Trends *in advanced* chassis control

Motorola vehicle system developers examine the state-of-the-art microprocessor and other electronics technologies driving the development of advanced braking, steering, suspension control, and collision warning/avoidance systems.

Electronically controlled chassis systems have enhanced safety enormously by optimizing the interface between tire and road surface, either in the longitudinal, lateral, or vertical directions. Antilock braking systems (ABS), four-wheel drive (4WD), and traction control systems (TCS) are three popular technologies that optimize dynamic stability in the longitudinal direction. Conventional 4WD systems typically use a transfer box with a viscous coupling that engages when a difference in the rotation speed between front and rear wheels occurs. However, newer electronically controlled systems are more efficient, according to Motorola product developers, because considerable slip is not required before the 4WD operates, and driveline torsion as well as traction and braking capacity can be better optimized.

In the vertical direction, roll stabilization and active-suspension systems can be implemented, although they are still in their infancy in terms of production applications. Sensors that detect vehicle roll can also be used for rollover protection systems as well as for roof and curtain airbags.

Lateral stability can be handled by vehicle chassis control systems such as four-wheel steering (4WS), which increases stability while cornering at high speeds, and by systems that compensate for understeer or oversteer, which are referred to as electronic stability programs (ESP).

Taking the ESP concept slightly further, a fully integrated chassis control system could control suspension, steering, and braking functions. Such a system could control the interoperability of all related subsystems in the near future; however, this next step will require real-time vehicle information on all six degrees of freedom as well as on the status of each system's control variables and a real-time communication link with all relevant systems, including the powertrain.

A chipset solution for these and other chassis control systems means product development time can be significantly reduced, according to product developers at Motorola. A total chipset need not necessarily come from one semiconductor supplier, although it often does.

Braking processor performance to increase

The real value of a chipset is that it can be applied across a number of closely related products. Basic system requirements can be met with a chipset, while interchangeability with pin-for-pin compatible variants allows upgradability to higher performance systems.

Braking and chassis control applications are a good example. Vehicle chassis control systems are often based on a single platform but vary in features and functionality, depending on the model in which they are implemented. Because differences between ABS, TCS, and ESP are small in terms of hardware and software, a chipset approach to these solutions works well. The software is written in a modular style, and electronic-component performance is determined with worst-case system requirements in mind.

A chipset solution for ABS/TCS/ESP is illustrated in Figure 1. Every automotive electronic control unit (ECU) has four basic elements: conditioning system inputs, conditioning system outputs, processing, and "housekeeping" functions such as power-supply maintenance. Three basic semiconductor technologies are applied: high-speed complementary metal oxide silicon for the processing portion, analog application-specific integrated circuits (ASIC) for input/output conditioning and housekeeping, and some PowerFETs (field-effect transistors) for driving power stages—in this case, for switching the hydraulic pump motor rated at over 100 A. The three technologies make infinite partitioning possible.

The input portion translates analog signals to digital waveforms that are applied directly to the microcontroller I/O (Figure 1 shows all of the sensor inputs grouped together in a single device). Although a single input-conditioning device is possible, it is seldom implemented; the device—because of the interface for steering-angle, low-*g*, and yaw-rate sensors—is only required for ESP, and it would not normally be cost effective for an ABS-only system. For this reason, at least two interface devices are usually specified, the second added to the basic chipset if ESP is included.

Two processing elements are typically included in the processing portion of the circuit as a "fail-safe" to ensure that faults in the electrical/electronics system are self-diagnosed and result in a shutdown. This leaves the conventional hydraulic brakes fully functional with the absence only of ABS control. Theoretically, a single microcontroller could observe and check each part of the system; the second is used to observe the operation of the first.

The output-conditioning portion of the system, as with the input portion, is implemented using analog-based technology, with an ASIC allowing incorporation of basic logic to enhance performance. This "smart" functionality is used for diagnostics and to enhance fail-safe operation.

One of Motorola's more advanced braking technologies is the M68HC12 microcontroller architecture

