MECHATRONIC SYSTEMS
– INNOVATIVE PRODUCTS WITH EMBEDDED CONTROL –

Rolf Isermann

Institute of Automatic Control
Darmstadt University of Technology, Germany
risermann@iat.tu-darmstadt

Abstract: Many technical processes and products in the area of mechanical and electrical engineering are showing an increasing integration of mechanics with digital electronics and information processing. This integration is between the components (hardware) and the information-driven functions (software), resulting in integrated systems called mechatronic systems. Their development involves finding an optimal balance between the basic mechanical structure, sensor and actuator implementation, automatic information processing and overall control. Of major importance are the simultaneous design of mechanics and electronics, hardware and software and embedded control functions resulting in an integrated component or system. This technical progress has a very large influence on a multitude of products in the area of mechanical, electrical and electronic engineering and changes the design, for example, of conventional electromechanical components, machines, vehicles and precision mechanical devices with increasing intensity. This contribution summarizes ongoing developments for mechatronic systems, shows design approaches and examples of mechatronic products and considers various embedded control functions and system´s integrity. One field of ongoing developments, automotive mechatronics, is described in more detail by discussing mechatronic suspensions, mechatronic brakes, active steering and roll stabilization systems.

Keywords: mechatronics, component integration, embedded control, actuators, machines, automobiles, diagnosis, fault-tolerance, hardware-in-the-loop simulation, mechatronic suspensions, mechatronic brakes, active steering, roll-stabilization.

1. INTRODUCTION

Integrated mechanical electronic systems emerge from a suitable combination of mechanics, electronics and control/information processing. Thereby, these fields influence each other mutually. First, a shift of functions from mechanics to electronics is observed, followed by the addition of extended and new functions. Finally, systems are being developed with certain intelligent or autonomous functions. For these integrated mechanical electronic systems, the term “mechatronics” has been used for several years.

1.1 From mechanical to mechatronic systems

Mechanical systems generate certain motions or transfer forces or torques. For an oriented command of, e.g., displacements, velocities or forces, *feedforward* and *feedback control systems* have been applied for many decades. The control systems operate either without auxiliary energy (e.g., fly ball governor), or with electrical, hydraulic or pneumatic auxiliary energy, to manipulate the commanded variables directly or with a power amplifier. Figure 1 summarizes this development, beginning with the purely mechanical

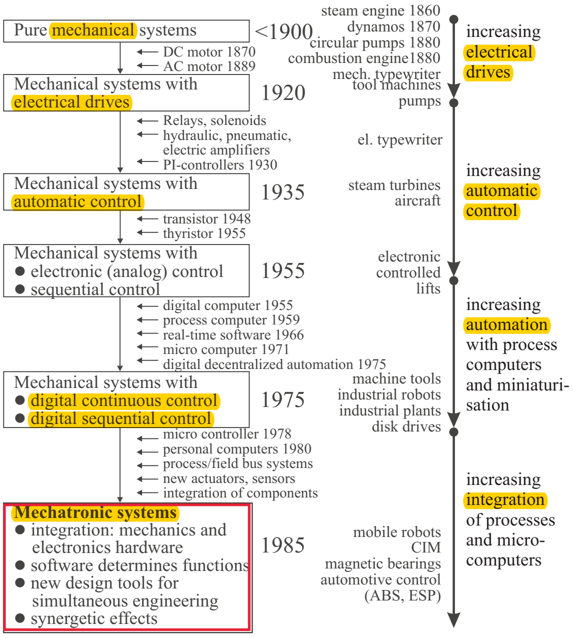

Fig. 1. Historical development of mechanical, electronic and mechatronic systems

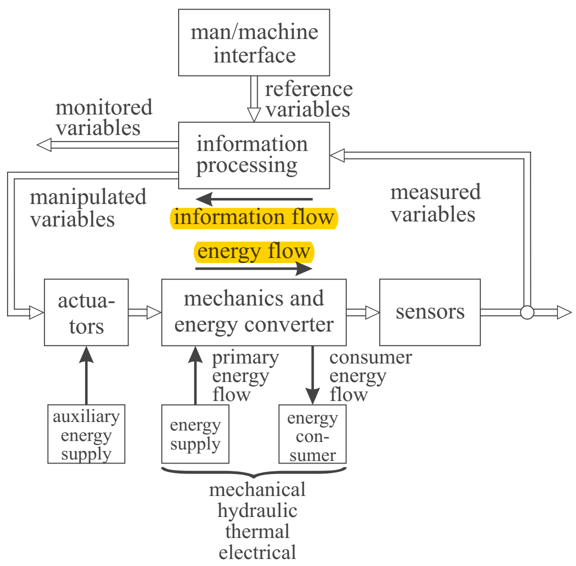

Fig. 2. Mechanical process and information processing develop towards a mechatronic system

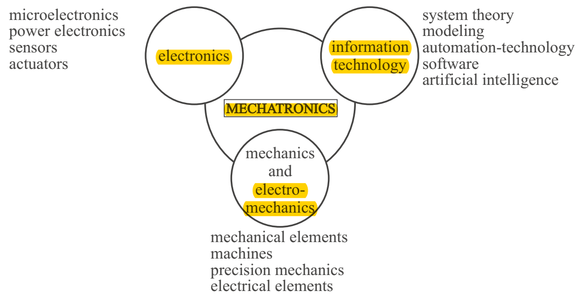

Fig. 3. Mechatronics: synergetic integration of different disciplines

systems of the nineteenth century to mechatronic systems in the 1980s.

Figure 2 shows the forward oriented energy flow of a mechanical energy converting systems (e.g., a motor) and the backward oriented information flow, which is typical for many mechatronic systems. Herewith, the digital electronic system acts on the process based on measurements or external command variables.

If the electronic and the mechanical systems are merged to an autonomous overall system, an integrated mechanical-electronic system results, called *mechatronic system* from conjoining MECHAnics and ElecTRONICS. The word "mechatronics" was probably first created by a Japanese engineer in 1969, (Kyura and Oho, 1996). Several definitions can be found in the literature, e.g., Mechatronics (1991), IEEE/ASME Transactions on Mechatronics (1996). The IFAC Technical Committee on Mechatronic Systems, founded in 2000, (IFAC-T.C 4.2., 2000), uses the following description: "Many technical processes and products in the area of mechanical and electrical engineering show an increasing integration of mechanics with electronics and information processing. This integration is between the components (hardware) and the information-driven function (software), resulting in integrated systems called *mechatronic systems*. Their development involves finding an optimal balance between the basic mechanical structure, sensor and actuator implementation, automatic digital information processing and overall control, and this synergy results in innovative solutions."

Hence, mechatronics is an interdisciplinary field, in which the following disciplines act together, Figure 3:

(1) *mechanical systems* (mechanical elements, machines, precision mechanics);
(2) *electronic systems* (microelectronics, power electronics, sensor and actuator technology);
(3) *information technology* (systems theory, control and automation, software engineering, artificial intelligence).

The solution of tasks for designing mechatronic systems is performed as well on the mechanical as on the digital-electronic side. Herewith, interrelations during the *design* play an important role; because the mechanical system influences the electronic system and *vice versa*, the electronic system has influence on the design of the mechanical system. This means that *simultaneous engineering* has to take place, with the goal of designing an overall integrated system ("organic system") and also creating synergetic effects.

A further feature of mechatronic systems is the *integrated digital information processing*. Except for basic control functions, more sophisticated control functions may be realized, e.g., the calculation of non-measurable variables, the adaptation of controller parameters, the detection and diagnosis of faults and, in the case of failures, a reconfiguration to redundant components. Hence, mechatronic systems are evolv-

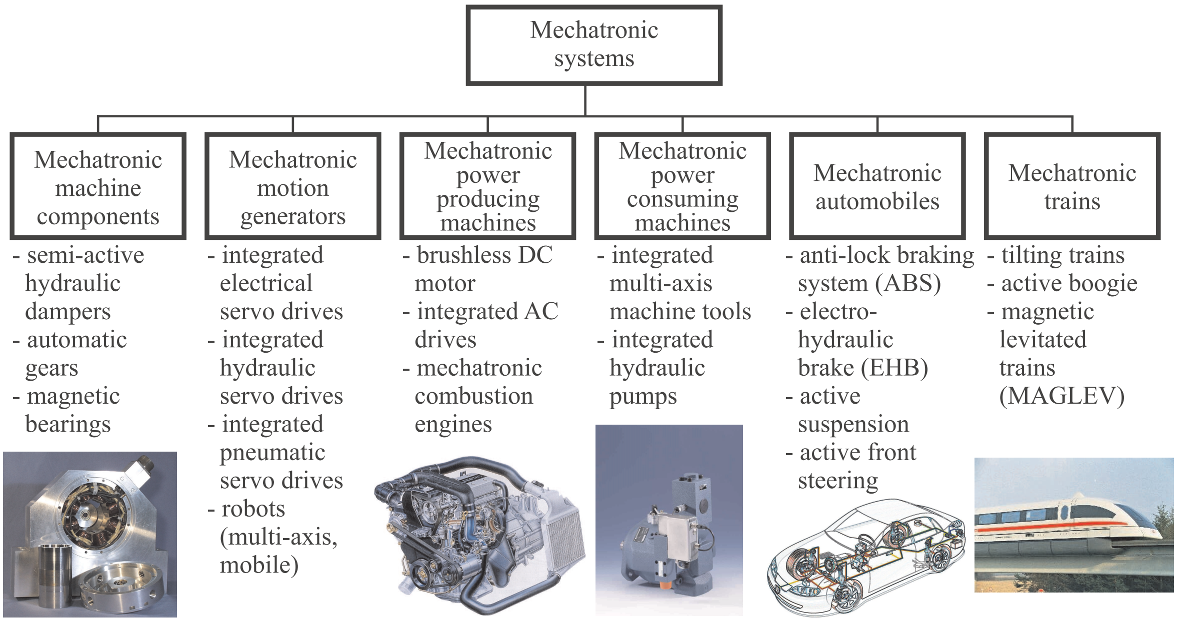

Fig. 4. Examples for mechatronic systems (macro-mechatronics)

ing with adaptive or even learning behavior which can also be called *intelligent mechatronic systems.*

The developments up until now can be followed in (Schweitzer, 1992), (Gausemeier *et al.*, 1995), (Harashima and Tomizuka, 1996), (Isermann, 1996), (Tomizuka, 2000), (VDI 2206, 2004). An insight into general aspects are given editorially in the journals (Mechatronics, 1991), (IEEE/ASME, 1996), the conference proceedings of, e.g., (UK Mechatronics Forum, 1990, 1992, 1994, 1996, 1998, 2000, 2002), (IMES, 1993), (DUIS, 1993), (ICRAM, 1995), (AIM, 1999, 2001, 2003), (IFAC, 2000, 2002, 2004), the journal articles by (Hiller, 1995), (Lückel, 1995), and the books of (Kitaura, 1986), (Bradley *et al.*, 1991), (McConaill *et al.*, 1991), (Heimann *et al.*, 2001), (Isermann, 2003), (Bishop, 2002).

