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Mechatronic systems—Innovative products with embedded control

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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. Simultaneous design of mechanics and electronics, hardware and software and embedded control functions resulting in an integrated component or system are all of major importance. 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, where especially large influences can be seen, is described in more detail by discussing mechatronic suspensions, mechatronic brakes, active steering and roll stabilization systems.

Keywords: Mechatronics; Component integration; Simultaneous design; Systems integrity; Automotive mechatronics

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. Fig. 1 summarizes this development, beginning with the purely mechanical systems of the 19th century to mechatronic systems in the 1980s.

Fig. 2 shows the forward-oriented energy flow of mechanical energy converting systems (e.g., a motor) and the backward-oriented information flow, which is typical for many mechatronic systems. In this way, 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 a *mechatronic system* from joining MECHAnics and ElecTRONICS. The word "mechatronics" was probably first created by a Japanese engineer in 1969, Kyura and Oho (1996).

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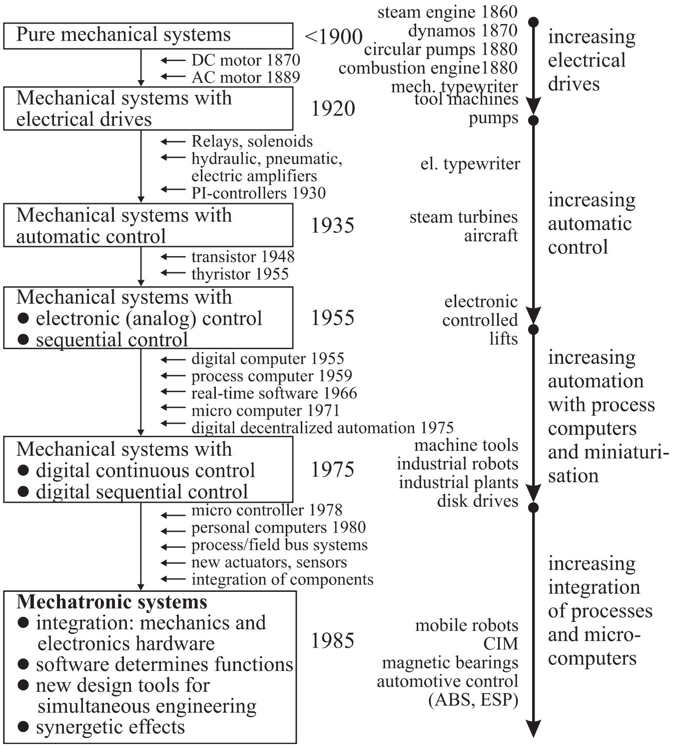

Fig. 1. Historical development of mechanical, electronic and mechatronic systems.

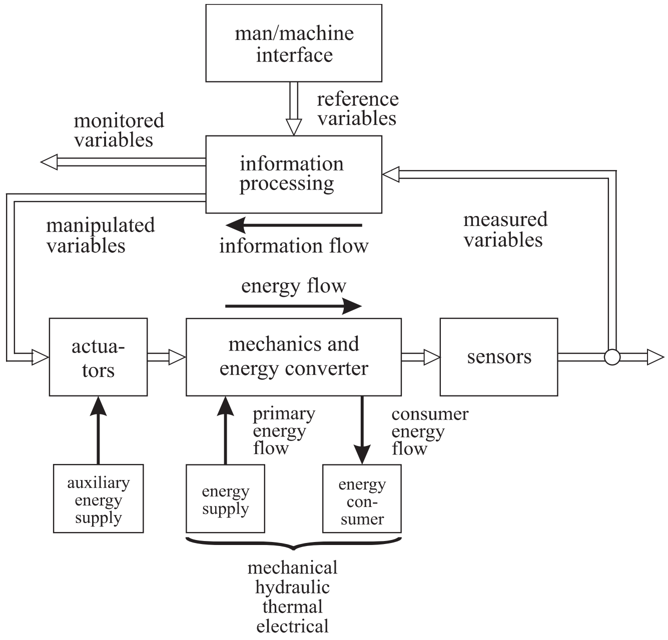

Fig. 2. Mechanical process and information processing develop towards a mechatronic system.