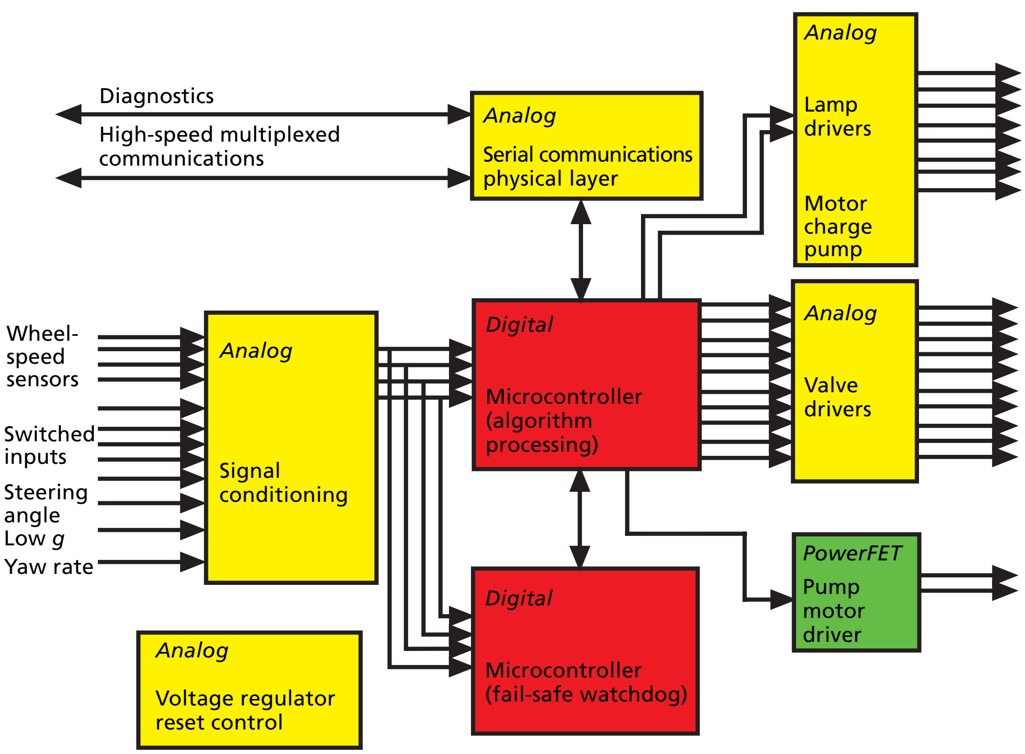


Figure 1. A typical chipset solution for ABS/TCS/ESP includes four basic elements: conditioning system inputs, conditioning system outputs, processing, and "housekeeping" functions.

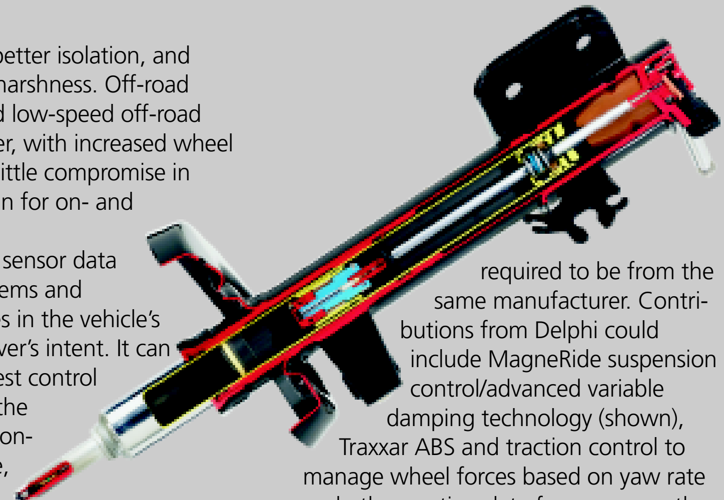
Delphi unifies chassis control

Unified Chassis Control (UCC) is a high-level vehicle dynamics control strategy from Delphi Automotive Systems that facilitates the integration of multiple chassis subsystems such as brakes, suspension, steering, and powertrain. A controller coordinates the functions of the subsystems to optimize overall vehicle control.

Delphi says that the combined functions of UCC improve vehicle safety, enhance handling performance, and increase comfort. The system helps keep the vehicle on course by sensing impending skids or spins and selectively assisting in the control of individual brakes, suspension forces, powertrain torque, and steering angles. It coordinates steering and braking on split-coefficient surfaces to shorten stopping distances and improve vehicle stability. With UCC, there is a reduced rollover propensity for all types of vehicles, especially high-c.g. vehicles such as SUVs and vans. Improved comfort results from reduced "head toss" and roll angles, better isolation, and reduced impact harshness. Off-road performance and low-speed off-road traction are better, with increased wheel articulation and little compromise in suspension design for on- and off-road driving.

UCC receives sensor data from the subsystems and monitors changes in the vehicle's state and the driver's intent. It can determine the best control strategy to help the driver maintain control. In the future, the control system will be able simultaneously to correct steering angles, reduce throttle, apply independent differential braking, modify front and rear roll stiffness, and selectively adjust dampers to improve safety.

The open architecture and standardized interfaces of the UCC supervisory control allow for the integration of multiple chassis systems, not all of which are required to be from the same manufacturer. Contributions from Delphi could include MagneRide suspension control/advanced variable damping technology (shown), Traxxar ABS and traction control to manage wheel forces based on yaw rate and other motion data from sensors, the Galileo family of intelligent-brake and brake-by-wire technologies, Quadrasteer rear-wheel steering, E-Steer electric power steering, and Dynamic Body Control active roll control technology.



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for electronic-braking systems, which was developed specifically for real-time embedded control applications with custom specific features for ABS applications. One such feature is the enhanced capture timer (ECT) that is implemented on a number of variants. The ECT consists of a 16-bit, software-programmable counter driven by a prescaler, and it can be used for purposes such as input waveform measurements while simultaneously generating an output waveform. There are eight input-capture/output-compare channels, four of which include a buffer called a holding register to allow two different timer values to be "memorized" without the generation of an interrupt. Four pulse accumulators are associated with the four buffered channels to count pulses during a time specified by a 16-bit modulus counter.