Mechanical systems can be dedicated to a large area of mechanical engineering. According to their construction, they can be subdivided into mechanical *components*, *machines*, *vehicles*, *precision mechanical devices* and *micromechanical components*. Figure 4 shows some examples of mechatronic components, machinery and vehicles. Examples for *precision mechatronic devices* are gyros, laser and ink jet printers, hard disk drives. Mechatronic products in the field of *microelectromechanical systems* (MEMS) are piezoelectric acceleration sensors, micro actuators and micropumps.

1.2 Functions of mechatronic systems

1.2.1. Distribution of mechanical and electronic functions. Mechatronic systems permit many improved and new functions. In the design of mechatronic systems, the *interplay for the realization of functions* in the mechanical and electronic part is crucial. Some examples are:

- *decentralized electrical drives* with microcomputer-control (multi-axis systems, automatic gears);
- *lightweight constructions*: damping by electronic feedback (drive-trains of vehicles, elastic robots, space constructions);
- *linear overall behavior* of nonlinear mechanics by proper feedback (hydraulic and pneumatic actuators, valves);
- *operator adaptation* through programmable characteristics (accelerator pedal, manipulators).

1.2.2. Operating properties. Process behavior adapted feedback control enables for example:

- *increase of mechanical precision* by feedback;
- *adaptive friction compensation*;
- *model-based and adaptive control* to allow wide-range operation (flow-, force-, speed-control, engines, vehicles, aircraft);
- *high control performance* due to closer set-points to constraints (engines, turbines, paper machines).

1.2.3. New functions. Mechatronic systems make functions possible that could not be performed without (embedded) digital computers, like:

- *control of nonmeasurable variables* (tire slip, internal tensions or temperatures, slip angle and ground speed of vehicles, damping parameters);
- *advanced supervision and fault diagnosis*;
- *fault-tolerant systems* with hardware and analytical redundancy;
- *teleservice functions* for monitoring, maintenance, repair;

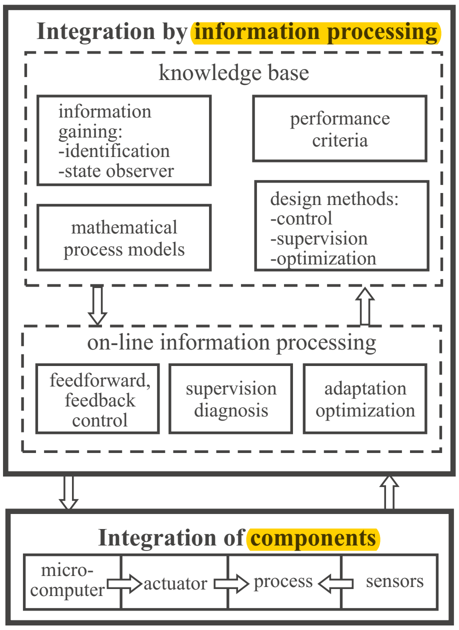

Fig. 5. Integration of mechatronic systems: integration of components (hardware integration); integration by information processing (software integration)

- *flexible adaptation* to changing boundary conditions;
- *programmable functions* allow changes during design, commissioning and after-sales, and shorter time-to-market.

1.3 Integration forms

With increasing improvements of the miniaturization, robustness and computing power of microelectronic components, one can try to put more weight on the electronic side and to design the mechanical part from the beginning with a view to a *mechatronic overall system*. Then, more autonomous systems can be envisaged, e.g., in the form of capsular units with wireless signal transfer or bus connections and robust microelectronics. The integration within a mechatronic system can be performed mainly in two ways, through the integration of components and through integration by information processing.

The *integration of components* (*hardware integration*) results from designing the mechatronic system as an overall system and embedding the sensors, actuators and microcomputers into the mechanical process, see Figure 5. This spatial integration may be limited to the process and sensor or the process and actuator. The microcomputers can be integrated with the actuator, the process or sensor, or be arranged at several places. Integrated sensors and microcomputers lead to *smart sensors* and integrated actuators and microcomputers develop into *smart actuators*. For larger systems, bus connections will replace the many cables.

Integration by information processing (*software integration*) is mostly based on advanced control functions. Besides a basic feedforward and feedback control, an additional influence may take place through the process knowledge and corresponding on-line information processing in higher levels, see Figure 5. This includes the solution of tasks like supervision with fault diagnosis, optimization and general process management. The respective problem solutions result in an *on-line information processing*, especially by real-time algorithms, which must be adapted to the mechanical process properties, e.g., expressed by mathematical models. Therefore, a *knowledge base* is required, comprising methods for design and information gain, process models and performance criteria. In this way, the mechanical parts are governed in various ways through higher level information processing with intelligent properties, possibly including learning, thus forming an *integration by process adapted software*.

2. DESIGN PROCEDURE

The design of mechatronic systems requires a systematic development and use of modern software design tools. As with any design, mechatronic design is also an iterative procedure. However, it is much more involved than for pure mechanical or electrical systems. In addition to the traditional domain specific engineering (mechanical, electrical/electronic, automation, user interface) an integrated, simultaneous (concurrent) engineering is required. It is the *integration of engineering across traditional boundaries* that is typical for the development of mechatronic systems.

A representation of important design steps, which distinguishes especially between the *mechatronic system design* and *system integration* is depicted in Figure 6. This scheme is represented in form of a "V"-model, which originates probably from software development, (STARTS GUIDE, 1989), (Bröhl, 1995), see also (VDI 2206, 2004).

Within this V-model-development scheme only some examples for specific mechatronic issues are considered here. The *system design* includes the task distribution between mechanical, hydraulic, pneumatic, electrical and electronic components, the used auxiliary power, the type and placement of sensors and actuators, the electronic architecture, the software architecture, the control engineering design and the creation of synergies. Because of the many varieties of designs the advance *modelling* and *simulation* plays an important role, also to save the number of realized prototypes. Therefore, theoretical/physical modelling of the heterogeneous components is required, using general modelling principles. For this purpose object-oriented software tools like DYMOLA, MODELICA, MOBILE, VHDL-AMS, 20 SIM are especially suitable, see (Otter and Cellier, 1996), (Elmqvist, 1993),

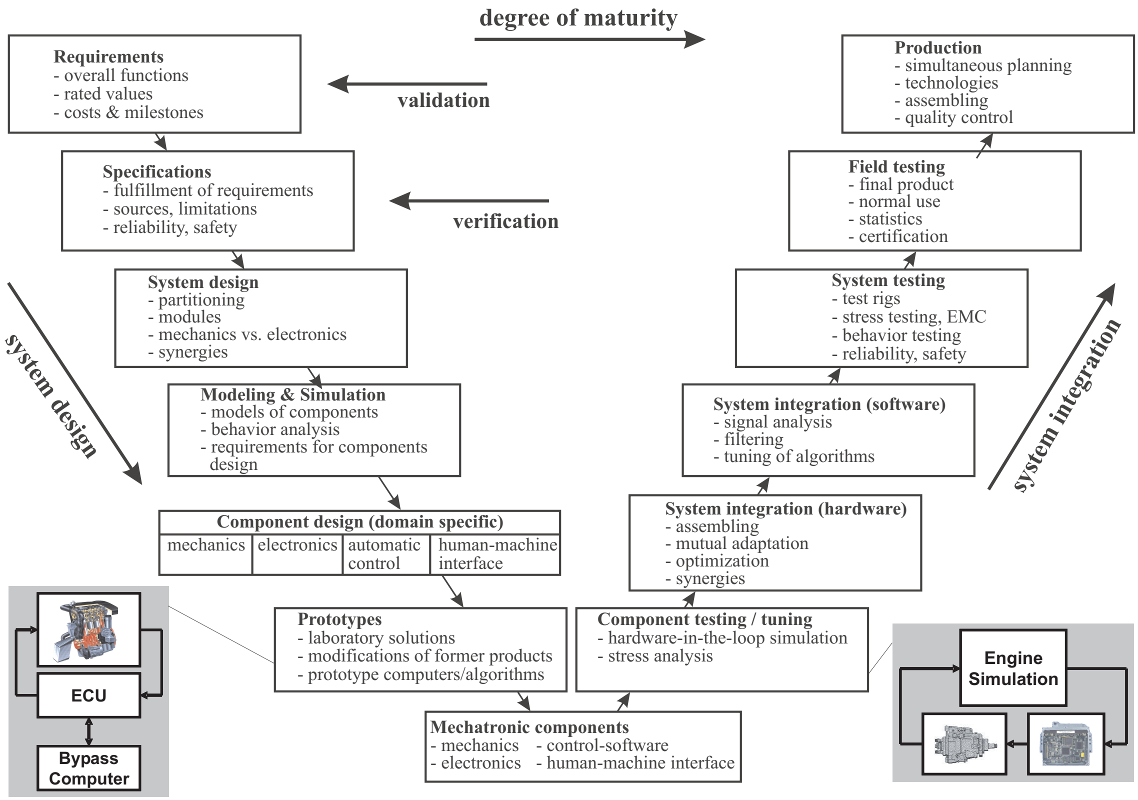

Fig. 6. “V” development scheme for mechatronic systems

(Hiller, 1995), (van Amerongen, 2004), together with simulation tools like MATLAB/SIMULINK.

In this stage of development, use is made of *software-in-the-loop simulation* (SiL), i.e., components and control algorithms are simulated on an arbitrary computer without real-time requirements to obtain, e.g., design specifications, dynamic requirements and performance measures. The *component design* is domain specific and uses general CASE-tools, like CAD/CAE for mechanics, CFD-tools for fluidics, circuit board layout-tools (PADS), microelectronic design tools (VHDL) and CADCS-tools for automatic control design. Also the reliability and safety is considered, see Section 4. Then prototypes are build as laboratory solutions. The system integration begins with first steps to combine the different components. Because of the different development status of the components during the simultaneous design, minimization of iterative development cycles and meeting of short time-to-market schedules, frequently use is made of different kind of *real-time simulations*, Figure 7 and (VDI 2206, 2004).

