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A Matter of Torque
Electric power steering system

Electric power steering offers greater vehicle safety by adapting variable steering ratios to human needs, filtering drivetrain influences and even adjusting active steering torque in critical situations. In addition, it can make cars lighter and more fuel efficient when compared to those using hydraulic steering systems.

The central electronic elements of today's power steering systems are modern 32-bit microcontrollers (MCUs). Only high-performance MCUs can provide sufficient computing power and specialized peripherals for complex motor control functions. Since power steering is a safety-critical function, it also requires new MCU elements that support the functional safety of the overall system.

This article provides an overview of the latest generation of Power Architecture® based MCUs and describes how they are used in power steering applications. New innovative elements, such as the cross-triggering unit for motor control and the fault collection unit for monitoring and reporting safety critical signals, are explained.

Introduction

During the last decade, advanced chassis control functions have become main technology drivers for active safety systems in vehicles, and electric power steering (EPS) nicely combines vehicle safety with higher fuel efficiency. With the first systems entering the market in the mid 1990s, purely electronic steering systems have migrated to almost every segment of the vehicle market.

EPS in modern cars can significantly reduce fuel consumption when compared to cars using hydraulic solutions. Industry studies have shown that EPS can save up to 85 percent of the energy normally needed to steer a vehicle with conventional hydraulic systems. The result is fuel consumption reductions of up to 0.3 liters per 100 kilometers driven. EPS is so efficient because the system is only activated when steering support is really needed. As a result, a permanent engine load is not required.

EPS systems also can help ensure safer driving. The steering torque is adapted to the vehicle's speed and optimized for different driving situations. For example, during low-speed driving maneuvers, such as parking, EPS provides a higher level of assistance than it does at higher speeds, when electronic power assist is gradually reduced to enable more direct steering and better feedback from the road.

By integrating sensors and network connectivity, EPS can further enhance its safety characteristics through improved dynamic control and warning functions:

- Improved vehicle dynamics control
  - Helping and guiding the driver with additional steering torque in over-steer situations
  - Reducing stopping distance by coordinating with the electronic stability control (ESC) system on roadways with differing friction levels
- Warning functions
  - Generating a slight counter-steering torque in order to prevent the vehicle from unintentionally drifting out of its lane

System overview

Depending on the level of assisting forces required, various types of EPS systems exist. The different architectures include:

- Column-drive systems
  - Typical for relatively light vehicles with lower steering forces
  - DC or BLDC EPS motor integrated with the steering column
- Rack-drive systems
  - Typical for larger vehicles requiring high steering forces
  - Assist power is directly applied to the steering rack with a BLDC EPS motor

The elements that all EPS architectures have in common are a steering wheel with integrated steering angle sensor, a steering torque sensor, a power steering control module and a motor for generating the required assist force.