In the ECT, data are latched into the input-capture and pulse-accumulator holding registers. At the end of a control-loop cycle, all the relevant information required to calculate wheel speed is available directly from the central processing unit (CPU) in these registers. Wheel speed can be calculated if the time of the first and last pulse is known along with the number of pulses acquired during the cycle.

In the near future, hydraulic braking systems are expected to be replaced by fully electrical systems. Although there are still challenges to be overcome, the expected advantages of such systems make a strong argument for the development of brake-by-wire (see Table 1).

Table 1
Brake-by-wire Advantages

- No brake fluid—ecologically friendly and reduced maintenance
- Lighter weight
- Fuel economy—pad clearance control
- Increased performance—brakes respond more quickly
- Minimized brake wear—more control of friction material application
- More simplistic/faster assembly and testing—modular structure
- More robust electrical interfacing
- No mechanical linkages through bulkhead—enhanced safety
- Electronic architecture is more easily upgradable
- Consistent pedal characteristics, constant travel
- Significantly fewer parts than a hydraulic-based system

One of several issues being addressed in brake-by-wire development is the actuation energy required for braking. A disc brake requires about 1 kW of actuation energy, and a drum brake requires around 100 W. Although a 12-V based vehicular electrical system does not easily support the high power requirements needed for electrical brake actuation, future higher-voltage developments will facilitate this level of support.

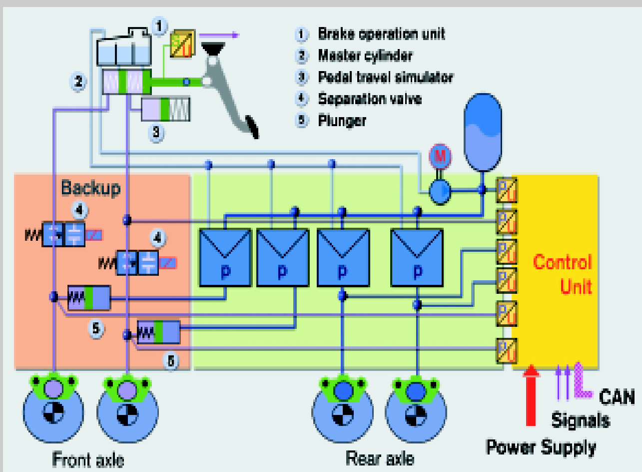
Another major challenge of brake-by-wire systems is the fault-tolerance requirement. In systems where hydraulics have been completely removed, no independent backup actuation system exists; rather than employ systems that fail safely, fault-tolerant or "fail-operational" systems are required. Although many clever techniques can enhance the safety of fault-tolerant systems, the underlying approach is to provide redundancy. If nodes or ECUs fail, backups come online without destroying existing system integrity. The degree of fault-tolerance is likely to differ from application to application, but important sensors and controllers are expected to be replicated. In addition, the serial communications between each of the nodes in the system must support fault-tolerance.

Bosch to introduce electronic braking for 2002

Bosch engineering development of systems for fully automated vehicle guidance and steering is quickening the trend toward by-wire replacements for mechanical and hydraulic systems. In addition to working on currently available drive-by-wire, company engineers are working intensively on electronic systems in the areas of braking and steering. Steer- and brake-by-wire systems are prerequisites for new safety and comfort enhancing functions, according to Gunther Plapp, Executive Vice President Development, ABS and Brakes Division of Robert Bosch GmbH.

Brake-by-wire separates the mechanical and hydraulic connections between the brake pedal and wheel brake. Sensors determine the driver's intent and transmit this information to an ECU, and the corresponding actuators apply the brakes.

Bosch is at the forefront of the electrification of braking, the company introducing an interim step to the full brake-by-wire system this fall on the Mercedes-Benz SL. Its electrohydraulic brake (EHB) system uses proven hydraulic brake components combined with electric elements. The system (shown) provides the brakes with a brake-fluid supply from a hydraulic high-pressure reservoir sufficient for several braking events. A piston pump driven by an electric motor supplies a controlled brake fluid pressure of 14,000 and 16,000 kPa (140 and 160 bar) from a gas diaphragm reservoir. When the brakes are activated, the EHB control unit calculates the desired target brake pressures at the individual wheels. Braking pressure for each of the four wheels is regulated individually via a wheel pressure modulator, which consists of one inlet and one outlet valve controlled electronically. Normally, the brake master cylinder is detached from the brake circuit, with a pedal travel simulator creating normal pedal feedback. If ESP intervenes, the high-pressure reservoir supplies the required brake pressure quickly and precisely to the wheel brakes.



