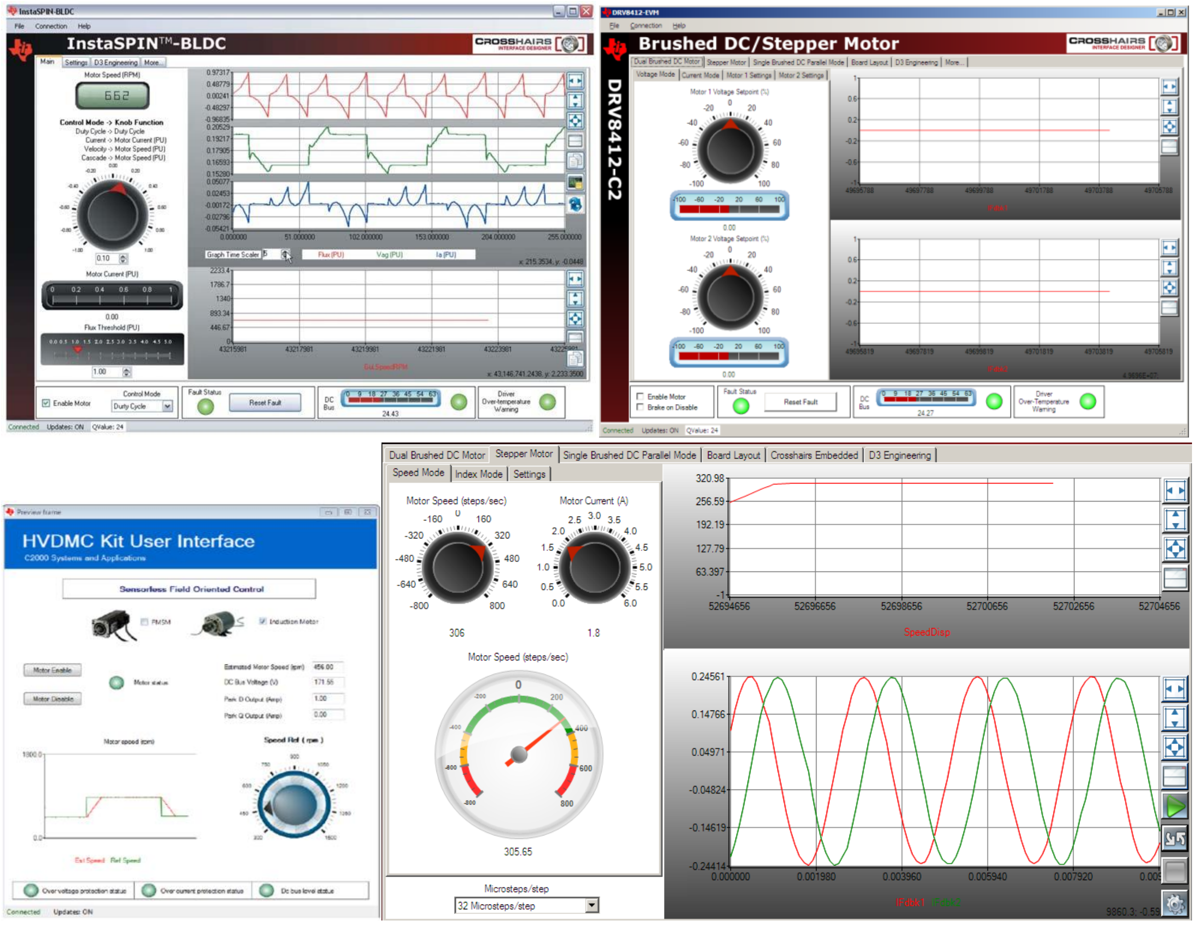

FIGURE 3. Graphical user interfaces (GUI) for electric drives control with BLDCM, PMSM, ACIM, BDCM and SM

The use of InstaSPIN technology allows better control of the electric drive. Unlike the current signal, the amplitude of the back EMF signal decreases at low speed, which leads to poor quality of the control system. InstaSPIN technology provides smoother control of low speed and ensure a more reliable safe start of the motor even at very high loads.