Steering Control Module Block Diagram

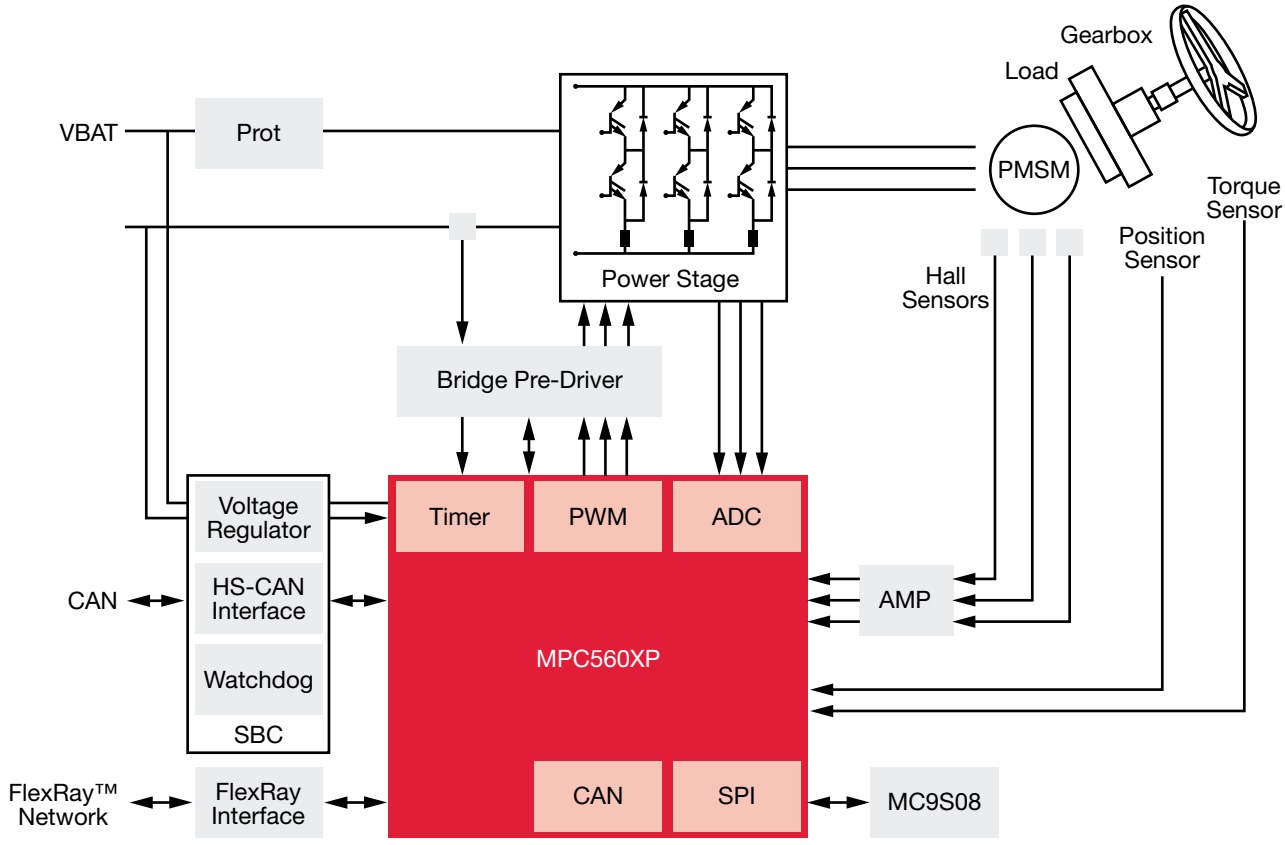


Figure 1

Permanent magnet synchronous motors (PMSM) with their improved efficiency and higher reliability are now widely used in electric power steering systems. Minimizing the non-linearity in the motor torque characteristic while generating the maximum torque requires a sophisticated motor control approach called vector control, which requires real-time processing for the stator phase currents and rotor position.

Figure 1 illustrates the basic architecture of a power steering control module, and its main functions:

- Generating and monitoring the component supply voltages
- Monitoring/preprocessing steering torque and steering angle sensor signals
- Receiving vehicle speed and engine speed signals via CAN or FlexRay™ protocols
- Receiving control inputs from other systems, such as the braking controller
- Calculating the necessary assisting force/torque
- Motor signal processing and torque vector control
- PWM signal conditioning and controlling the MOSFETs typically used in 3-phase motor drives for power steering

The Freescale MPC560xP family of Power Architecture-based MCUs is specifically designed for advanced motor control applications. It provides all high-precision analog-to-digital converter (ADC) and timer functions required for motor signal acquisition, a powerful Harvard architecture core and flexible PWM modules that allow center, edge-aligned and asymmetric PWM duty cycles.

The new MC33905 family of system basis chips consists of integrated power management solutions for 32-bit MCUs and other components of a power steering control unit. The devices combine dual 5V/3.3V selectable voltage regulators with an ISO11898 high-speed CAN interface and up to two LIN 2.0 interfaces. Integrated monitors guarantee undervoltage detection as well as voltage, current and temperature protection.