"The crucial performance feature of the EHB is that it raises braking comfort," according to Plapp. The vehicle controller intervenes early and stabilizes the vehicle without the typical ABS feedback and is almost undetected by the driver. This allows vehicle guidance functions such as ESP and Adaptive Cruise Control (ACC) to be designed in a less intrusive way. Additional advantages include a dry brake function, which carries out regular short and weak brake impulses on wet roads to dislodge the brake-disc water film and ensure full and immediate braking. A "traffic assistant" can brake the vehicle with predefined deceleration when the driver removes his/her foot from the accelerator pedal; a "drive away assistant" can prevent rolling backward on a hill and simplifies the drive away process.

In parallel to EHB, Bosch engineers are also looking at the "full-value" electromechanical brake (EMB), but its introduction will come later. A significant problem is the task of developing a low-cost and light wheel brake that fits into the tight confines of the wheel rim. In addition, the EMB requires a high-grade (42-V) power supply. In contrast, EHB does not have additional space requirements near the wheel brake and does not add extra weight. To save energy, a well-designed 14-V power supply is adequate. Because of these advantages, Bosch expects that EHB will take over the market quickly.

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In a by-wire system, each wheel would likely have a motor-controlled actuator with an associated control circuit. If an individual wheel unit should fail, the vehicle could still be braked to a stop using the remaining three wheel units. However, a brake-pedal-position sensor failure could be catastrophic, so it is likely that a redundant sensor would be added to this part of the system.

Facilitating technologies required to make brake-by-wire (Figure 2) a common solution are an enhanced vehicular power management system and a cost-effective fault-tolerant serial communications architecture. From a semiconductor standpoint, the enabling technologies for conventional electronically controlled braking systems and brake-by-wire systems are similar. The major differences are the employment of fault-tolerant and motor-control technologies. Though incorporation of fault-tolerance will not present a significant challenge, the implementation of motor-controlled actuators is likely to drive cost-effective semiconductor technology to a higher temperature capability to withstand the temperatures generated in the vicinity of the braking actuator. Figure 2 illustrates a possible configuration of a brake-by-wire system.

As braking and steering systems become more complex and future systems become networked to provide additional safety features, performance requirements of the central algorithmic processor will see a significant increase in required capabilities.

Steering, brakes, suspension to be linked

Although it could be argued that the steering system is not a safety system, there is no argument that it is a safety-critical system and, as such, requires carefully implemented electronic controls. In the future, it will be closely integrated with other chassis control functions such as braking and suspension to form an overall chassis control system.

The current trend is to implement direct-assist electric-motor steering systems in place of the more conventional electrohydraulic power steering systems (both shown in Figure 3). In the event of a system fault, the direct-assist system requires additional safety precautions to ensure that the driver can retain steering control. In contrast with ABS, the direct-assist system must be fault-tolerant; in the event of a failure,

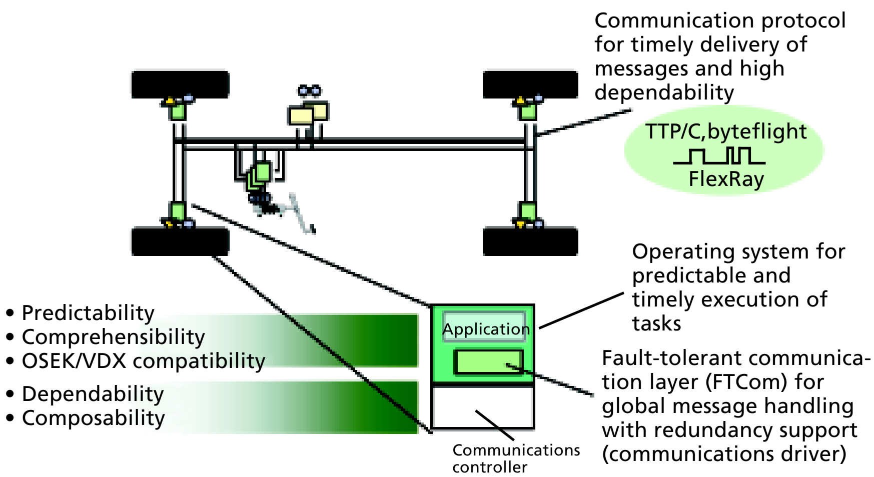

Figure 2. The facilitating technologies required to make brake-by-wire a common solution are an enhanced vehicular power management system and a cost-effective fault-tolerant serial communications architecture.

"steerability" must be maintained, so additional protective elements are designed into the controller—typically via smart diagnostics.

Both systems have similar controller architectures that include microcontroller units (MCU) and power stages, although the requirements of these components differ, depending on motor type and its associated control strategy. A simple permanent magnet dc motor is typically controlled by an eight-bit MCU such as Motorola's M68HC11.

As chassis control for steering systems becomes more complex, additional fast-math capability and microcontroller functionality may be required. The algorithmic controller must provide capabilities such as control-oriented instructions, higher code density, and easy programming capability using high-level languages. Some designers have considered digital-signal processors (DSP) to provide this capability, but are finding that more integrated devices with both digital-signal-processing as well as microcontroller capabilities may be a better fit.