A first case is the *rapid control prototyping* (RCP) where the real process is operated together with the *simulated control* by a high-speed hardware and software other than the final electronic control unit (ECU) (either full-passing or partially by-passing the ECU with special software functions on the RCP-computer). A second case is the *hardware-in-the-loop simulation* (HiL), where the real-time simulated process runs with the real ECU hardware and also actuator hardware. This is an especially demanding task, because the real-time process simulation must be rather precise and the sensor outputs signals have to be realized with special interface circuits. Advantages of HiL are, e.g., testing in laboratory environment, testing under extreme operating conditions and with faults, reproductive experiments, design of human-machine interface. The *system integration* comprises the spatial integration of the *hardware components* by embedding the sensors, actuators, cables and buses on or into the mechanics and creation of synergetic effects and the functional integration by the *software* with all algorithms from control through adaptation to supervision, fault diagnosis, fault tolerance and human/machine operation.

3. AUTOMATIC CONTROL OF MECHATRONIC SYSTEMS

3.1 Control design

The applied feedforward and feedback control algorithms depend on the individual properties of the electrical, mechanical, hydraulic, pneumatic and also thermal processes. They can be brought into a general knowledge-based multi-level control structure as shown in Figure 8. The knowledge base consists of mathematical process models, identification and parameter estimation algorithms, controller design methods and control performance criteria. The feedback control can be organized into lower level and higher level controllers, a reference value generation module

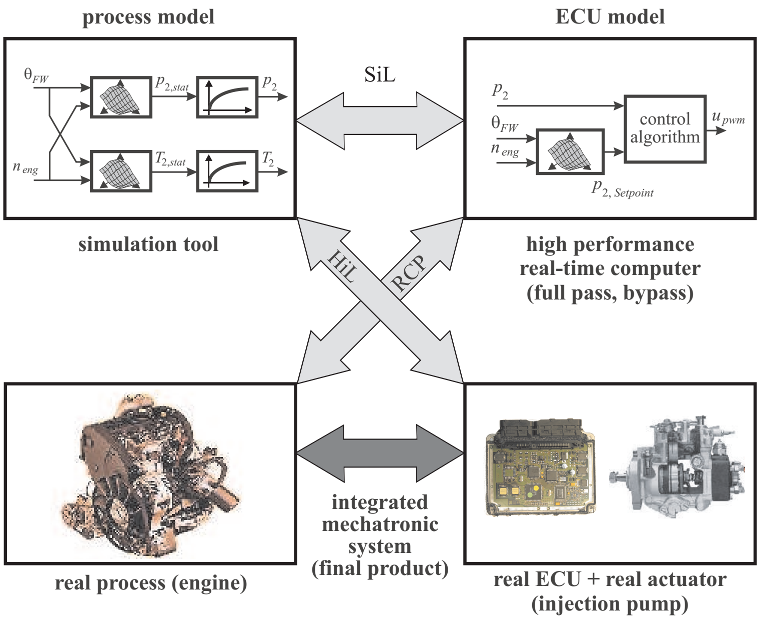

Fig. 7. Various kinds of combining real and simulated parts for development: SiL: Software-in-the-loop; RCP: rapid control prototyping; HiL: Hardware-in-the-loop

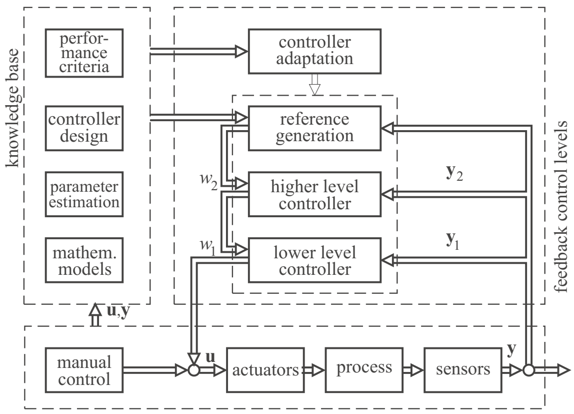

Fig. 8. Knowledge-based multi-level feedback control for mechatronic systems

and controller parameter adaptation. Because of the large variety of possibilities, only some control principles will be considered briefly. More methods are, for example, presented in (Spong and Vidyasagar, 1989), (Morari and Zafirov, 1989), (Åström and Wittenmark, 1997), (Isidori, 1999), (Dorf and Bishop, 2001) and (Goodwin *et al.*, 2001).

Some basic design requirements are limited computations because of real-time constraints, nonlinearity of the processes, limited actuator speed and range, robustness, transparency of solutions, maintainability, etc. Of major importance is the *simultaneous design* of the *mechatronic process* and the *control*. This means that the static and dynamic behavior of the process, the type and placement of the actuators, the type and position of the sensors are designed appropriately, resulting in an “control dynamic friendly” overall behavior. (A very important item for any control design.)

The goal of the *lower level feedback* is to provide a certain dynamic behavior (e.g., enforcement of damping), to compensate nonlinearities like friction, to reduce parameter sensitivity and to stabilize. Some typical examples are:

Damping of high-frequency oscillations: weakly damped oscillations appear, e.g., in multi-mass drivetrains or pneumatic and hydraulic actuators. The damping can generally be improved by high-pass filtering the outputs and using a state variable or PD (proportional-derivative) feedback.

Compensation of nonlinear static characteristics: nonlinear static characteristics are present in many subsystems of mechanical processes. Figure 9 shows a typical example, the often required position control for a nonlinear actuator. Frequently, a first nonlinearity appears in the force- or torque-generating part like an electromagnet or a pneumatic or hydraulic actuator where, e.g., the force $F_D = f(U)$ follows a nonlinear static characteristic. This nonlinearity can now be compensated by an inverse characteristic $U = f^{-1}(U')$ such that the I/O behavior $F_D = f(U')$ becomes approximately linear and a linear (PID-type) controller G_{c1} can be applied.

Friction compensation: for many mechanical systems, the overall friction can be described approximately by

$$F_{F\pm}(t) = f_{FC\pm}\,\mathrm{sign}\,\dot{Y}(t) + f_{Fv\pm}\,\dot{Y}(t) \quad |\dot{Y}(t)| > 0 \tag{1}$$

where f_{FC} is the Coulomb friction and $f_{F\nu}$ the linear viscous friction coefficient which may be dependent on the motion direction, indicated by $+$ or $-$. The Coulomb friction has a strong negative effect on the control performance. Different methods such as compensating the relay function, see Figure 9, dithering, feedforward compensation and adaptive friction compensation are alternatives, see, e.g., (Isermann and

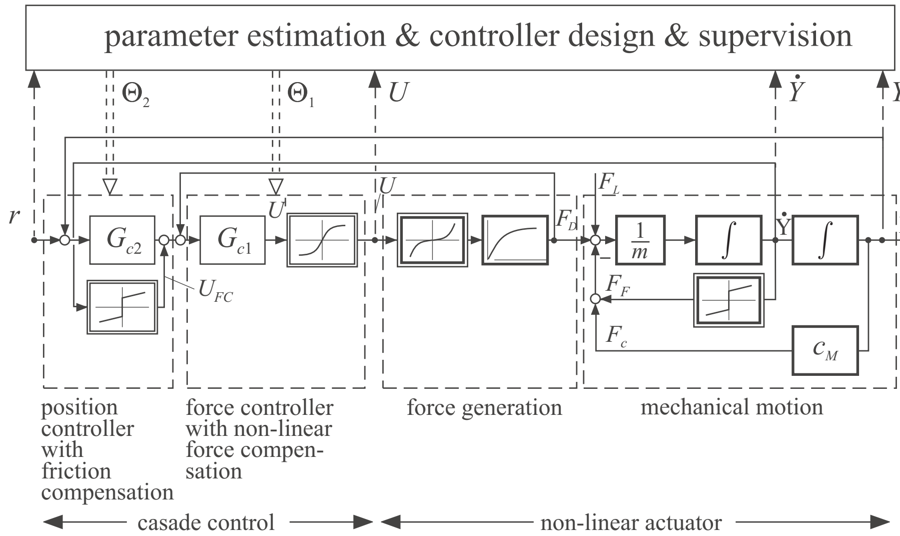

Fig. 9. Adaptive position control of a nonlinear electromechanical, hydraulic or pneumatic actuator (example)

Raab, 1993), (Tomizuka, 1995) and (Canudas de Wit *et al.*, 1995).

An alternative for position control of nonlinear actuators is the use of a *sliding mode controller*. It consists of a nominal part for feedback linearization and an additional feedback to compensate for model uncertainties, (Utkin, 1977), (Slotine and Weiping, 1991). The resulting chattering by the included switching function hereby generates a dither signal. A comparison with a fixed PID-controller with friction compensation shows (Pfeufer *et al.*, 1995).

Stabilization: unstable mechatronic systems like magnetic bearings, magnetic levitated trains or skidding automobiles have to be stabilized in the lower control level by appropriate feedback laws. The stabilization feedback usually includes derivative terms and in the case of magnetic actuators compensating terms for the nonlinearities.

Switching actuator control: low-cost actuators in the form of solenoids or pneumatic membrane-types are usually manipulated by pulse-width-modulated input signals of higher frequency allowing approximately linear behavior for control of their position or fluid pressure in the lower frequency band.

The control scheme of the lower level control may be expanded by additional feedback controllers from a load or working process that is coupled with the mechanical process, resulting in a multiple-cascaded control system. A prerequisite for the application of advanced control algorithms is the use of well-adapted process models. This may lead to self-tuning or *adaptive control systems*.

The task of the *higher level controller* is to generate a good overall dynamic behavior with regard to changes of the position reference $r(t)$ and to compensate for external disturbances stemming, e.g., from load variations. This high-level controller may be realized as a parameter optimized controller of PID-type or internal model controller or a state controller with or without state observer.

Parameter scheduling: parameter (or gain) scheduling based on the measurement of, e.g., load-dependent variables is an effective method to deal with known varying process behavior.

Parameter-adaptive control systems: parameter-adaptive control systems are characterized by using identification methods for parametric process models. This is indicated in the adaptation level of Figures 8 and 9. Parameter estimation has proven to be an appropriate basis for the adaptive control of mechanical processes, including the adaptation to nonlinear characteristics, Coulomb friction, and the unknown parameters like masses, stiffness, damping, see (Isermann and Raab, 1993), (Isermann *et al.*, 1992), (Åström and Wittenmark, 1997).