3.4 ControlSUITE and C2000Ware: the single portals for all C2000 software

The free controlSUITE software for working with the peripherals of real-time C2000 microcontrollers is a powerfull set of elements of software infrastructure and software that significantly reduces the time for software development. (fig.4). ControlSUITE includes all the necessary tools, starting with the driver libraries for various peripherals and auxiliary software modules and ending with full-fledged basic examples of complex system applications that can be used at all stages of software development and evaluation of its operation. The controlSUITE package contains a large amount of documentation, function libraries, usage examples and ready-made solutions for C2000 core microcontrollers, which can be kept up to date with constant online updates. All sample projects can be found with a single mouse click in the CodeComposerStudio IDE for compilation and loading on the target hardware platform. In recent years, a migration of controlSUITE to TI's C2000Ware portal has begun. C2000Ware for C2000 microcontrollers is a unifying software development and documentation designed to minimize the development time of electric drive management software. C2000Ware is the successor to controlSUITE as a centralized, interactive, software repository for all C2000 microcontrollers. C2000Ware requires:

- Code Composer Studio™ IDE (CCS) v9.2.0 or later;
- C2000 Compiler v18.12.1 LTS or later;
- ARM Compiler v 18.12.1 LTS or later.

The sections shown in Table 3 describe the resources in controlSUITE and provide details on where to find these resources in the C2000Ware package.

Table 3. Structure of controlSUITE and its migration to the C2000Ware portal.

	controlSUITE	**C2000Ware**	**C2000Ware+SDK**
Online & CCS Resurce Explorer (GUI)		✓	✓
Device Support • Bit Field Source & Headers • Bit Field Examples • Linker Command Files	✓	✓	✓
Device Driver Library Support • Peripheral APIs • Driver Examples		✓	✓
DSP, Math, Communications, Calibration & Flash Libraries	✓	✓	✓
Application Libraries	✓		✓
Application Development Kits • Documentation • Solutions • Examples	✓		✓
Design Documentation, Schematics & Files • LaunchPad • ControlCard • ControlSTICK • Experimenter Kit • Peripheral Explorer Kit	✓	✓	✓
Power SUITE	✓		✓
Boot ROM Source & Flash Programmers	✓	✓	✓

4. Reference design kits for electric drive control systems based on C2000

TI Corporation manufactures a number of kits for the design of electric drive control systems based on control modules in the ControlCard format with C2000 microcontrollers. Brief descriptions of basic kits (currently they are 76 for the C2000 family) are shown in Table 4.

Table 4. Reference design kits for electric drive control systems.

Name	Purpose	Features
DRV8312-C2-KIT	DRV8312-C2-KIT Demonstration control kit for three-phase BLDC motors.	Power board of three-phase inverter DRV8312 with Piccolo F28035 controlCARD, programmed to control the motor via GUI.
TMDS1MTRPFCKIT	Motor control kit and power factor correction (PFC).	Vector control of one motor with integrated ControlCard F28035.
TMDS2MTRPFCKIT	Control set for two coupled motors and power factor correction (PFC).	Vector control of two motors with integrated ControlCard F28035.
TMDSHVMTRPFCKIT	Development kit of electric drive control systems and power factor correction (PFC).	Digital control of motors up to 1.5 kW and power factor correction (PFC) up to 700 W using Piccolo.
DRV8412-C2-KIT	Control set for low-voltage brushed direct current (DC) motors and stepper motors.	Motherboard with power supply DRV8412 (two bridges 6Anom./12Amax. at 50V) with Piccolo F28035 controlCARD, programmed to control the motors via GUI; XDS100 emulation with galvanic isolation and serial communication port. Two brushed DC motors (38mm); one stepper motor (23Y); 24V power supply. Integrated development environment IDE CCStudio.

