PART I

INTRODUCTION AND BACKGROUND

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1 Introduction

The century-old automobile – the preferred mode for personal mobility throughout the developed world – is rapidly becoming a complex electromechanical system. Various new electromechanical technologies are being added to automobiles to improve operational safety, reduce congestion and energy consumption, and minimize environmental impact. This chapter introduces these trends and provides a brief overview of the major automobile subsystems and the automotive control systems described in detail in subsequent chapters.

1.1 Motivation, Background, and Overview

The main trends in automotive technology, and major automotive subsystems, are briefly reviewed.

Trends in Automotive Control Systems

The most noteworthy trend in the development of modern automobiles in recent decades is their rapid transformation into complex electromechanical systems. Current vehicles often include many new features that were not widely available a few decades ago. Examples include hybrid powertrains, electronic engine and transmission controls, cruise control, antilock brakes, differential braking, and active/semi-active suspensions. Many of these functions have been achieved using only mechanical devices. The major advantages of electromechanical (or mechatronic) devices, as opposed to their purely mechanical counterparts, include (1) the ability to embed knowledge about the system behavior into the system design, (2) the flexibility inherent in those systems to trade off among different goals, and (3) the potential to coordinate the functioning of subsystems. Knowledge about system behavior – in terms of vehicle, engine, or even driver dynamic models or constraints on physical variables – is included in the design of electromechanical systems. Flexibility enables adaptation to the environment, thereby providing more reliable performance in a wide variety of conditions. In addition, reprogrammability implies lower cost through exchanged and reused parts. Sharing of information makes it possible to integrate subsystems and obtain superior performance and functionality, which are not possible with uncoordinated systems.

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Today's electrical and electronic devices have evolved into systems with good reliability and relatively low cost. They feature many new benefits including increased safety, reduced congestion and emissions, improved gas mileage, better drivability, and greater driver satisfaction and passenger comfort. Safety is perhaps the most important motivation for the increased use of electronics in automobiles. On average, one person dies every minute somewhere in the world due to a car crash. The cost of crashes totals 3 percent of the world's gross domestic product (GDP) and was nearly $1 trillion in 2000. Clearly, the emotional toll of accidents and fatalities is immeasurable (Jones 2002). Data from the National Highway Transportation Safety Association (NHTSA) show that 6,335,000 accidents (with 37,081 fatalities) occurred on U.S. highways in 1998 (NHTSA 1999). In 2008, the same statistic improved by about 10 percent to 5,811,000 accidents (with 34,017 fatalities) (NHTSA 2009). Data also indicate that although various factors contribute to accidents, human error accounts for 90 percent of all accidents (Hedrick et al. 1994).

Delays due to congestion are a major problem in metropolitan areas, providing strong motivation for an increase in automotive electronics. Traffic-information systems can reduce delays significantly by alerting drivers to accidents, congested areas, and alternate routes. Automated highway systems (AHS) at on ramps and tollbooths also can improve traffic flows. Significantly higher traffic flows can be achieved by closely packing automatically controlled vehicles in "platoons" on special highway lanes. These AHS concepts, developed and demonstrated in California, require automatic longitudinal and lateral control of vehicles (Rajamani et al. 2000).

In 1970, only 30 million vehicles were produced and 246 million vehicles were registered worldwide; by 1997, these numbers had increased to 56 million and 709 million, respectively. By 2005, 65 million vehicles were produced and more than 800 million were registered (Powers and Nicastri 2000). Consequently, another major factor that contributes to the increased use of electronics is the expanding government regulation of automotive emissions. For example, the 2005 standard for hydrocarbon (HC) emissions was less than 2 percent of the 1970 allowance; for carbon monoxide (CO), it was 10 percent of the 1970 level; and for oxides of nitrogen (NO_x), it was 7 percent of the 1970 level. The California requirements for ultra-low emission vehicles (ULEV) reduced the levels approximately by half again. Spilling 5.7 liters of gasoline on a driveway produces as many HC emissions as a ULEV vehicle driven more than 160,000 kilometers. At the same time, government regulations also require improved fuel economy. Advanced control technologies (e.g., fuel injection, air–fuel ratio control, spark-timing control, exhaust-gas recirculation [EGR], and idle-speed control) are and will continue to be instrumental in reducing emissions and improving fuel economy (e.g., hybrid-electric, all-electric, and fuel-cell vehicles).