If no appropriate sensors to measure the controlled variable are available *feedforward control* has to be used. Feedforward controls may be realized as simple proportional or proportional-derivative algorithms, as static nonlinear characteristics $u = f(y)$ or as nonlinear *look-up tables/maps* $\mathbf{u} = \mathbf{f}(\mathbf{y})$. The last case holds, e.g., for the control of internal combustion engines where low-cost sensors for torque and emissions are not available and stability problems have to be avoided under all circumstances.

A considerable part of the automation of mechatronic systems is performed by *sequential control*, e.g., for processes with repetitive operation (machine-tools, printing machines), start-up and shut-down (engines) or automatic gears. Hence, mechatronic systems make use of a large variety of different control methods, ranging from simple proportional or on-off controllers to internal model and adaptive nonlinear controllers. Because the process model structure is mostly known, structure optimized controllers can be realized. The process model order is usually not large, but nonlin-

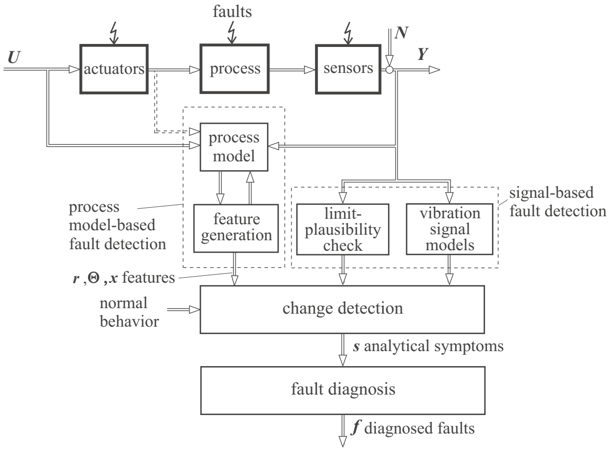

Fig. 10. Scheme for model-based fault detection

earities and especially the actuator behavior has to be taken into the design. A big advantage is that the process and its control is delivered from one manufacturer, such that optimal controllers can be implemented and maintained, however, subject to considerable real-time constraints. A detailed description can be given only for concrete processes, actuation principles and measurement configurations.

3.2 *Supervision and fault diagnosis*

As the right functioning of mechatronic systems depends not only on the process itself, but also on the electronic and electrical sensors, actuators, cables, plugs and electronic control units, an *automatic supervision* (health monitoring) and if possible, *fault detection* and *diagnosis* plays an increasingly important role, especially with regard to high reliability and safety requirements.

Figure 10 shows a process influenced by faults. These faults indicate unpermitted deviations from normal states and are generated either externally or internally. External faults are, e.g., caused by the power supply, contamination or collision, internal faults by wear, missing lubrication, actuator or sensor faults. The classical methods for fault detection are the *limit value checking* or *plausibility checks* of a few measurable variables. However, incipient and intermittent faults usually cannot be detected and an in-depth fault diagnosis is not possible with this simple approach. Therefore, *signal- and process-model-based fault detection* and diagnosis methods have been developed in recent years, allowing early detection of small faults with normally measured signals, also in closed loops, (Isermann, 1997), (Gertler, 1998), (Chen and Patton, 1999). Based on measured input signals $U(t)$, output signals $Y(t)$ and process models, features are generated by, e.g., *vibration analysis*, *parameter estimation*, *state* and *output observers* and *parity equations*, Figure 10.

These features are then compared with the features for normal behavior, and with change detection methods, analytical symptoms are obtained. Then, a *fault diagnosis* is performed via methods of *classification* or *reasoning*.

A considerable advantage is that the same process model can be used for both the (adaptive) controller design and the fault detection. In general, continuous time models are preferred if fault detection is based on parameter estimation or parity equations. However, discrete time models can also be used. Advanced supervision and fault diagnosis is a basis for improving reliability and safety, state-dependent maintenance and triggering of redundancies and reconfiguration for fault-tolerant systems, (Isermann, 2005).

4. RELIABILITY, SAFETY, FAULT TOLERANCE

Compared to pure mechanic, hydraulic or pneumatic systems, mechatronic systems replace very reliable mechanical parts by less reliable electrical, and electronic components and software. Therefore, the design must be paralleled by *reliability analysis procedures* like event tree analysis (ETA), fault-tree analysis (FTA) and failure mode and effect analysis (FMEA), (IEC 60812, 1985), (IEC 61508, 1997), (Storey, 1996), (Onodera, 1997). By using probability measures like failure rates or MTTF (mean-time-to-failure) it is tried to find weak spots of the design in early and later stages of development.

For safety-related systems a *hazard-analysis* with risk classification has to be performed, e.g., by stating quantitative risk measures based on the probability and consequences of dangers and accidents. Safety integrity levels (SiL) are introduced for different kinds of processes, like stationary machinery, automobiles, aircraft etc. After applying reliability and safety analysis methods during design and testing and quality control during manufacturing the development of certain faults and failures still cannot be avoided totally. Therefore, especially high-integrity systems require *fault-tolerance*. This means that faults are compensated such that they do not lead to system failures.

Fault-tolerance methods generally use redundancy. This means that in addition to the considered module, one or more modules are connected, usually in parallel. These redundant modules are either identical or diverse. Such redundant schemes can be designed for hardware, software, information processing, and mechanical and electrical components like sensors, actuators, microcomputers, buses, power supplies, etc. There exist mainly two basic approaches for fault-tolerance, static redundancy and dynamic redundancy, see Figure 11. Fault tolerance with dynamic redundancy and cold standby is especially attractive for mechatronic systems where more measured signals and embedded computers are already available and therefore fault detection can be improved considerably by applying process model-based approaches. Following *steps of degradation* are distinguished:

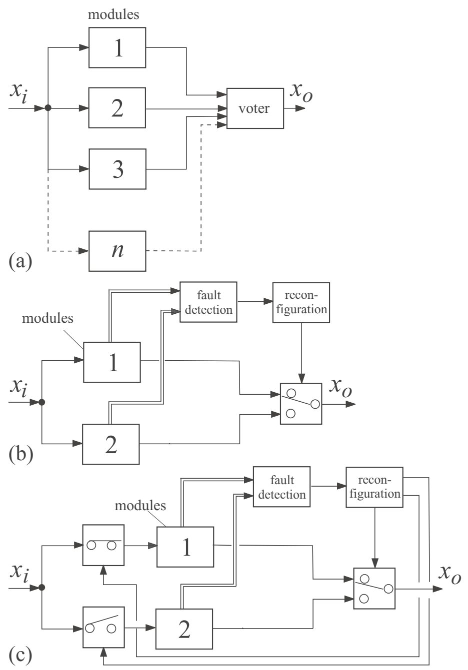

Fig. 11. Fault-tolerant schemes for electronic hardware: (a) static redundancy: multiple-redundant modules with majority voting and fault masking, *m* out of *n* systems (all modules are active); (b) dynamic redundancy: standby module that is continuously active, "hot standby"; (c) dynamic redundancy: standby module that is inactive, "cold standby"

- *fail-operational* (FO): one failure is tolerated, i.e., the component stays operational after one failure. This is required if no safe state exists immediately after the component fails;
- *fail-safe* (FS): after one (or several) failure(s), the component directly possesses a safe state (passive fail-safe, without external power) or is brought to a safe state by a special action (active fail-safe, with external power);
- *fail-silent* (FSIL): after one (or several) failure(s), the component is quiet externally, i.e., stays passive by switching off and therefore does not influence other components in a wrong way.

Generally, a graceful degradation is envisaged, where less critical functions are dropped to maintain the more critical functions available, using priorities, (IEC 61508, 1997).

For mechatronic systems fault-tolerant sensors, microcomputers and actuators are of interest. Especially attractive are sensors with model-based *analytical redundancy* and fault-tolerant actuators, where only the parts with lower reliability are redundant, like in hydraulic aircraft spool-valves or the potentiometer of electrical throttles for SI engines, see, e.g., (Isermann, 2000).

5. AUTOMOTIVE MECHATRONICS

Mechatronic products are especially advanced in the field of *automobiles*. Figure 12 gives a survey of presently realized mechatronic components and systems. The first mechatronic products for vehicles have been antilock-braking (ABS, 1979) and automatic traction control (ATC, ASR, 1986) and the last ones active body control (ABC, 1999), active front steering (AFS, 2003) and active anti roll bars (DDC, 2003). Mechatronic components for *engines* and *transmissions* began about the same time by electronic fuel injection (analog: 1967, digital: 1979), electrical throttle (1979) and automatic electronically controlled hydrodynamic transmissions (about 1983). Recent mechatronic components are common rail injection for Diesel engines (1997), direct injection for gasoline engines (2000), variable lift valve trains (VVT, 2001).

The value of electronics, electrics and mechatronics of today´s cars is about 20-25% of the total price, with a tendency towards 30-35% in 2010. A higher class passenger car contains about 2.5 km of cables, 40 sensors, 100-150 electromotors, 4 bus systems with 2500 signals and 45-75 microelectronic control units. According to manufacturers statements about 90% of all innovations for automobiles are due to electronics and mechatronics. Recent surveys on automotive mechatronics are (Schöner, 2004) and (Dieterle, 2004). Various control functions for automobiles are described in (Kiencke and Nielsen, 2000), (Johansson and Rantzer, 2003) and for engines in (Guzella and Onder, 2004). For a survey on mechatronic developments for trains see (Goodall, 1995).

In the following some examples of mechatronic developments for vehicles are shown with an emphasis on automatic control functions.

5.1 Mechatronic suspensions

The vehicle suspension system is responsible for driving comfort and safety as the suspension carries the vehicle-body and transmits all forces between body and road. In order to positively influence these properties, semi-active or/and active components are introduced, which enable the suspension system to adapt to various driving conditions.

The acceleration of the body $\ddot{z}_B$ is a quantity for the *comfort* of the passengers and the dynamic tire load variation F_{zdyn} is a measure for *safety*, as it indicates the applicable forces between the tire and the road. With fixed parameter suspensions usually a compromise is made within the $\ddot{z}_B F_{zdyn}$) relation.

Semi-active suspensions allow to adapt the damping characteristic of a shock absorber to varying load and suspension deflection by, e.g., an active throttle-valve, Figure 13a, (Bußhardt and Isermann, 1993). New possibilities emerge with electro-rheological fluids.