One such device is the automotive version of Motorola's Hawk processor (Figure 4), which was developed to address the needs of future steering applications as well as a variety of automotive motor-control applications. The Hawk processor combines MCU ease-of-use with the speed of a DSP to deliver the combined benefits of both. It uses a Harvard-style architecture that employs both a load/store bus (for data) and an instruction bus (for instructions), providing three 16-bit data address and three 16-bit address buses. Compared to a Von Neumann-style microcontroller architecture that uses a single bus for both data and instructions, the Harvard type is more powerful because it supports parallelism in retrieving data and instructions.

Active suspension requires significant power

Although electronically controlled vehicle suspension systems can optimize road holding, handling/stability, and ride quality, there has been little progress in bringing them to the market at an affordable price for the average consumer. One of the main reasons for this lack of progress is that suspension characteristics must be modified dynamically. Though the ECU could easily execute the required complex algorithm in real-time, a significant amount of power is required to actuate the suspension elements (hydraulic, pneumatic, or electromechanical). The trend toward higher vehicle voltage capabilities (*e.g.*, 42 V) is expected to help facilitate mainstream active suspension systems.

In a basic active hydraulic suspension system (Figure 5), many inputs must be evaluated during the control cycle, which means a very high performance microcontroller is required for the system. Each wheel unit will require *g*-sensor and vehicle-height inputs as well as information on the

Active tilt control from Visteon

Active tilt control (ATC) can be integrated into Visteon suspension modules to limit the amount of vehicle roll during turning maneuvers. The system employs hydraulic actuators to control a vehicle's stabilizer bars during steering maneuvers. A bidirectional pump supplies the energy required to correct vehicle tilt. ATC is capable of using various power sources to meet different packaging requirements, potentially leveraging electrohydraulic and electric-power-assist steering and 42-V technologies. Benefits are said to be improved ride and handling performance as well as greater driver confidence and passenger comfort. In addition, the system's electrohydraulic pump reduces energy consumption and promotes better fuel economy.

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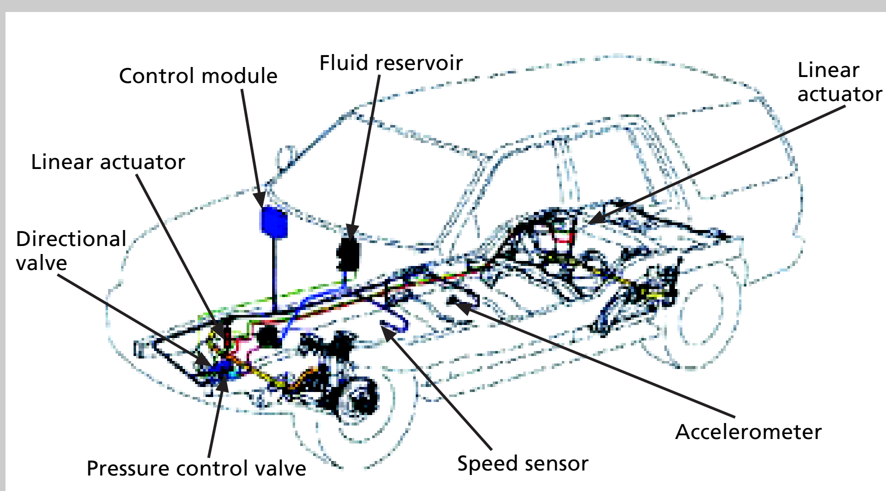