This evolution (some might say "revolution") of automotive electronics also is enabled by recent advances in relevant technologies, including solid-state electronics, computer technology, and control theory. Table 1.1 summarizes developments in automotive electronics from 1965 through 2010. The already-evident trend toward increased automotive electronics can be expected to continue in the foreseeable future (Cook et al. 2007; Ford 1986; Powers and Nicastri 2000). In the next decade, significant advances are expected in the use of power electronics, advanced control systems, and alternative powertrain concepts. Among others, new technologies are

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Table 1.1. *Historical development of automotive electronics*

Year	Examples of automotive electronics available
1965	Solid-state radio, alternator rectifier
1970	Speed control
1975	Electronic ignition, digital clock
1980	Electronic voltage regulator, electronic engine controller, electronic instrument cluster, electronic fuel injection
1985	Clock integrated with radio, audio graphic equalizer, electronic air suspension
1990	Antilock brakes, integrated engine and speed control, cellular phones, power doors and windows
1995	Navigation systems, advanced entertainment/information systems, active suspensions
2000	Collision avoidance, autonomous cruise control, vehicle stability enhancement, CVT
2005	Hybrid electric vehicles, driver monitoring, drive-by-wire, integrated vehicle controls
2010	Driver-assist systems (e.g., automated parallel parking), integrated telematics (i.e., location-aware vehicles via mobile devices), plug-in hybrid electric vehicles

being developed for fuel-efficiency management, integrated chassis control, power management of hybrid vehicles, electrical power steering, collision warning and prevention, automatic lane following, rollover and lane-departure warnings, and fuel-cell vehicles.

In the near future, it is anticipated that these advancements may reach beyond individual vehicles and eventually lead to the development of Intelligent Transportation Systems (ITS) (Jurgen 1995). Due to rapidly increasing highway congestion, it is necessary for automotive and transportation engineers to devise ways to increase safety and throughput on existing highways. The term *ITS* (previously referred to as Intelligent Vehicle/Highway Systems [IVHS]) defines a collection of concepts, devices, and services to combine control, sensing, and communication technologies to improve the safety, mobility, efficiency, and environmental impacts of vehicle and highway systems. The importance of ITS is in its potential to produce a paradigm shift in transportation – that is, away from individual vehicles and roadways and toward the development of those that can cooperate effectively, efficiently, and intelligently.

Major Automobile Subsystems

To provide background for subsequent chapters, this section is an introductory overview of an automobile and its major subsystems. Refer to other sources, including Bastow et al. (2004), Bosch (2009), Dixon (1992), Ellis (1969), Gillespie (1992), Mizutani (1992), Ribbens (2003), Segel (1986), Washine (1989) and Wong (2008), for more in-depth discussions. The functional systems of an automobile are shown in Figure 1.1 and are classified as follows:

> *Chassis or Body*. This basic structure of an automobile supports many other systems described herein, as well as passengers and loads. It is supported by the suspension, which connects it to the axles and the wheels. The design of the chassis also affects vehicle dynamics, aerodynamic drag, fuel efficiency, and passenger comfort. The current trend is toward lighter body structures, including

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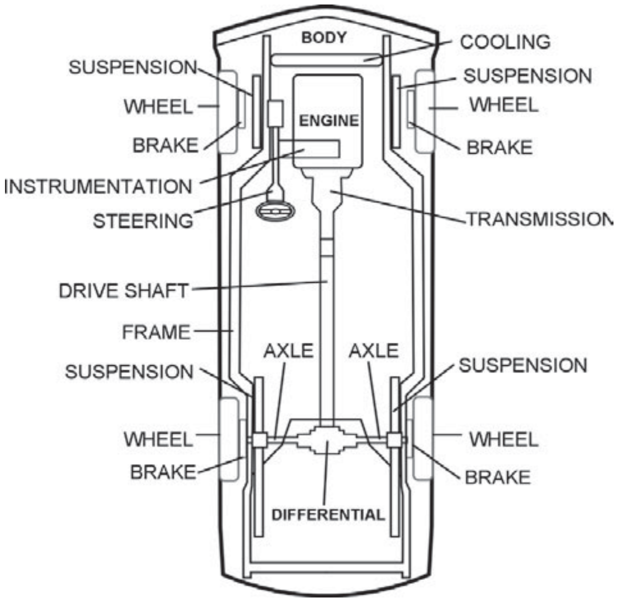

Figure 1.1. Vehicle subsystems.

the more efficient use of lighter-weight materials that nonetheless are durable and crashworthy.