The MC33937 pre-driver integrates high side and low side FET drivers with greater than 1A gate drive capability. The device can be directly interfaced to the microcontroller's PWM outputs and is configurable via an SPI port.

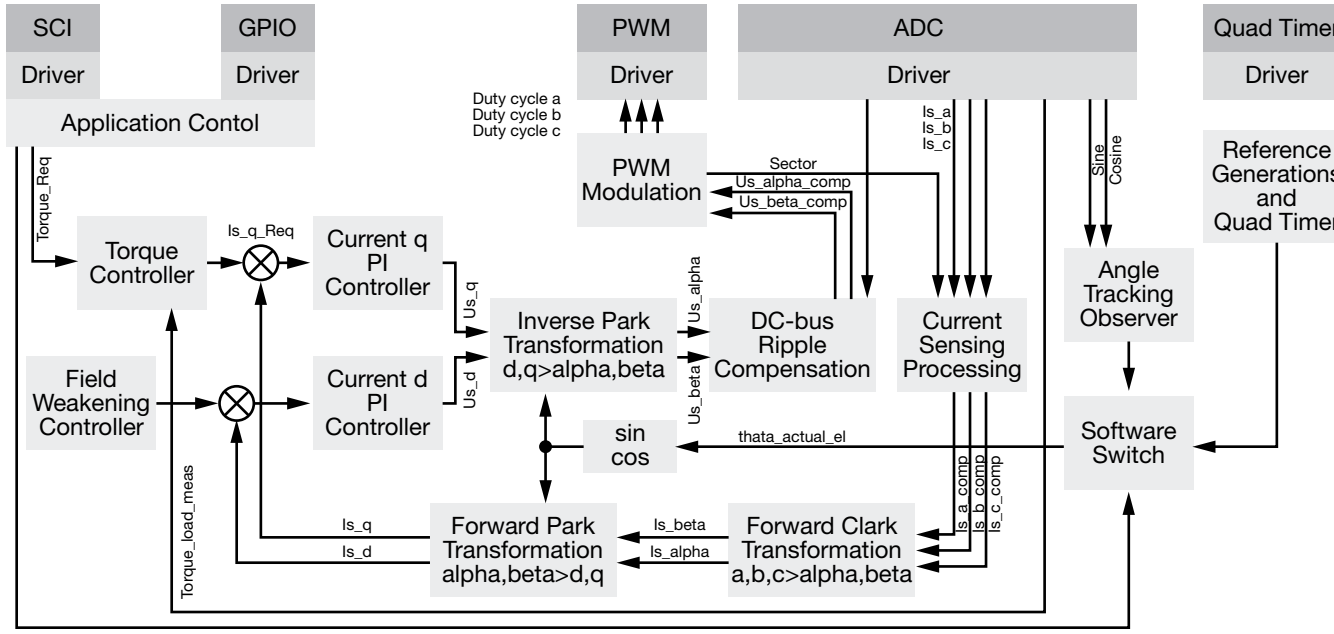


Figure 2

Technical challenges

Vector control seeks to align the PMSM's rotor and stator fields in a way that delivers maximum torque. The optimum solution is when both fields are oriented 90 degrees from each other. The control scheme designed to keep the 90 degree field alignment is often referred to as field oriented control (FOC).

The typical cycle time for a PMSM control scheme is about 50 µs, during which the following tasks will normally need to be performed:

- Motor phase currents and DC bus current measurements and calculations
- Encoder/resolver signal processing and rotor position calculation
- Motor current processing (id, iq) via Clark/Park transformation
- Processing current control algorithms
- Generating new PWM signals via reverse Park/Clark transformation

Due to the tasks outlined above and the functional safety system requirements, electric power steering control unit designers will face the following technical challenges.

Fast and precise acquisition of state variables

Given the PWM control cycle time, a fast and precise ADC is needed to acquire the DC bus current and/or phase currents. The ADC needs to provide high conversion speed in order to allow for oversampling of multiple data points within a single PWM cycle. A typical requirement is ≤1.5 µs conversion time with at least nine bits.