A laboratory for specialized electric drive control systems in robotics is being built at TU-Sofia, Branch Plovdiv, which is already equipped with a number of control sets for various electric motors in order to introduce the latest advances in their control technology and test new control approaches on real hardware platforms. The hardware of this laboratory is shown in Appendix 1.

5. Conclusion

Real-time C2000 microcontrollers continue to evolve. To accelerate development and release to market, TI Corporation continues to expand the range of reference and evaluation boards for them. DIMMs allow debugging solutions to be transferred to target platforms at minimal cost. The combination of ready-made M3 core data exchange algorithms and C28 core control algorithms, as well as the competently designed interprocessor interface allow us to state that they will find a worthy application for upgrading existing and designing new electric drive control systems. Texas Instruments Corporation offers competitive microcontrollers for embedded applications, as well as tools for developing and debugging them, which can significantly reduce the design time of control devices and make the development and debugging process more convenient.

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Appendix 1 - Reference design kits and control software in the Laboratory for specialized electric drive control systems in robotics at TU - Sofia, Branch Plovdiv.

№	**Name** **Purpose**	**Illustartions**
1	**Specialized AC drives II:** **TMDSHVMTRINSPIN** High Voltage Motor Control Kit with InstaSPIN-FOC and InstaSPIN-MOTION enabled Piccolo MCU ControlCards – TMS320F28069M, TMS320F28027F and TMDSCNCD28054MISO. TMDSHVMTRINSPIN is a DIMM100 control CARD based motherboard evaluation module. The High Voltage Motor Control Kit with InstaSPIN™ technology provides a great reference platform to learn and experiment with digital control of high voltage motors, utilizing the revolutionary InstaSPIN-FOC and InstaSPIN-MOTION motor control technologies included on Texas Instruments' C2000™ InstaSPIN 32-bit microcontroller family. [13]	
2	**Specialized AC drives:** **TMDSHVMTRPFCKIT** Digital control of motors up to 1.5 kW and power factor correction (PFC) up to 700 W using Piccolo. TMDSHVMTRPFCKIT is a DIMM100 controlCARD based motherboard evaluation module. The High Voltage Motor Control and PFC Developer's Kit provides a great reference platform to learn and experiment with digital control of high voltage motors with Texas Instruments' C2000™ 32-bit microcontroller family. This kit is a superb, all-around motor inverter design tool, showcasing control of the most common types of high voltage, three phase motors – including AC induction (ACI), brushless DC (BLDC), and permanent magnet synchronous motors (PMSM). Digital motor control methods are demonstrated, including trapezoidal, variable frequency (V/F), and field oriented control (FOC), using sensored or sensorless back-EMF techniques. Users learn design and digital control of a full inverter design from AC input – with Power Factor Correction (PFC) – all the way through the motor drive stages and motor control. [15]	