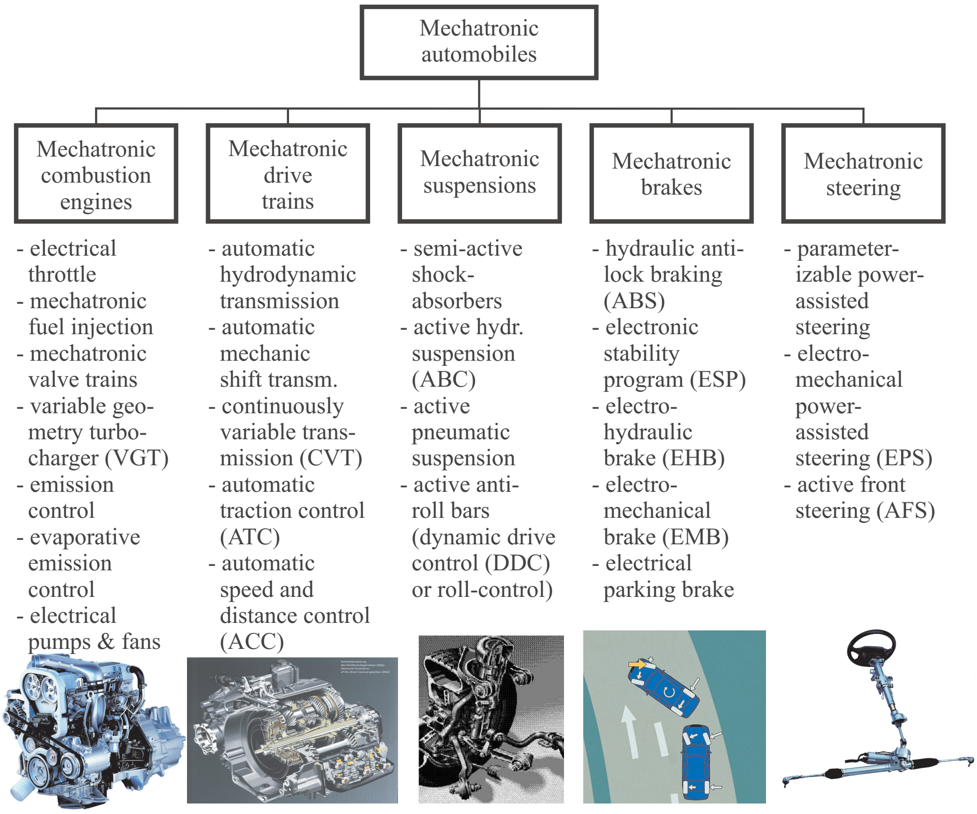

Fig. 12. Survey of mechatronic components and systems for automobiles and engines

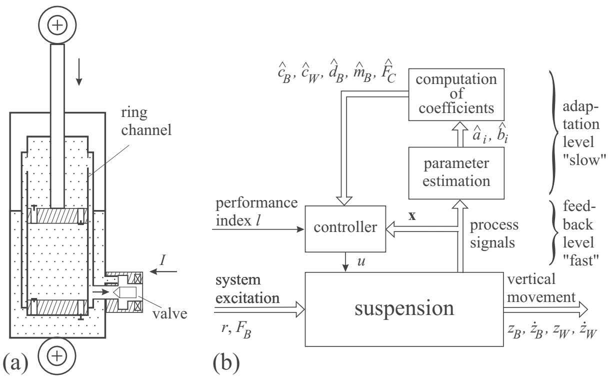

Fig. 13. Semi-active shock absorber (a) and its control (b)

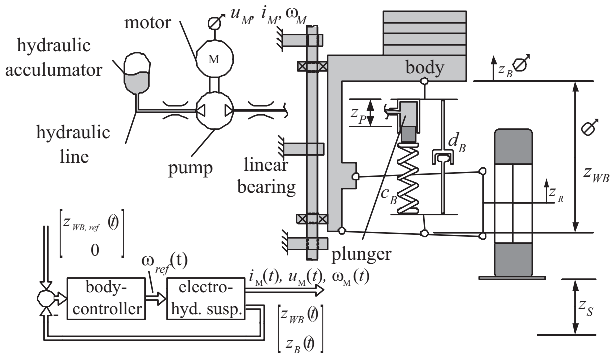

Fig. 14. Active hydraulic suspension system (ABC, Mercedes CL and S-class), measured signals

Active suspensions provide an extra force input in addition to existing passive springs. They may be realized as hydraulic, hydro pneumatic or pneumatic systems. The required energy is for passenger cars and an operating range between 0 to 5 Hz about 1-2 kW and between 0-12 Hz about 2-7 kW. Figure 14 shows as one example a hydraulic active suspension with a hydraulic piston in series with the steel spring, (Merker *et al.*, 2001). This concept is designed to reduce low frequent body motions ($f < 2\,\text{Hz}$), due to rolling and pitching and to reduce higher frequent road excitations ($f < 6\,\text{Hz}$). It is controlled by a state-feedback controller with measurement of deflection z_{BW} between body and wheel and body acceleration $\ddot{z}_B$. A recent survey on mechatronic suspensions is given by (Fischer and Isermann, 2004) and a model-based fault detection of an active suspension by (Fischer *et al.*, 2004).

5.2 Mechatronic brake systems

The conventional hydraulic brake systems with two independent, redundant hydraulic circuits are the standard solution for passenger cars. However, due to driver assisting functions like ABS and ESP they become more complex. In order to increase the functionality further, to safe space and assembling costs and to increase the passive safety, two types of mechatronic brake-by-wire systems were developed, the electrohydraulic brake (EHB), since 2001 in series production (Mercedes SL and E-class), and the electromechanical

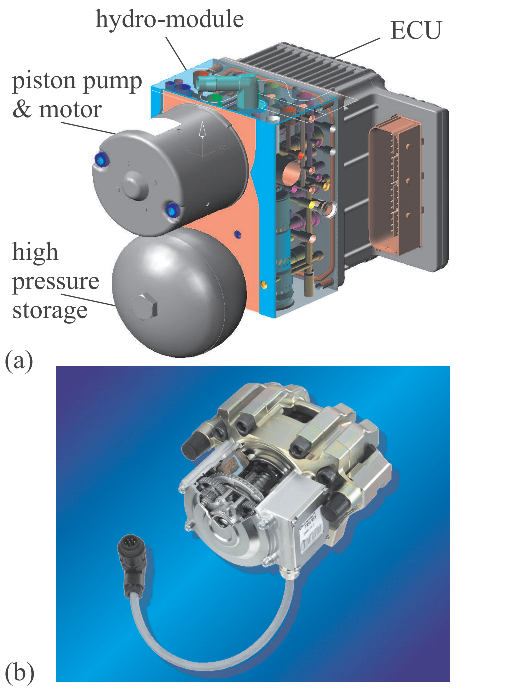

Fig. 15. Illustration of brake-by-wire-systems: (a) Electrohydraulic brake control (EHB), Bosch; (b) Electromechanical brake (EMB), Continental Teves

brake (EMB), for which prototypes exist, see Figure 15.

Figure 16 shows the different stages for *brake systems* of passenger cars or light weight trucks. In the case of the *conventional hydraulic brake*, the mechanical linkage between the pedal and the hydraulic main cylinder is paralleled by the power supporting pneumatic actuator (booster). If the pneumatic actuator fails, the mechanical linkage transfers the (larger) pedal force from the driver. The hydraulic cylinder acts on two independent hydraulic circuits in parallel. That means the brake system is fault-tolerant with regard to a failure of one of the two hydraulic circuits. Failures in the electronics of brake control systems as ABS bring the hydraulic actuators (e.g., magnetic valves) into a fail-safe status such that the hydraulic brake gets the pressure from the hydraulic main cylinder directly. The ABS functions are realized by switching valves, which have three positions for lowering, holding or increasing the fluid pressure and thus allow only a discrete actuation of the brake torque, with strong oscillations.

A first step towards brake-by-wire is the *electrohydraulic brake* (EHB), Figures 16a) and 15a), where the mechanical pedal has sensors for position and hydraulic pressure, (Jonner *et al.*, 1996), (Stoll, 2001). Their signals are transferred to separated hydraulic pressure loops with proportional magnetic valves, manipulating hydraulic liquid flows from a 160 bar storage/pump system to the wheel brakes. If the electronics fail the separation of the pedal to the wheel brakes

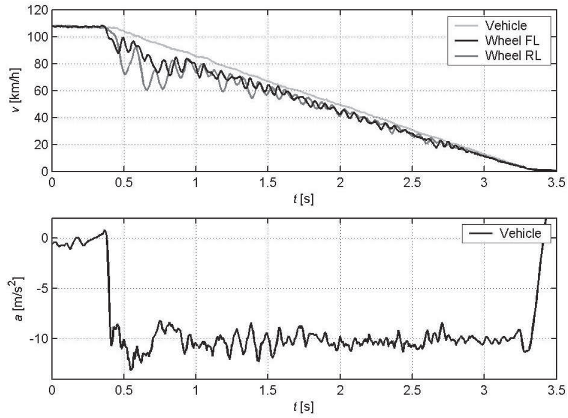

Fig. 18. Braking with model-based ABS- (anti-lock-braking system) functions, measured on dry asphalt. Continuous nonlinear, adaptive slip control with EHB (electrohydraulic brake) generates maximal brake froces (FL, RL: front, rear left)

is released. Hence, a hydraulic back-up serves to fail safe as for conventional hydraulic brakes.

The *electromechanical brake* (EMB) according to Figures 16b) and 15b) does not contain hydraulics anymore. The pedal possesses sensors and its signals are sent to a central brake control computer and wheel brake controllers which both act through power electronics to the electromotors of, e.g., disc brakes. Because no mechanical or hydraulic connection does exist a mechanical or hydraulic fail-safe is not possible. Hence, the complete electrical path must be build with fault tolerance, see the architecture in Figure 17. Both, the EHB and EMB, have many advantages with regard to *control functions*. One important property is the ability to continuously manipulate the brake torque during ABS actions. Figure 18 shows an example for full braking with ABS functions based on continuous, proportional acting slip controlled EHB-brakes, (Semmler *et al.*, 2002). The applied controller is a feedback linearized nonlinear controller which optimizes the slip to result in maximal braking forces. Except EHB, the further introduction of brake-by-wire, like EMB, is not decided yet.

However, presently the introduction of complete brake-by-wire and steer-by-wire systems is undecided, because many functions can also be realized with electromechanical and electrohydraulic systems, too high costs and missing 42 V-electrical system.