Engine. This component provides the power for moving a vehicle as well as operating various subsystems. The most prevalent of the many engine designs is the piston-type, spark-ignited, liquid-cooled, internal combustion engine with four strokes per cycle and gasoline fuel. Engine controls, which improve engine performance in various ways, are used widely. Many new engine technologies (e.g., homogeneous-charge compression-ignition, electric, hybrid, and fuel-cell) also are being developed (Ashley 2001).

Drive Train or Powertrain. This system consists of the engine, transmission, driveshaft, differential, and driven wheels. The transmission is a gear system that adjusts the ratio of wheel speed to engine speed to achieve near-optimum engine performance. Automatic transmissions already are commonplace, and electronic transmission-control systems and continuously variable transmissions (CVT) are being introduced. A driveshaft is used in front-engine, rear-wheel-drive systems to transmit the engine power to the drive wheels. The differential provides not only the right-angle transfer of the driveshaft rotary motion to the wheels but also a torque increase through the gear ratio, thereby allowing the driven wheels to turn at different speeds (e.g., when turning a corner). The wheels and pneumatic tires provide traction between the vehicle and the road surface. Traction-control systems have been developed to provide good traction under a variety of road-surface conditions.

Steering. Steering allows a driver to change the orientation of a vehicle's front wheels to control the direction of forward motion. A rack-and-pinion steering-system design is typical in many modern automobiles. Power-assisted steering is now commonplace and four-wheel-steering (4WS) vehicles are emerging.

Suspension. The two major functions of the suspension system are to (1) provide a smooth ride inside the automobile, and (2) maintain contact between the

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wheels and the road surface. An independent-strut–type suspension design is common. A semirigid axle suspension system also is typical on the rear wheels of front-wheel-drive (FWD) vehicles. The suspension design also influences vehicle dynamics. Active and semi-active suspensions, which use electronic controls, are currently available on some vehicles.

Brakes. The brakes are the means for bringing a vehicle to a stop. Two common designs are drum and disk brakes. Antilock brakes, which use electronic controls to limit wheel slip, are now common on many commercial vehicles.

Instrumentation. A modern vehicle includes many electronic sensors, actuators, and other instrumentation. In today's cars, there are more than two dozen sensors in the powertrain alone. Most vehicles also now include dozens of microprocessors (e.g., for electronic engine control and diagnostics). Technologies such as the global positioning system (GPS) are starting to be used in automobiles. The average value of automotive electronics per vehicle, which was less than \$100 in the 1960s, reached approximately \$1,000 in 1990 and more than \$2,000 by 2000 (Ford 1986). Due to increasing power needs, today's 14-volt (V) electrical systems (with a 12-V battery) eventually may be replaced with a 42-V system (with a 36-V battery).

1.2 Overview of Automotive Control Systems

The automobile is rapidly becoming a complex electromechanical system due in part to advances in computing and sensing technologies as well as advances in estimation and control theory. Vehicles now include hierarchically distributed, onboard computing systems, which coordinate several distinct control functions. Among these are control functions associated with the engine and transmission, cruise control, traction control, and active suspensions, which are discussed in subsequent chapters of this book.

The control functions in an automobile can be grouped as follows: (1) powertrain control, (2) vehicle control, and (3) body control (Mizutani 1992). Before discussing each topic in detail, we briefly introduce these control systems, the basic concepts, and the terminology associated with control-system design.

Powertrain control consists of engine- and transmission-control systems and is discussed in Part II. The engine-control systems may include fuel-injection control, carburetor control, ignition or spark-timing control, idle-speed control, antiknock-control systems, and exhaust-gas recirculation (EGR) control. The goal of engine-control systems is to ensure that an engine operates at near-optimal conditions at all times. Electronic transmission control is used primarily in automatic transmissions. Transmission-control systems determine the optimal shift point for the torque converter and the lockup operation point based on throttle-angle and vehicle-speed measurements. Often, a single electronic control unit (ECU) handles both engine and transmission control functions. Four-wheel drive (4WD) systems are used (1) to obtain the optimal torque–transmission ratio, (2) in braking and acceleration, and (3) between the front and rear wheels. This optimal ratio depends on the vehicle forward velocity.