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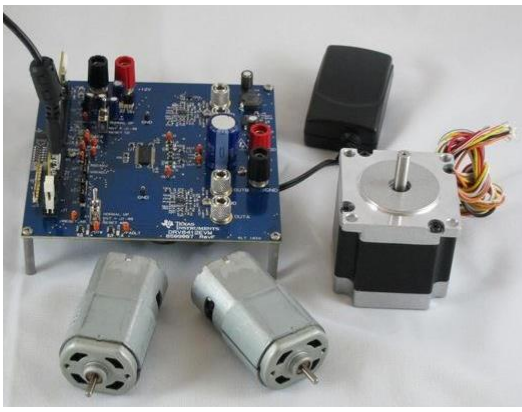
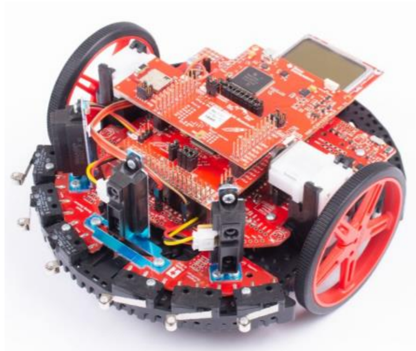
3	**Specialized electric drives for brushed DC motors and stepper motors:** **TIDM-THREEPHASE-BSDC**. This reference design demonstrates a motor control solution for spinning three-phase brushed DC or single stepper motor – featuring the C2000™ Piccolo™ microcontroller and the DRV8412 three-phase motor driver. This highly integrated, robust motor control and driver solution accelerates development time for brushed and stepper motors running up to 6 A continuous / 12 A peak at 50 V. Typical applications include medical pumps, gate openers, stage lighting, textile manufacturing tools, and industrial or consumer robotics. This reference design is based on the DRV8412 evaluation kit. [16],[22]	
4	**Specialized electric drives for autonomous robotic system:** **TIRSLK-EVM** TI-RSLK MAX is low cost robotics system learning kit for university students and engineers. The TI Robotics System Lab kit MAX (TI-RSLK MAX) accelerates the learning and building of robotics systems, leading students to explore real-world applications. The TI-RSLK MAX is the fast track to getting students up and running with their own solderless robotic kit, providing hardware and curriculum that help students learn how to design their own electronic system. Details on the kit and curriculum available on ti.com/rslk. [23]	
5	**Specialized drives for three-phase brushless motors II:** **TIDM-SERVODRIVE** TMDXIDDK379D - Industrial Servo Drive and AC Inverter Drive Reference Design. The DesignDRIVE Development Kit is a reference design for a complete industrial drive directly connecting to a three phase ACIM or PMSM motor. Many drive topologies can be created from the combined control, power, and communications technologies included on this single platform. Includes multiple position sensor interfaces, diverse current sensing techniques, hot-side partitioning options and expansion for safety and industrial Ethernet. [24]	
6	**Specialized drives for three-phase brushless motors I:** **TIDM-THREEPHASE-BLDC-HC-SPI-INST** Three Phase BLDCM & PMSM Motor Kit with DRV8301 and InstaSPIN-enabled Piccolo TMS320F28069M MCU (DRV8301-69M-KIT). This reference design demonstrates a motor control solution for spinning three-phase brushless DC (BLDCM) and brushless AC (BLACM) - often referred to as “permanent magnet synchronous (PMSM)” - motors featuring the C2000™ Piccolo™ microcontroller	

	enabled with InstaSPIN-FOC and InstaSPIN-MOTION in ROM and the DRV8301 three-phase motor driver. It provides three half-bridge drivers, each capable of driving two N-type MOSFETs, one for the high side and one for the low side. It supports up to 2.3A sink and 1.7A source peak current capability and only needs a single power supply with a wide range from 6V to 60V. The reference design features a high-performance, power-efficient, cost-effective platform that speeds development for quicker time to market. Applications include CPAP and pumps, e-bikes, e-scooters, medical pumps and drills, power tools, and robotics. This reference design is based on the DRV8301 evaluation kit. [25]	
7	**Specialized AC drives I:** **LAUNCHXL-F28379D** **BOOSTXL-3PHGANINV** **BOOSTXL-DRV8305EVM** **BOOSTXL-POSMGR** C2000 Delfino MCU F28379D LaunchPad™ development kit 48-V Three-Phase Inverter With Shunt-Based In-Line Motor Phase Current Sensing Evaluation Module DRV8305N 3-Phase Motor Drive BoosterPack Evaluation Module C2000 DesignDRIVE Position Manager BoosterPack™ This evaluation kit allows the assembly of a specialized electric drive depending on the specific requirements with the possibility of using different power converters and the inclusion of POSManager for the use of InstaSPIN Motion control technology. [4],[5],[6]	    
8	**Motors** [17],[18],[19]	HVBLDCMTR, LVACIMTR, HVPMSMMTR, BLDCM/BLACM NEMA17 55W Motor, 2MTR-DYNO InstaSPIN-FOC.
9	**Software** [26]	CCS, C2000Ware, controlSUITE™, PowerSUITE™.

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