Real-time control code processing

In order to derive new PWM control values for the motor, the measured/calculated phase currents have to be transformed into direct and quadrature components of a rotating reference frame. The advantage of this transformation is that current components have DC steady-state values now, which allows relatively simple PI-Type control algorithms for error compensation. Resulting control signals are transformed back to 3-phase quantities and applied to the motor via PWM outputs. Figure 2 shows a typical example of such a control cycle.

Synchronizing A/D conversion, timer inputs and PWM

In a control scheme as described above, it is important to schedule the acquisition of the state variables, such as currents or position counter information, with respect to the PWM cycle. With traditional MCU peripherals, complex schedules require substantial central processing unit (CPU) involvement. Examples include ADC configuration and adapt handling or pre-setting the timer and PWM registers for the next control cycle.

Compliance with functional safety standards

An EPS system is a safety-critical element that needs to meet the requirements of industry standards, such as IEC61508 or ISO26262. State-of-the-art functional safety concepts for power steering control units require sophisticated fault monitoring of MCU functions in order to allow the system to enter a safe state in case of malfunction. Collecting internal faults and reporting these to an external circuitry, even if the CPU is malfunctioning, is a typical technical requirement for power steering controller solutions.

MPC560xP Block Diagram

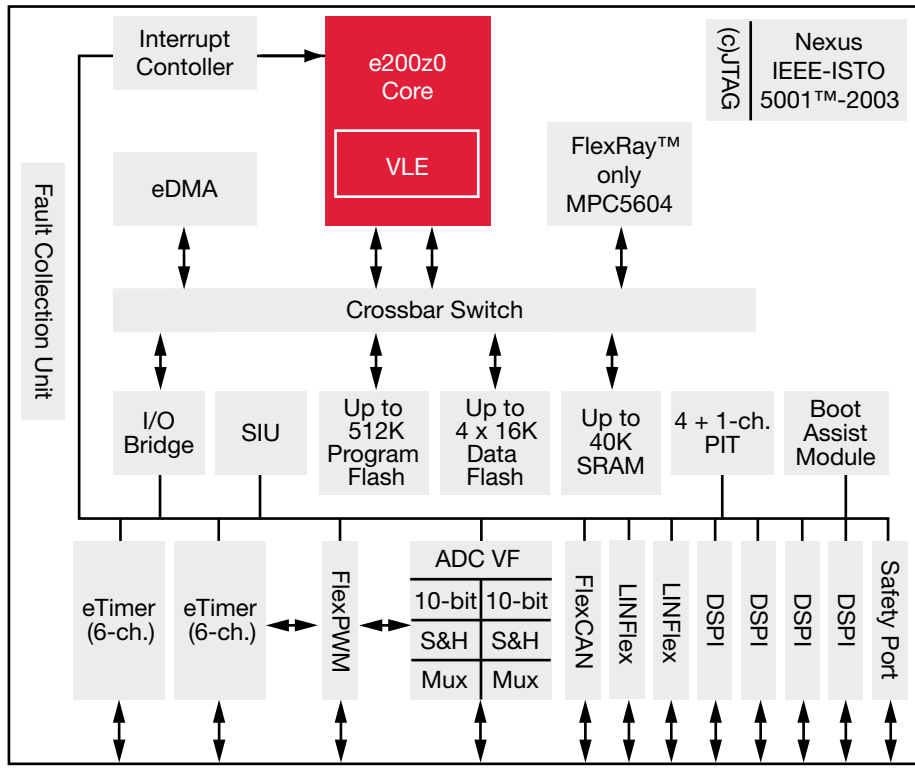


Figure 3

MPC560xP controller family for motor control

Freescale's new MPC560xP family of 32-bit MCUs, with a Harvard-type Power Architecture core and a set of powerful motor control peripherals, provides an ideal solution for EPS and other advanced motor control applications. Features include:

- High-performance 64 MHz 32-bit e200z0 Power Architecture CPU with variable length encoding (VLE) for code compression
- Up to 512 KB on-chip flash memory with ECC, additional 4 x 16 KB on-chip data flash memory with ECC for system configuration data storage and fault events
- Up to 40 KB on-chip RAM with ECC protection
- One 16-channel enhanced direct memory access (eDMA) controller
- Two general purpose eTimer modules, each with six timers, 16-bit resolution cascadable counters and quadrature signal decoding
- One 16-bit resolution PWM module with configurable dead-time insertion and fault inputs
- Two 10-bit ADCs supporting simultaneous conversions in less than 1 µs with a linearity error of ±1 LSB
- Cross triggering unit that allows automatic generation of ADC conversion requests during the PWM period without CPU load and dynamic configuration optimization via DMA
- Four serial peripheral interface modules for communication with MC33905 system basis chips, MC33937 pre-drivers and other control unit components
- Two serial communication interface modules with LIN support
- Up to two CAN modules with 32 message buffers
- One dual-channel FlexRay controller with 32 message buffers for safe communication with other control units
- Fault collection unit for collecting internal controller faults and reporting these to an external circuitry, even in the case of a malfunctioning CPU
- Safety elements, such as a programmable watchdog timer, redundant 16 MHz internal RC oscillator, junction temperature sensor and a non-maskable interrupt
- On-chip single-supply voltage regulator supporting 3.3V and 5V

In order to guarantee optimal peripheral performance as well as highest timer and PWM resolution, all motor control related modules can be configured to use a dedicated clock domain supporting up to 120 MHz. All other peripherals use the 64 MHz main system clock.

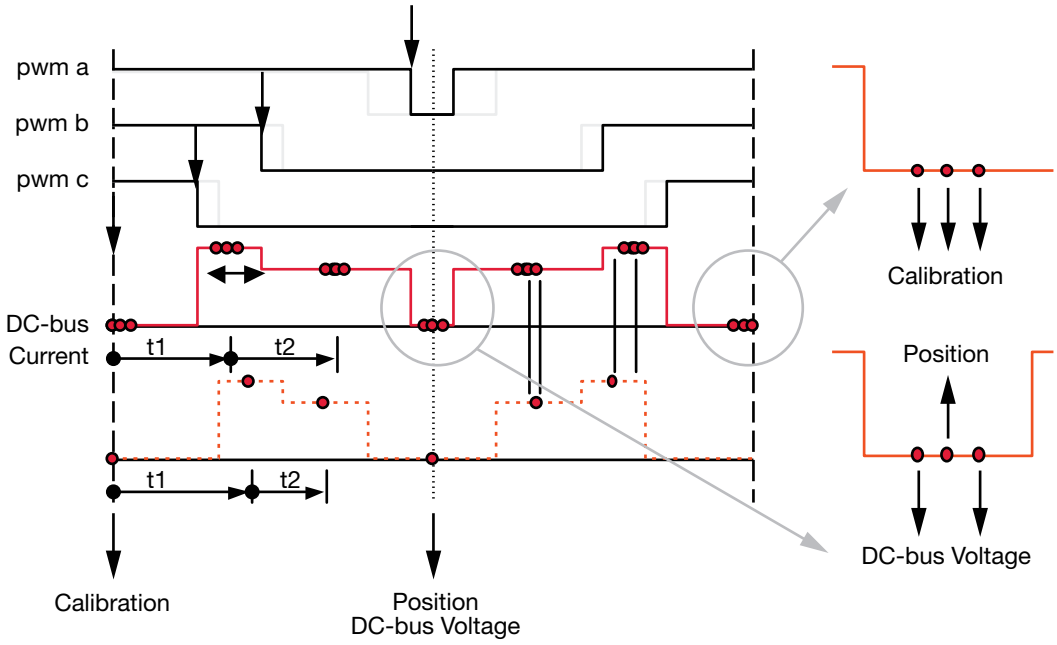


Figure 4

State variable acquisition: scheduling problems

As discussed before, scheduling state variable acquisition with respect to the PWM cycle is technically challenging and often results in a significant interrupt load for MCU. In order to completely avoid CPU involvement in the acquisition of key state variables, a new hardware element, the cross triggering unit (CTU), was introduced on the MPC560xP family.