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Table 1.2. *Automotive control functions and variables*

	Controlled variable	Control input	Control algorithm	Sensors and actuators
Fuel Control	Air–fuel ratio	Injected fuel	Smith Predictor	Airflow, EGO, fuel injector
EGR Control	EGR rate	EGR valve opening	Optimal control	Valve position, EGR valve
Spark-Timing Control	Spark timing	Primary current	Rule-based, optimal control	Crank angle, vibration
Idle-Speed Control	Idle speed	Airflow rate	PI, linear quadratic regulator	Engine speed, idle speed control valve, throttle
Cruise Control	Vehicle speed	Airflow rate	PI, adaptive PI	Vehicle speed, throttle
Transmission	Gear ratio	Pressure, current	Rule-based	Vehicle speed, MAP
All-wheel drive, four-wheel drive	Torque distribution	Pressure, current	Rule-based, P, PI, PID	Engine speed, steering angle, control valve
Four-wheel steering	Wheel angle	Stepper motor	Feed forward, PI	Vehicle speed, wheel angle, stepper motor
ABS	Slip ratio	Pressure, current	Rule-based, sliding mode	Vehicle speed, wheel speed, control valve

Typically, 4WD systems have been achieved using mechanical rather than electromechanical components and are not discussed in this book.

Vehicle control systems, discussed in Part III, include suspension control, steering control (e.g., 4WS), cruise control, braking control (e.g., antilock brake systems [ABS]), and traction control. These systems improve various vehicle functions including response, steering stability, ride, and handling; many were introduced in recent decades or are currently being developed.

Body control refers to systems such as automatic air conditioning, electronic meters, multi-instrument displays, energy control systems, security systems, communication systems, door-lock systems, power windows, and rear-obstacle detection. The intent of these systems is to increase driving comfort and convenience and to improve the value of the automobile. These features often are perceived immediately by drivers as a benefit and typically are introduced first in luxury vehicles. Body-control systems are not discussed in detail in this book.

Several of the systems listed here are shown in Table 1.2, including the controlled variable, the manipulated variable (i.e., control input), the control logic (or control algorithm) used, the measured variables, and the actuators used to generate the control input. These vehicle control systems can be compared to the “generic” control-system block diagram shown in Figure 1.2. A typical feedback-control system consists of four basic elements: (1) controller, (2) actuator, (3) controlled system, and (4) sensor. The controller receives a reference (or set-point) input, which defines the desired value of the controlled variable, and a feedback signal from the sensor, which is a measurement of the controlled variable. The controller then applies a particular control logic (or law or algorithm) to compute a control signal. The control

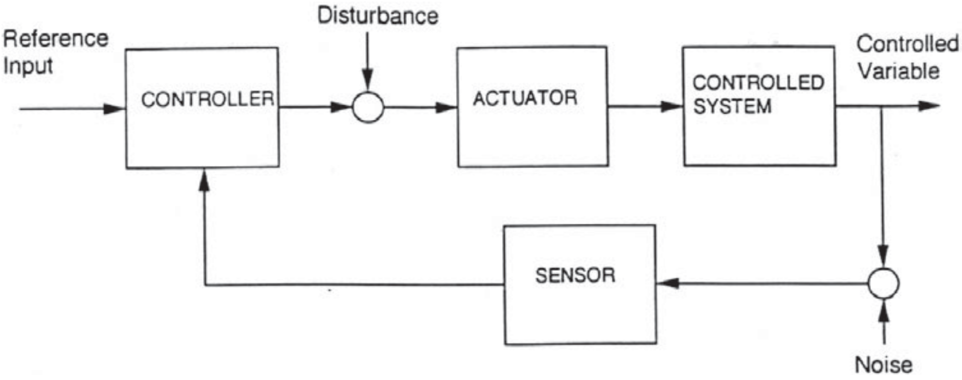

Figure 1.2. Control-system block diagrams.

signal is sent to the actuator, which supplies energy to the system by converting this information-type input signal to a power-type input to the controlled system. The controlled system responds to the actuator input as well as any other uncontrolled inputs (i.e., disturbances) that act on it. The sensor provides a measurement of the controlled variable for the purpose of feedback to the controller.