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. (2006), 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, Fig. 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. Thus, 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 evolving with adaptive or even learning behaviour, which can also be called *intelligent mechatronic systems*.

The developments up until now can be found in Schweitzer (1992), Gausemeier, Brexel, Frank, and Humpert (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), Kaynak, Özkan, Bekiroglu, and Tunay (1995), AIM (1999, 2001, 2003), IFAC (2000, 2002, 2004), the journal articles by Hiller (1995), Lückel (1995), van Amerongen (2003), and the books by Kitaura (1986), Bradley, Dawson, Burd, and Loader (1991), McConaill, Drews, and Robrock (1991), Heimann, Gerth, and Popp (2001), Isermann (2003a), Bishop (2002), van Brussel (2005).

Mechanical systems can be dedicated to a large area of mechanical engineering. According to their construction, traditional classification and industrial branches, they can be subdivided into *mechanical components, machines, vehicles, precision mechanical devices* and *micromechanical components*.

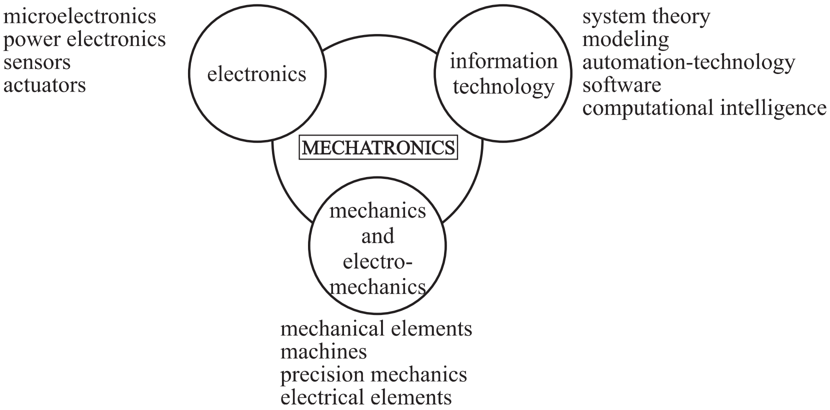

Fig. 3. Mechatronics: synergetic integration of different disciplines.

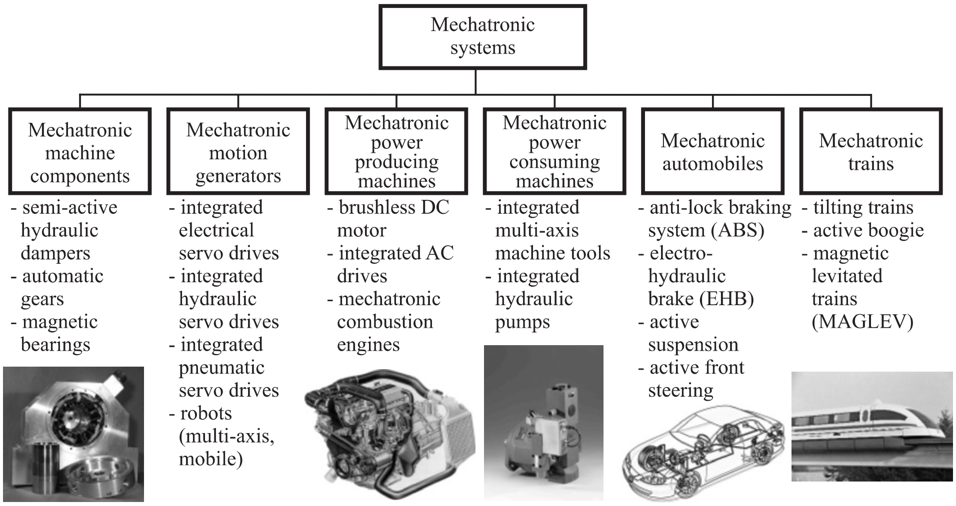

Fig. 4. Examples for mechatronic systems (macro-mechatronics).