The CTU receives inputs from internal controller sources, such as the PWM module and timers, but also allows an external trigger from a GPIO port. Inputs can be on the rising edges, falling edges or both edges of each received signal. A trigger generator handles incoming signals in terms of input selection, active edges definition and master reload signal generation. On the basis of incoming signals, the trigger generator can generate up to eight trigger events. Two modes are supported:

- Triggered mode: each source of the incoming signal can generate up to eight trigger event outputs
- Sequential mode: each source of the incoming signals can generate one trigger event output only

Depending on the trigger events generated, a scheduler unit generates specific outputs, including:

- Command or stream of commands for the ADC
- Pulse for the timer module
- External trigger pulse via GPIO

Example: A/D conversion

In order to avoid any CPU intervention, the ADC module must be controlled by the CTU. This requires the ADC to be switched to CTU control mode, which allows the scheduler unit to send ADC commands when a trigger event occurs. As an alternative to conventional results registers, ADC results can be stored in one of four FIFOs. These FIFOs allow conversion results to be dispatched according to the type of acquisition (i.e., phase currents, rotor position, ground noise).

Further minimizing CPU load, the CTU is fully DMA supported. The master reload signal provided by the trigger generator can be used as a DMA request, for example. DMA transfers are also used to read data from the result FIFOs.

All CTU registers are double buffered, which allows setting a new configuration while actual acquisitions are made. Figure 4 is an example of a triggered sequence of A/D conversion that can be implemented very efficiently using the new CTU.

Functional safety: fault collection

Another innovation introduced with the MPC560xP family is the fault collection unit (FCU). This hardware module is intended to simplify controller-level fault reporting in safety-critical applications. The FCU can handle up to 32 controller internal fault signals, such as loss of system clock, loss of PLL lock or multi-bit ECC failures. The module allows the user to select how different fault signals will be treated. Three options can be configured:

- No Action: no specific counter measures needed to manage the fault
- Alarm: allows software and/or hardware to recover from the fault
- Fault: direct communication to external circuitry via two dedicated GPIO pins

Three different protocols can be used to communicate with external circuitry. The dual-rail scheme is one example of a supported protocol. As long as no critical fault occurs, the FCU output pins will toggle between (0,1) and (1,0) with a configurable frequency. By default, this value is f=976 Hz@64 MHz. If a fault is detected, these pins will toggle between (0,0) and (1,1) at the same frequency, which would allow external circuitry to bring the system into a safe state.

In order to guarantee CTU independence in case other controller modules or the main core malfunction, the module runs on a separate internal 16 MHz RC clock. This allows deterministic computation of output signals and time outs. Additional safety elements, such as a programmable watchdog timer, a junction temperature sensor and FlexRay support, complete the list of controller features that support IEC61508 or ISO26262 certifiable systems design.

Summary

The Freescale MPC560xP family of Power Architecture controllers provides an optimal solution for advanced automotive motor control applications, such as EPS. Such technical challenges as timed acquisition of state variables are resolved with a new cross triggering unit that allows significantly reduced interrupt load due to hardware synchronization of the PWM cycle, timers and the ADCs.

The fault collection unit, a new hardware element, supports power steering system certification according to such safety standards as IEC61508 and ISO26262. The FCU is intended to ease controller-level fault reporting in safety-critical applications and completes the set of safety features available on the MPC560xP controller family. This family, in combination with MC33937 pre-drivers and MC3390x system basis chip solutions that integrate power supply, network interfaces and signal monitoring capabilities, provides the main building block for state-of-the-art EPS systems.

Based in Munich, Germany, Thomas Böhm is global marketing manager for chassis, safety and driver assistance solutions for Freescale Semiconductor. He joined Freescale in 2000 as a system engineer and has worked in several business development positions since 2004. He earned a degree in electrical engineering from Chemnitz University of Technology and received an MBA from OUBS in the United Kingdom.