The control system illustrated in Figure 1.2 is a simple feedback loop with a single-input/single-output (SISO) system, which attempts to control only one variable. In reality, many automotive control systems consist of several such loops that interact in a complex manner. For example, an electronic engine-control system includes many controlled variables, actuators, and sensors; in fact, they are multi-input/multi-output (MIMO) control systems. The detailed analysis of these control problems can be carried out but is a complex process. Instead, the first stage of control-system analysis or design can be performed by neglecting the interactions among the various control tasks and treating each as an independent SISO control system. In a typical electronic engine-control system, the following SISO control systems can be identified (see Table 1.2):

Air–Fuel Ratio Control. The air–fuel ratio is the controlled variable and it is controlled by fuel injection at each cylinder. A mass airflow sensor is used and the fuel injector is the actuator. An optimal control is used to maintain the air–fuel mixture at *stoichiometry* (i.e., air–fuel ratio = 14.7); this reference is selected because in conjunction with a catalytic converter, it provides near-optimal performance in an engine. Thus, accurate air–fuel ratio control is important from the perspective of reducing emissions as well as other performance measures. Current systems use an EGO sensor for air–fuel ratio control.

EGR Control. The controlled variable is the EGR rate, the EGR control valve is the actuator, and the engine temperature and speed measurements are used to compute the proper EGR rate. EGR effectively reduces peak combustion temperature, thereby reducing emissions. The drawbacks of EGR include increased HC emission, deteriorated fuel economy, and combustion instability at idle or low engine speed and/or when an engine is cold. Typically, the EGR function may be turned off when an engine is cold or when a vehicle is accelerating or idling.

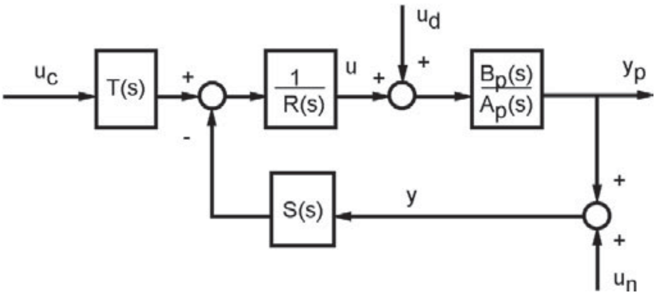

Figure 1.3. Control-system block diagram: Mathematical representation.

Spark-Timing Control. Spark timing is adjusted to affect engine-torque output. Moreover, the response is usually much faster than throttle-angle manipulations. It also is used to affect emission and fuel economy and to minimize engine knock. Because the “timing” is with respect to top dead center (TDC), the crank angle must be measured.

Electronic-Transmission Control. The hydraulic pressure and solenoid status can be controlled for fuel economy (i.e., shift-point control) and comfort (i.e., torque control during shifting). The shift point typically is regulated based on two measurements: vehicle speed and manifold absolute pressure (MAP), or throttle angle. The latter measurement is an indicator of engine load.

Idle-Speed Control. The purpose of the idle-speed control function is to maintain idle speed in the presence of load disturbance as well as to minimize speed for reduced fuel consumption and emission. An idle-speed controller typically measures the idle speed and adjusts the airflow rate using either the throttle or an idle-speed control valve.

Subsequent chapters describe in more detail not only these powertrain (i.e., engine and transmission) control functions but also vehicle-control functions such as cruise control, traction control, active suspensions, and 4WS. For design purposes, each function is treated as a stand-alone SISO control system. In fact, they are interacting MIMO systems, which must be accounted for when they are integrated in an automobile. In addition, they become the building blocks for even higher-level control functions, such as those described in Part IV, the ITS chapters.

Control Structures and Algorithms

Figure 1.3 is a typical mathematical representation of the physical elements shown in Figure 1.2. Note that the actuator, controlled system, and sensor blocks are combined into a process (or plant) transfer function:

$$G_p(s) = \frac{B_p(s)}{A_p(s)} \tag{1.1}$$

where s is the Laplace transform variable.