Fig. 4 shows some examples of macro-mechatronic components, machinery and vehicles. Examples for *precision mechatronic devices* are gyros, laser and ink jet printers, hard disc drives, see e.g., Horowitz, Yunfeng, Oldham, and Kon (2004), Peng, Chen, Lee, and Venkataramanan (2004). Mechatronic products in the field of *microelectromechanical systems* (MEMS) are piezoelectric acceleration sensors, microactuators and micropumps, see e.g. Gad-el-Hak (2000), Madon (2001), Lyshevski (2001), Janocha (2004), Slatter and Degen (2004). Because of the wide area of mechanical products, which are influenced by these mechatronic developments, related recent publications are greatly diversified. Except the cited books some special sections of journals allow to give a further overview, like Daniel (2002), Lee and Siciliano (2002), Ume (2002), Nakamura (2003), Lee, Tan, and Vadakkepat (2003), Tomizuka (2004) and Moheimany (2005).

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 behaviour* of nonlinear mechanics by proper feedback (hydraulic and pneumatic actuators, valves, vehicles);
- *operator adaptation* through programmable characteristics (accelerator and brake pedal, manipulators).

1.2.2. Operating properties

Process behaviour 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 setpoints 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, for example:

- *integrated process design and control design* (mutual optimization of process and control performance, model-based control, adaptive and learning control strategies);
- *control of nonmeasurable variables* (tyre slip, internal tensions or temperatures, slip angle and ground speed of vehicles, damping parameters);
- *integrated advanced supervision* and *fault diagnosis*;
- *fault-tolerant systems* with hardware and analytical redundancy;
- *teleservice functions* for monitoring, maintenance, repair;
- *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 Fig. 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.

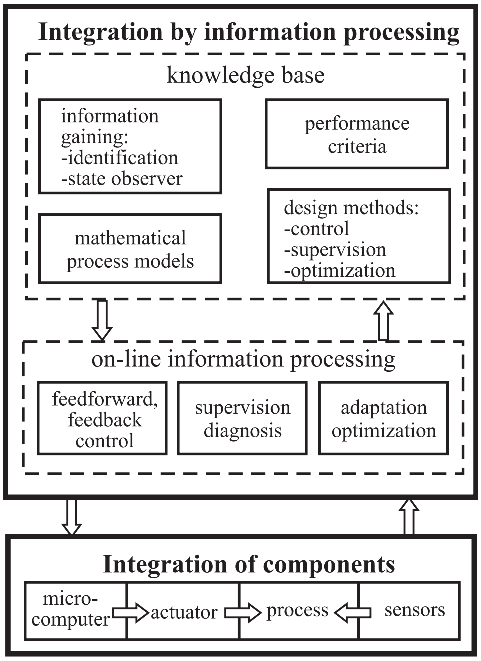

Fig. 5. Integration of mechatronic systems: integration of components (hardware integration); integration by information processing (software integration).

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 online information processing in higher levels, see Fig. 5. This includes the solution of tasks like supervision with fault diagnosis, optimization and general process management. The respective problem solutions result in an *online 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

2.1. Mechatronic engineering

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 Fig. 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).