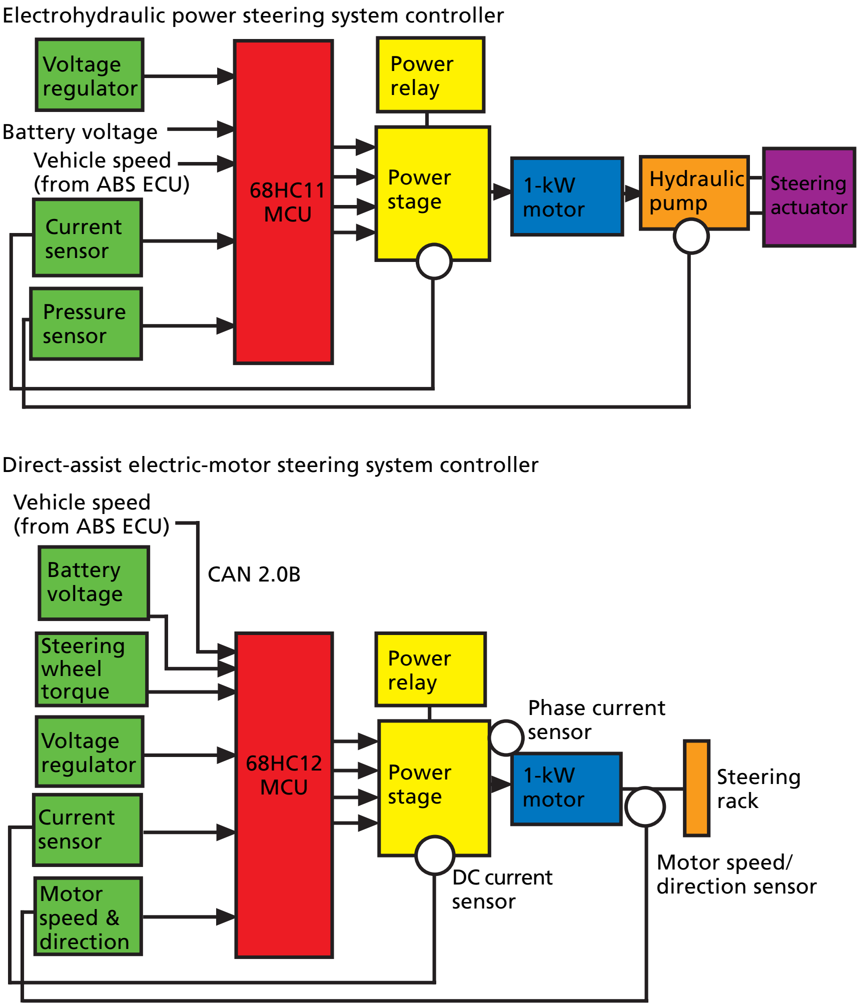

Figure 3. The current trend is to implement direct-assist electric-motor steering systems (bottom) in place of more conventional electrohydraulic systems (top).

braking, acceleration, and steering behavior of the vehicle. The control algorithm can be simplified by using a fuzzy-logic-based approach, which is much more intuitive and exploits the tolerance in the result.

With the more demanding, high-performance requirements of next-generation active-suspension control, devices such as Motorola's MPC555 microcontroller (Figure 6) are being selected by automotive designers. The microcontroller consists of a CPU, various peripherals attached to the IMB3 bus, the flash EEPROM and RAM memory arrays, and the integration module that contains all control/arbitration functions as well as the external interface. Although the throughput of the CPU (including a floating point unit) is very high, most of the peripherals are intelligent, performing many operations with minimal or zero CPU intervention.

For the suspension-control application, the microcontroller has certain characteristics to ensure that it is robust and will operate in harsh, "electrically noisy" environments such as underhood, which has operating temperatures of up to 125°C (255°F), and in a dual power-supply configuration. Although the processing features dictate that the CPU must operate with a nominal 3.3 V supply voltage, a 5-V I/O system is provided to ensure that the chip can interface easily with its neighboring system devices. The MPC555 also has a Harvard-style architecture with a load/store bus and an instruction bus. Though physically larger and more complex, it too supports parallelism in retrieving data and instructions.

High-performance peripherals of the MPC555 include a Timer Processor Unit 3 (TPU3), which is an onboard co-processor developed for timing control functions. Operating simultaneously with the main CPU, the TPU3 processes instructions, schedules/processes real-time hardware events, performs I/O, and accesses shared data without CPU intervention, which results in a higher CPU

Denso pioneers ACC braking in North America

Denso's laser distance sensor is the key component of the Lexus LS430's adaptive cruise control (ACC) system. In production since 1997, the sensor was adapted for the LS430 to detect vehicles preceding the driver's vehicle. The sensor uses high-speed, 2D (+8° azimuth, 4° elevation) data scanning to distinguish a vehicle from obstructions on the road ahead. It feeds data on the distance, relative speed, and relative acceleration of the preceding vehicle to the car's ACC ECU, which controls the vehicle's acceleration and deceleration.

According to Denso, the ACC system, with Denso's advanced brake control technology, is the leading edge of what is expected to become a completely autonomous driving system, which may allow future vehicles to safely navigate along prerouted traffic systems. The cruise control system is the first in North America that can throttle down, downshift, and apply the brakes.

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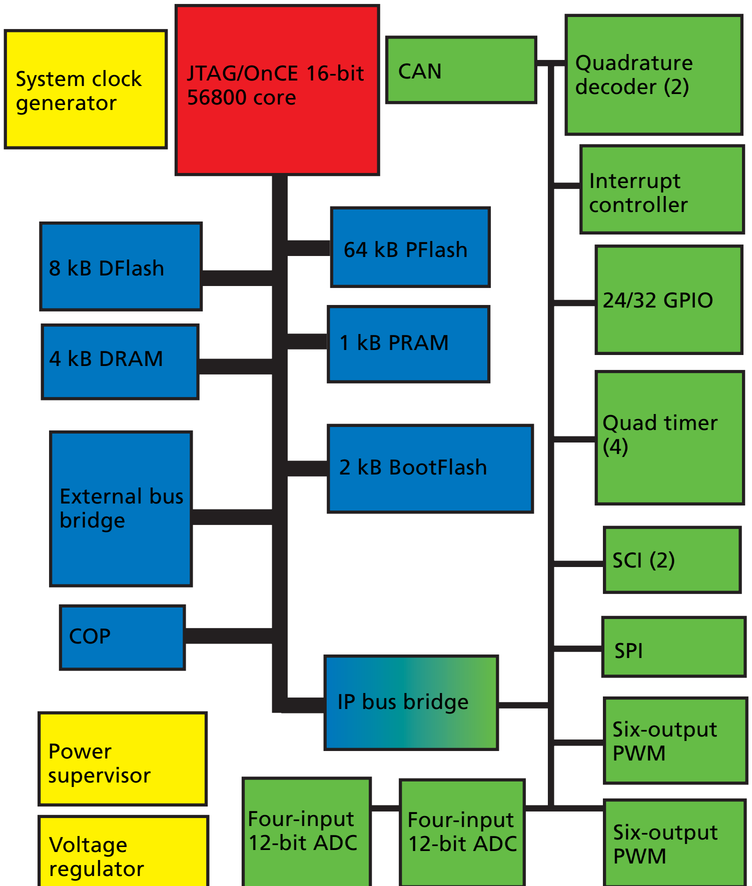