5.3 *Mechatronic steering systems*

Hydraulic assisted power steering goes back until around 1945. This classical steering was continuously improved, especially in adapting the required force or torque support to the speed. Later developments realized this reducing support with increasing speed by electronically controlled electromagnetic by-pass valves, also called “parameterizable steering”. Figure

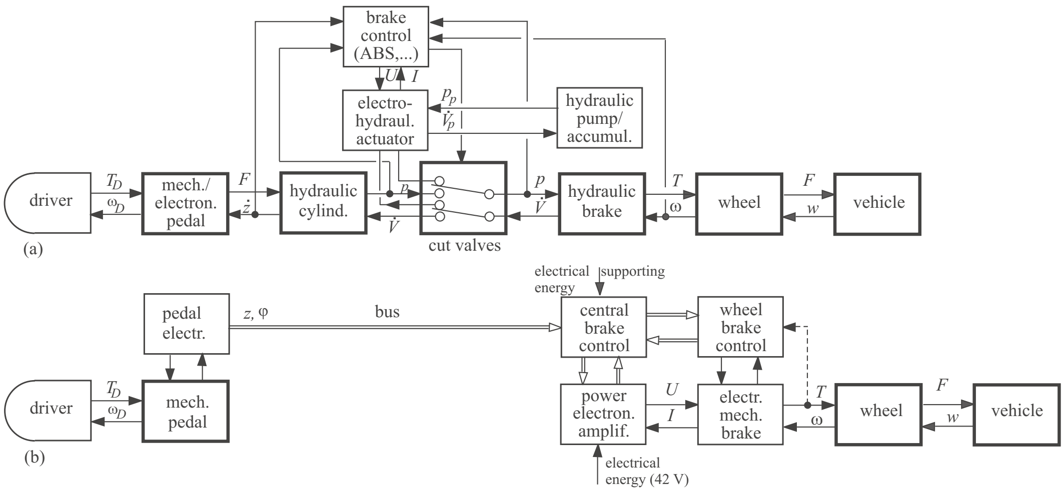

Fig. 16. Signal flow diagram for different mechatronic brake systems of passenger cars: (a) Electrohydraulic brake (EHB) with hydraulic brake; (b) Electromechanical brake (EMB) without mechanical backup

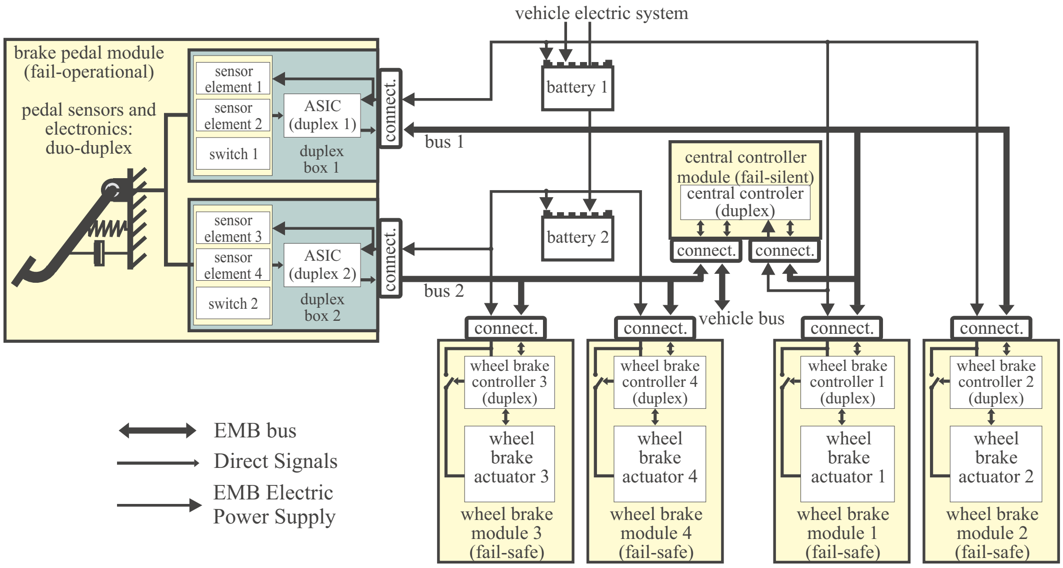

Fig. 17. Fault-tolerant electromechanical brake (EMB) system architecture (prototype)

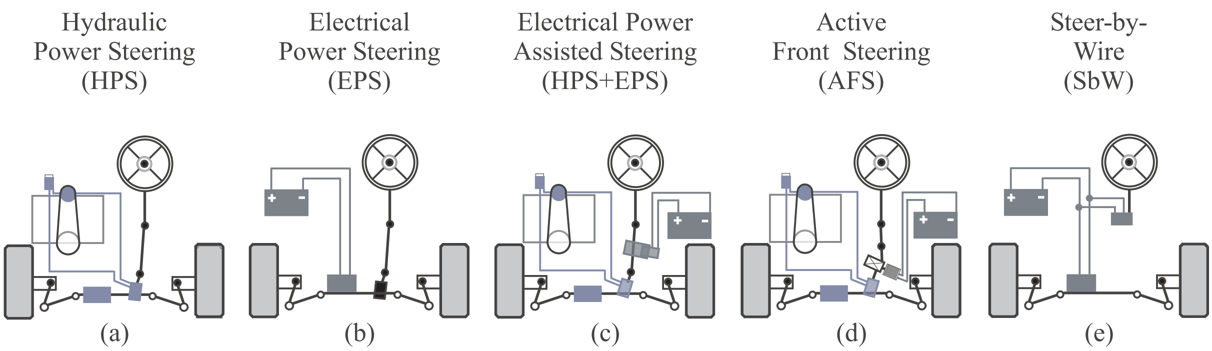

Fig. 19. Mechatronic steering systems: (a) conventional hydraulic power steering (HPS) (since about 1945); (b) electrical power steering (EPS) for smaller cars (1996); (c) electrical power assisted steering (HPS+EPS) for larger cars; (d) active front steering (AFS): Additional wheel angles generated by a planetary gear and a DC motor (2003); (e) steer-by-wire (SbW). (Not introduced by now.)

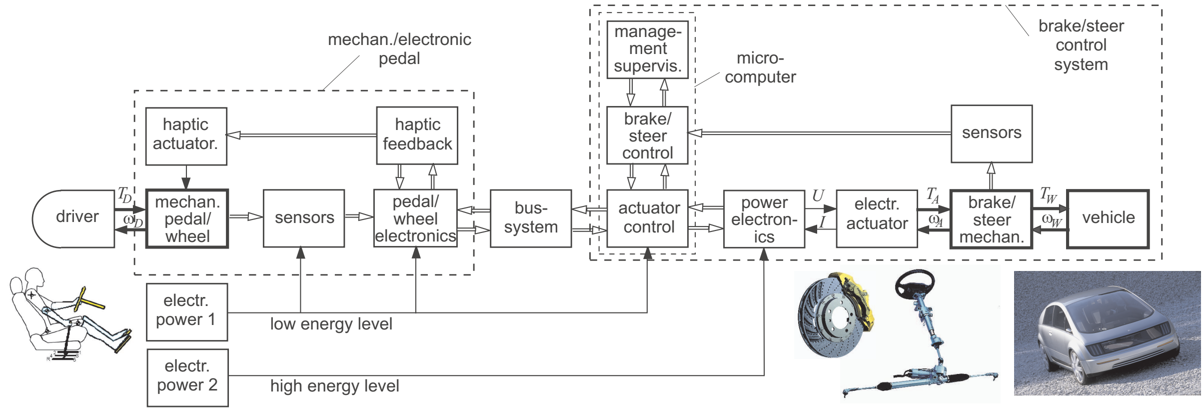

Fig. 20. Signal flow diagram of drive-by-wire systems

19 shows some mechatronic steering systems. Since about 1996 electrically assisted power steering (EPS) is on the market for smaller cars, (Connor, 1996). For larger cars the hydraulic power steering (HPS) is paralleled by electrical power steering (EPS), allowing electrical inputs for, e.g., automatic parking. A recent development is the *active front steering* (AFS) introduced in 2003, where additional steering angles are generated with a DC motor acting on a planetary gear, (Konik *et al.*, 2000). By this construction the mechanical linkage to the wheels is maintained and electrical inputs can be superimposed. This enables to increase the steering gain with lower speed, a higher dynamic steering and allows yaw changes and, e.g., sidewind compensation.

Figure 20, shows a general signal flow diagram of a *drive-by-wire system*. The driver‘s operating unit (steering wheel, braking pedal) has a mechanical input (e.g., torque or force) and an electrical output (e.g. bus protocol). It contains sensors and switches for position and/or force, microelectronics and either a passive (spring-damper) or active (el. actuator) feedback to give the driver a haptic information ("pedal-feeling") on the action. A bus connects to the brakes or steer control system with actuator control, brake or steer function control, supervision and different kinds of management (e.g. fault tolerance with reconfiguration), (Stölzl, 2000), (Stölzl *et al.*, 1998) and (Isermann *et al.*, 2002). Important are redundant electrical power supplies (12 V and 42 V), like two batteries and a generator.

5.4 Active front steering control with active anti-roll bar stiffness variation (an example)

An active front steering according to Figure 19d) is considered which generates steering angles $\delta_c(t)$ through a planetary gear and a DC motor in addition to the driver´s steering angle $\delta(t)$, Figure 21, see e.g., (Ackermann *et al.*, 1995). The task of the steering feedback controller shown in Figure 22 is to manipulate the steering angle sum $\delta_w(t)$ such that the yaw rate behavior $\dot{\psi}(\delta)$ for the driver is close to a one-track

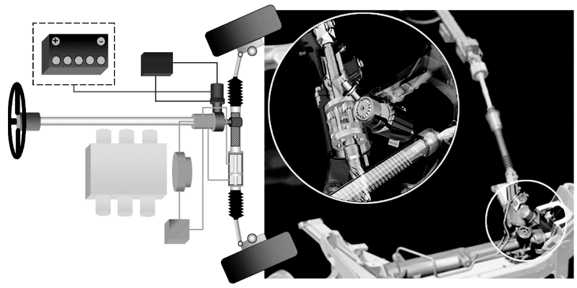

Fig. 21. Active front steering, generating additional steering angles through a planetary gear and brushless DC motor (BMW).

reference model. This reference model is identical with the expected steering behavior for normal driving situations with velocity-dependent behavior and includes the dynamics of lateral tire forces, (Schorn *et al.*, 2005). The steering controller is a PID-controller with velocity-dependent parameters designed with local linear one-track models. Figure 23 shows the simulated resulting steering behavior for a vehicle entering a curve with 144 km/h using a verified comprehensive two-track model including lateral and vertical dynamics. The one-track model yields in the case of stationary cornering for the required steering angle δ related to the Ackermann steering angle $\delta_0 = i_l l/\rho$

$$\frac{\delta}{\delta_0} = 1 + \frac{1}{v_{ch}^2} v^2 = 1 + \frac{SG}{l} v^2 \qquad (2)$$

with

$$SG = \frac{l}{v_{ch}^2} \;\; \text{(under) steer gradient} \qquad (3)$$

$$v_{ch}^2 = \frac{c_{\alpha F} c_{\alpha R} l^2}{m(c_{\alpha R} l_R - c_{\alpha F} l_F)} \;\text{characteristic velocity} \qquad (4)$$

(c_α wheel cornering stiffness, $l_{F,R}$ distance between CG and axle, F front, R rear, $l = l_F + l_R$).