Figure 4. Motorola's Hawk processor, which combines MCU ease-of-use with the speed of a DSP, was developed to address the needs of future steering applications as well as a variety of automotive motor-control applications.

throughput. Flash EEPROM is provided as the program memory, and a total of 448 kB as well as another 64 kB are associated with the peripheral modules and control registers. In addition, there are 26 kB of RAM.

Collision warning/ avoidance systems

Although collision warning and avoidance systems may still be regarded as being in their infancy in terms of vehicle penetration, their perceived value in enhancing safety and reducing accidents is high. As the driving public ages and their reaction time increases while sight and hearing diminish, they expect to continue to be able to drive safely. Automakers have been developing radar systems for vehicles since the 1950s; however, most of this work has not led to practical and economically viable products mainly due to limited electronics and radar capabilities as well as the high cost of enabling technologies such as semiconductors.

Two categories of available systems are passive collision warning and active collision avoidance. A passive system detects a hazard and alerts the driver to risks, while an active system detects the hazard and attempts preventive action to avoid the collision. Both require object detection with the main difference being how a collision is diverted following object detection—by the driver or automatically. Both systems operate on the same principles of object detection, although the active system will control throttle, braking, and, in the future, steering systems to avoid collisions.

Several technologies are used for obstacle detection, the main approaches employing scanning laser radar sensors, frequency modulated constant wavelength techniques, and cameras in conjunction with algorithms that detect hazardous objects. The detection system is usually mounted at the front of the vehicle to detect objects in its forward path. Other techniques can involve a combination of sensors, including those for backing up.

For frontal systems, long-range and large-azimuth-resolution radar is required because of the high vehicle speeds and the need to determine objects in adjacent lanes. The forward range of these systems is usually about 100-200 m (330-660 ft), which allows around 3-6 s for warning of a stationary hazard when the host vehicle is traveling at 100 km/h (62 mph). Frontal radar requires higher operating frequencies (thus shorter wavelengths) than rear systems for better azimuth resolution. Frontal active systems—also called autonomous, intelligent, active, or adaptive cruise control—are a subset of collision-avoidance systems and, unlike conventional cruise control, adapt to the speed of slower vehicles ahead automatically.

A key difference between the object detection system used in active and passive systems is that the active system will require more accurate object recognition to identify objects such as road signs. Basic object detection is relatively straightforward; the most challenging problem is determining if an object is potentially hazardous while traveling at high speed with many objects present. If a warning is given to the driver for all

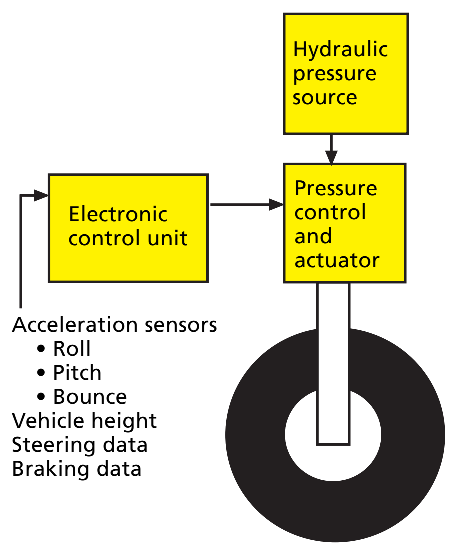

Figure 5. Many inputs must be evaluated during the control cycle of a basic active hydraulic suspension system, which means a high-performance microcontroller is required for the system.

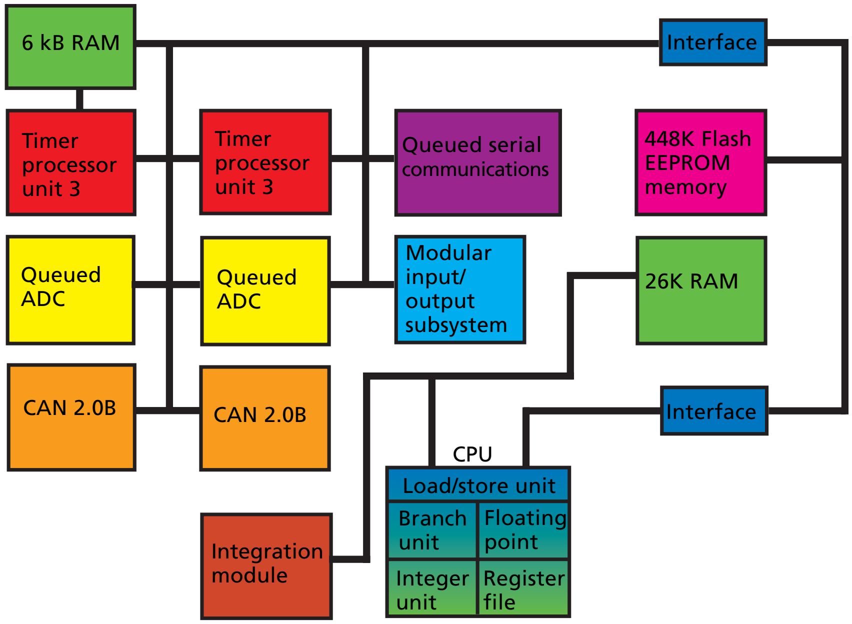

Figure 6. Motorola's MPC555 microcontroller is suited to the demanding requirements of next-generation active-suspension control.

obstacles, the alarms for nonhazardous objects will be irritating to the driver and will defeat the purpose of the warning. In a collision-avoidance system, automatic braking caused by a false alarm is likely to be dangerous.

The most popular technology for current frontal collision-warning systems is the scanning-pulse-based radar, which transmits a pulse of light back and forth horizontally (hence scanning). Distance is calculated by the microcontroller using the time interval between the transmitted and received pulses. The pulse radar is often referred to as laser radar because a pulse laser diode is used as the emitting device. Since the transmission frequency is phase-coherent from pulse to pulse, it is also possible to measure the Doppler shift of the target, yielding its motion, speed, and direction.

A simplified control circuit for this type of system consists of a microcontroller that executes the control algorithm and generates output signals to control the laser diode (Figure 7). The laser diode signal is reflected via a system of mirrors and lenses controlled by a stepper motor, which also allows the beam to be deflected horizontally in a scanning motion. A time value is measured using a microcontroller-integrated counter enabled upon the transmission of the pulse and when the input is received from the signal amplifier. Because of the high speed of light, microcontroller clock speed must be reasonably high to measure distance with acceptable resolution.

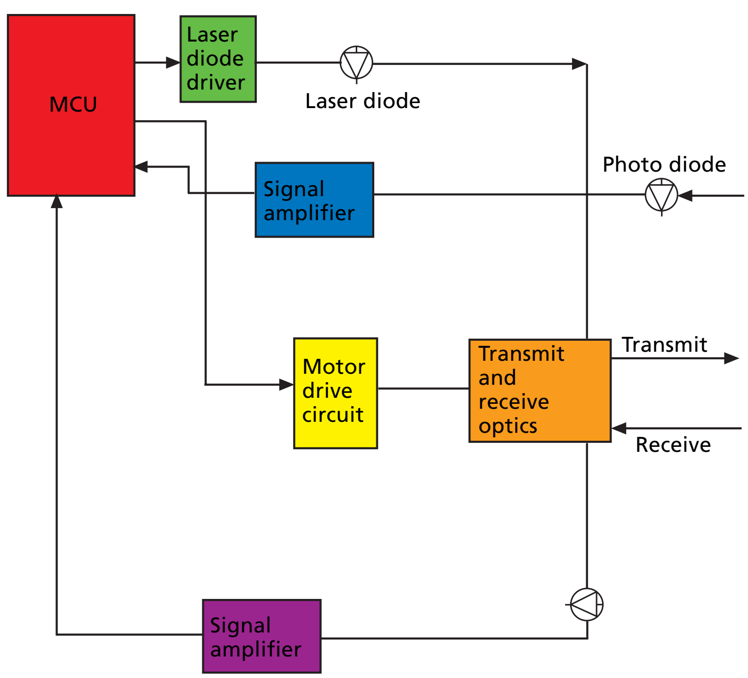

Figure 7. A simplified scanning radar control circuit consists of a microcontroller that executes the control algorithm and generates output signals to control the laser diode.

Combining MCUs and DSPs

A variety of new systems requirements and semiconductor technologies will be combined to meet the needs of the automotive industry for more advanced, more integrated, and safer chassis systems for vehicles. Designers of tomorrow's systems must ensure not just fail-safe operation but fully fault-tolerant operation. Semiconductors will meet this need with a variety of algorithmic processors, offering various performance levels with MCUs and DSPs, and in some cases both processing capabilities, on one device. Chassis systems of the future will bring braking and steering systems together with advanced communications technologies for the primary motivation of improved driver safety. However, the benefits will extend well beyond safety to include new functionalities that enable a cleaner environment, increased fuel economy, and greater reliability.

Information was provided by **Debbie Sallee** and **Ross Bannatyne**, Motorola Transportation Systems Group.

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