Thus, $(SG > 0), (SG = 0), (SG < 0)$ indicates understeering, neutral steering and oversteering.

After entering the curve at $t = 0$ s, the vehicle starts to oversteer at $t = 2$ s because the velocity is by far

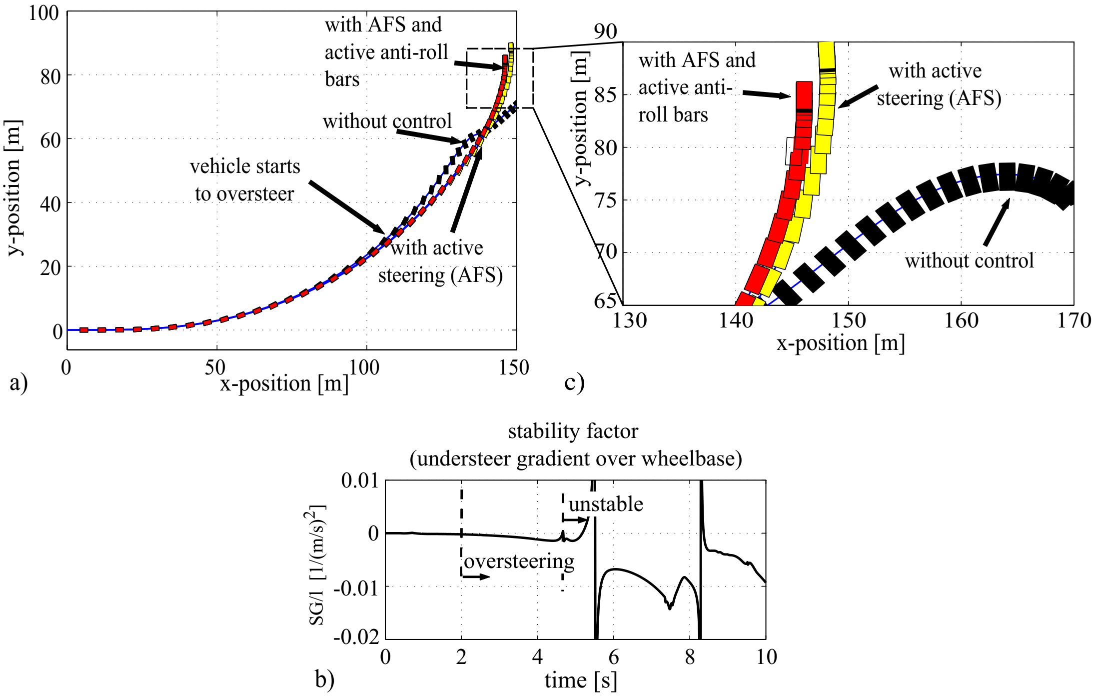

Fig. 23. Simulations of position and orientation of a vehicle for cornering and braking in a curve with 144 km/h entrance velocity: a) without control, with active front steering (AFS), with AFS and active anti-roll bars; b) inverse quadratic characteristic velocity (steer gradient), c) zoom of a)

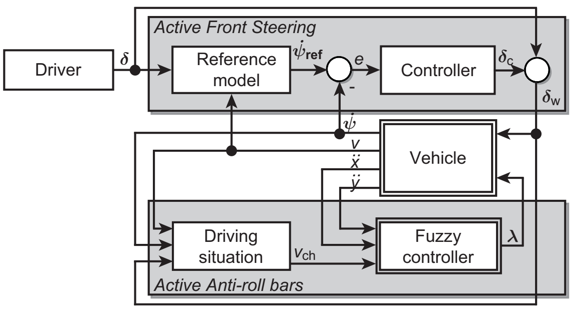

Fig. 22. Scheme for reference model-based active front steering control and active anti-roll bars

too high. At $t = 3$ s the driver brakes with full brake pressure $p_B = 100$ bar. (The brake system possesses an ABS system). At $t = 5$ s the vehicle becomes unstable and later leaves the road. With *active front steering*, however, the vehicle is stabilized and follows the curve, but with too large radius.

An additional active control input can now be obtained by *active anti-roll bars*, Figure 24, which are primarily introduced for roll stabilization. (The selection of the stiffness c_{stiff} of passive roll bars at the front and rear axle allows to influence the selfsteering behavior). By introducing, e.g., hydraulic anti-roll bars as shown in Figure 25, additional distortion torques can be generated thus changing the stiffness distribution parameter λ

$$\lambda = \frac{c_{stiff,r}}{c_{stiff,f} + c_{stiff,r}} \qquad \lambda \in [0,1] \tag{5}$$

($\lambda = 1$ means that the whole anti-roll bar torque applies at the front axle, resulting in strong understeer). By properly changing λ, the steering behavior can be influenced, making the vehicle more agile and better to handle in critical situations, (Konik *et al.*, 2000) and (Öttgen and Bertram, 2002).

The anti-roll bar stiffness distribution parameter λ is now manipulated by a driving-situation dependent fuzzy-controller such that a desired steering behavior with given *SG* results. The vehicle then stays on the curve, Figure 23. In addition, the handling by the driver in this critical situation is improved, because of smaller steering angles and smaller yaw rates, (Schmitt *et al.*, 2005).

6. CONCLUSIONS

The development of mechatronic systems influences the design, functions and manufacturing of many products in the areas of machines, vehicles and precision mechanics. It is characterized by the integration of components (hardware) and through information processing (software). This integration of engineering across traditional boundaries requires a systematic development procedure which includes modelling and different kinds of simulations like software-in-the-loop and hardware-in-the-loop, prototyping computers for control design and different kinds of testing after system integration. Of special importance is the implemented (embedded) control with all kind of linear and nonlinear control algorithms, ranging from gain-scheduled PID-, through internal model and state controllers to nonlinear feedforward control with look-up tables. Mechatronic systems offer the possibility to

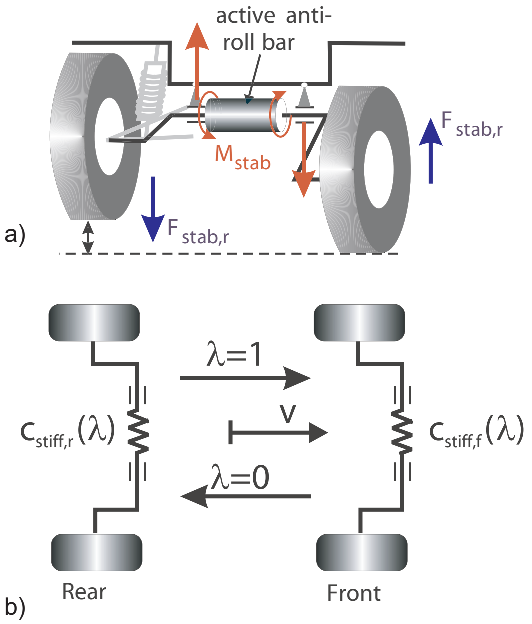

Fig. 24. Active anti-roll bars: a) schematic diagram; b) distribution parameter λ of the anti-roll bar stiffness

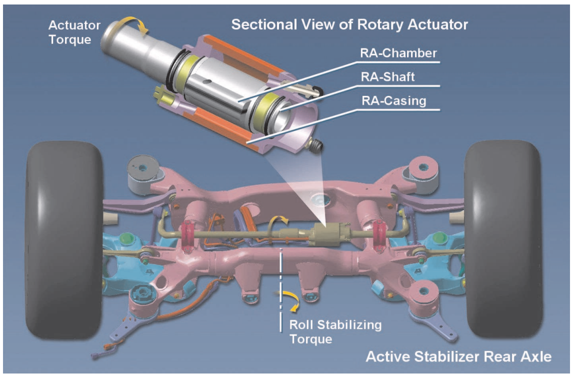

Fig. 25. Active anti-roll bar system for roll stabilization and steering support (BMW)

include complex control algorithms, condition monitoring and fault-diagnosis methods and require fault-tolerant components for safety-related processes.

The contribution gives an overview of the structure and design of mechatronic systems and considers various embedded control functions and fault tolerance. As example for innovations the economically important area of automotive mechatronics is highlighted. Mechatronic suspensions, brake systems and steering systems change the design of automobiles fundamentally, improving functionality, safety, economy and comfort. Similar developments can be observed for combustion engines, trains, aircraft, machine tools, and automation components, etc. Thus, mechatronic development is an emerging area for innovative engineering.

REFERENCES

Ackermann, J., J. Guldner, W. Sienel, R. Steinhauser and V.I. Utkin (1995). Linear and nonlinear controller design for robust automatic steering. *IEEE Control System Technology* **3**, 132–140.

AIM (1999, 2001, 2003). *IEEE/ASME Conference on Advanced Intelligent Mechatronics. Atlanta (1999), Como (2001), Kobe (2003)*.

Åström, K.H. and B. Wittenmark (1997). *Computer-controlled Systems. Theory and Design*. Prentice Hall. Upper Saddle River.

Bishop, C.M. (2002). *The mechatronics handbook*. CRC Press. Boca Raton.

Bradley, D.A., D. Dawson, D. Burd and A.J. Loader (1991). *Mechatronics-electronics in products and processes*. Chapman and Hall. London.

Bröhl, A. P., Ed.) (1995). *Das V-Modell - Der Standard für Softwareentwicklung, 2nd edn.*. Oldenbourg. München.

Bußhardt, J. and R. Isermann (1993). Parameter adaptive semi-active shock absorbers. In: *ECC European Control Conference*. Vol. 4. Groningen, Netherlands. pp. 2254–2259.

Canudas de Wit, C., H. Olsson, K.J Åström and P. Linschinsky (1995). A new model for control of systems with friction. *IEEE Trans. on Automatic Control* **40**, 419–425.

Chen, J. and R.J. Patton (1999). *Robust model-based fault diagnosis for dynamic systems*. Kluwer. Boston.

Connor, B. (1996). Elektrische Lenkhilfen für Pkw als Alternative zu hydraulischen und elektrischen Systemen. *Automobiltechnische Zeitschrift* **98**(7-8), 406–410.

Dieterle, W. (2004). Mechatronic systems: industrial applications and modern design methodology. In: *3rd IFAC Symposium on Mechatronic Systems*. Sydney, Australia.

Dorf, R.C. and R.H. Bishop (2001). *Modern control systems, 9th ed.*. Prentice Hall. Englewood Cliffs.

DUIS (1993). *Mechatronics and Robotics. M. Hiller, B. Fink (eds). 2nd Conference, Duisburg/Moers, Sept 27-29*.

Elmqvist, H. (1993). *Object-oriented modeling and automatic formula manipulation in Dymola*. Scandin. Simul. Society SIMS. Kongsberg.

Fischer, D. and R. Isermann (2004). Mechatronic semi-active and active vehicle suspensions. *Control Engineering Practice* **12**, 1353–1367.

Fischer, D., H.-P. Schöner and R. Isermann (2004). Model-based fault detection for an active vehicle suspension. In: *FISITA World Automotive Congress*. Barcelona, Spain.

Gausemeier, J., D. Brexel, T. Frank and A. Humpert (1995). Integrated product development. In: *3rd Conference on Mechatronics and Robotics*. Teubner, Stuttgart. Paderborn, Germany.

Gertler, J. (1998). *Fault detection and diagnosis in engineering systems*. Marcel Dekker. New York.

Goodall, R. (1995). Mechatronics in motion - some railway applications. In: *3rd IFAC Symposium on Mechatronic Systems*. Sydney, Australia.

Goodwin, G.C., S.F. Graebe and M.E. Salgado (2001). *Control system design*. Prentice Hall. Englewood Cliffs.

Guzella, L. and C.H. Onder (2004). *Introduction to modeling and control of internal combustion engine systems*. Springer. Berlin.

Harashima, F. and M. Tomizuka (1996). Mechatronics – "what it is, why and how?". *IEEE/ASME Trans. on Mechatronics* **1**, 1–2.

Heimann, B., W. Gerth and K. Popp (2001). *Mechatronik*. Fachbuchverlag Leipzig. Leipzig.

Hiller, M. (1995). Modelling, simulation and control design for large and heavy manipulators. In: *International Conference on Recent Advances in Mechatronics*. Istanbul, Turkey.

ICRAM (1995). *Recent Advances in Mechatronics. Proceedings of International Conference ICRAM'95, Istanbul, August 14 16*.

IEC 60812 (1985). *Analysis techniques for system reliability procedure for failure mode and effects analysis (FMEA)*. International Electrotechnical Commission. Switzerland.

IEC 61508 (1997). *Functional safety of electrical/electronic/programmable electronic systems*. International Electrotechnical Commission. Switzerland.

IEEE/ASME (1996). *Transactions on Mechatronics*. Vol. 1.

IFAC (2000, 2002, 2004). *IFAC-Symposium on Mechatronic Systems: Darmstadt (2000), Berkeley (2002), Sydney (2004)*. Elsevier. Oxford.

IFAC-T.C 4.2. (2000). *IFAC Technical Committee on Mechatronics Systems. http://rumi.newcastle.edu.au/reza/TCM/*.

IMES (1993). *Integrated Mechanical Electronic Systems Conference (in German) TU Darmstadt, March 2-3*. Vol. Fortschr.-Ber. VDI Reihe 12. VDI-Verlag. Düsseldorf.

Isermann, R. (1996). Modeling and design methodology of mechatronic systems. *IEEE/ASME Trans. on Mechatronics* **1**, 16–28.

Isermann, R. (1997). Supervision, fault-detection and fault-diagnosis methods. an introduction. *Control Engineering Practice* **5**(5), 639–652.

Isermann, R. (2000). Mechatronic systems: concepts and applications. *Trans. of the Institute of Measurement and Control*.

Isermann, R. (2003). *Mechatronic Systems. (German edition: 1999)*. Springer. Berlin.

Isermann, R. (2005). *Fault diagnosis and fault tolerance*. Springer. Heidelberg, Berlin.

Isermann, R. and U. Raab (1993). Intelligent actuators - ways to autonomous actuating systems. *Automatica* **29**(5), 1315–1331.

Isermann, R., K.-H. Lachmann and D. Matko (1992). *Adaptive Control Systems*. Prentice Hall International UK. London.

Isermann, R., R. Schwarz and S. Stölzl (2002). Fault-tolerant drive-by-wire systems. *IEEE Control Systems Magazine* (October), 64–81.

Isidori, A., Ed.) (1999). *Nonlinear Control Systems II*. Springer. London.

Johansson, R. and Rantzer, A., Eds.) (2003). *Nonlinear and hybrid systems in automotive control*. Springer. London.

Jonner, W.D., H. Winner, L. Dreilich and E. Schunck (1996). Electrohydraulic brake system - the first approach. In: *SAE Technical paper Series*. number 960991. Warrendale.

Kiencke, U. and Nielsen, L., Eds.) (2000). *Automotive control systems. For engine, driveline and vehicle*. Springer. Berlin.

Kitaura, K. (1986). *Industrial Mechatronics (in Japanese)*. New East Business Ltd.

Konik, D., R. Bartz, F. Bärnthol, H. Brunds and M. Wimmer (2000). Dynamic drive - the new active roll stabilization system from bmw group. In: *Proceedings of AVEC 2000, 5th International Symposium on Advanced Vehicle Control*.

Kyura, N. and H. Oho (1996). Mechatronics – an industrial perspective.. *IEEE/ASME Trans. on Mechatronics* **1**, 10–15.

Lückel, J., Ed.) (1995). *Third Conference on Mechatronics and Robotics. Paderborn, Oct. 4-6*. Teubner. Stuttgart.

McConaill, P.A., Drews, P. and Robrock, K.-H., Eds.) (1991). *Mechatronics and robotics*. ICS Press. Amsterdam.

Mechatronics (1991). *An International Journal. Aims and Scope*. Pergamon Press. Oxford.

Merker, T., J. Wirtz, M. Hiller and M. Jeglitzka (2001). Das SL-Fahrwerk.. *ATZ - Automatisierungstechnische Zeitschrift. Special Issue: Der neue Mercedes SL* pp. 84–91.

Morari, M. and F. Zafirov (1989). *Robust process control*. Prentice Hall. Englewood Cliffs.

Onodera, K. (1997). Effective techniques of fmea at each life-cycle stage. In: *1997 Proceedings: Annual Reliability and Maintainability Symposium*. IEEE. pp. 50–56.

Otter, M. and C. Cellier (1996). Software for modeling and simulating control systems. In: *The Control Handbook* (W.S. Levine, Ed.). CRC Press. Boca Raton.

Öttgen, O. and T. Bertram (2002). Influencing vehicle handling through active roll moment distribution. In: *Proceedings of AVEC 2002. 6th International Symposium on Advanced Vehicle Control*. Hiroshima, Japan. pp. 129–134.

Pfeufer, T., T. Landsiedel and R. Isermann (1995). Identification and model-based nonlinear control of electro-mechanical actuators with friction. In: *IFAC-Workshop Motion Control*. Munic, Germany.

Schmitt, J., R. Isermann, M. Börner and D. Fischer (2005). Model-based supervision and control of

lateral vehicle dynamics. *Control Engineering Practice*.
Schöner, H.P. (2004). Automotive mechatronics. *Control Engineering Practice* **12**, 1343–1351.
Schorn, M., J. Schmitt, U. Stählin and R. Isermann (2005). Model based braking control with support by active steering. In: *Proceedings of the 16th IFAC World Congress 2005, Prague, Czech Republic*.
Schweitzer, G. (1992). Mechatronics – a concept with examples in active magnetic bearings. *Mechatronics* **2**, 65–74.
Semmler, S., R. Isermann, R. Schwarz and P. Rieth (2002). Wheel slip control for antilock-braking systems using brake-by-wire actuators. Vol. SAE 2002-01-0303. Detroit, USA.
Slotine, J.J.E. and L. Weiping (1991). *Applied nonlinear control, Chapter 7 in Sliding Control*. Prentice Hall. Englewood Cliffs.
Spong, M.W. and M. Vidyasagar (1989). *Robust dynamics and control*. J. Wiley. New York.
STARTS GUIDE (1989). *A guide to methods and software tools for the construction of large real-time systems.*. National Computing Centre. Manchester.
Stoll, U. (2001). *Sensotronic brake control (SBC)*. Vol. VDI-Ber. 1646. VDI. Düsseldorf.
Stölzl, S. (2000). *Das elektrohydraulische Bremssystem von Contintental Teves*. Vol. Fortschr.-Ber. VDI Reihe 12. VDI-Verlag. Düsseldorf.
Stölzl, S., R. Schwarz, R. Isermann, J Böhm, J. Nell and P. Rieth (1998). Control and supervision of an electromechanical brake system. In: *FISITA World Automotive Congress, The Second Century of the Automobile*. Paris, France.
Storey, N. (1996). *Safety-critical computer systems*. Addison Wesely Longman Ltd.. Essex.
Tomizuka, M. (1995). Robust digital motion controller for mechanical systems. In: *International Conference on Recent Advances in Mechatronics*. Istanbul, Turkey.
Tomizuka, M. (2000). Mechatronics: from the 20th to the 21th century. In: *1st IFAC Conference on Mechatronic Systems*. Elsevier, Oxford. Darmstadt, Germany.
UK Mechatronics Forum (1990, 1992, 1994, 1996, 1998, 2000, 2002). *Conferences in Cambridge (1990), Dundee (1992), Budapest (1994), Guimaraes (1996), Skovde (1998), Atlanta (2000), Twente (2002)*.
Utkin, V.I. (1977). Variable structure systems with sliding mode: a survey. *IEEE Trans. on Automatic Control* **22**, 212–222.
van Amerongen, J. (2004). Mechatronic education and research – 15 years of experience. In: *3rd IFAC Symposium on Mechatronic Systems*. Syndey, Australia. pp. 595–607.
VDI 2206 (2004). *Entwicklungsmethodik für mechatronische Systeme*. Beuth Verlag. Berlin.