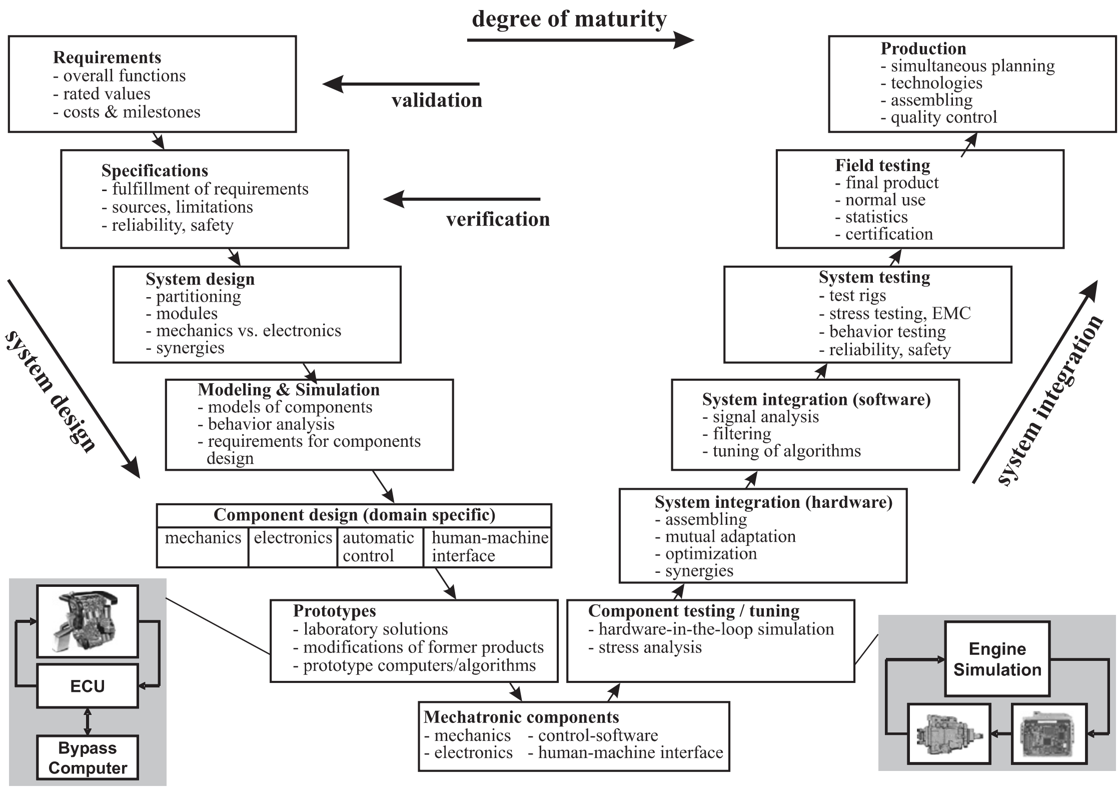

Fig. 6. “V” development scheme for mechatronic systems.

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, resulting in totally new functions.

2.2. Modelling, simulation and software tools

Because of the many varieties of designs the advanced *modelling* and *simulation* plays an important role, as well as saving 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), 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 4.2. Then prototypes are built 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*, Fig. 7, see e.g., 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

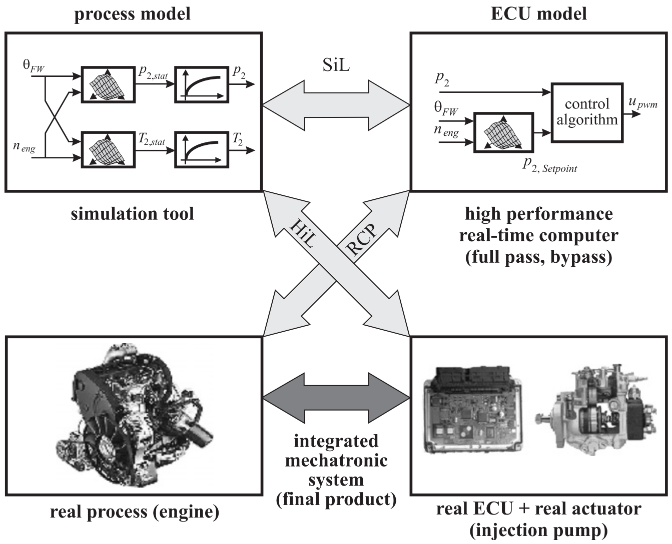

Fig. 7. Various kinds of combining real and simulated parts for development: SiL: Software-in-the-loop; RCP: rapid control prototyping; HiL: Hardware-in-the-loop.

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. Summarizing, mechatronic engineering means *integration across traditional boundaries*. Many software tools for domain-specific modelling and general simulation do exist. However, design tool chains across several boundaries are still missing and need to be developed.

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 Fig. 8. The knowledge base consists of mathematical process models, identification and parameter estimation algorithms, controller design methods and control performance criteria, as well as other processes. The feedback control can be organized into lower level and higher-level controllers, a reference value generation module 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), Aström and Wittenmark (1997), Isidori (1999), Dorf and Bishop (2001) and Goodwin, Graebe, and Salgado (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 behaviour of the process, the type and placement of the actuators, and the type and position of the sensors are designed appropriately, resulting in an ‘‘control dynamic friendly’’ overall behaviour. (Like linearity, low order, small or no dead times, good natural damping, or other important items for control design.)

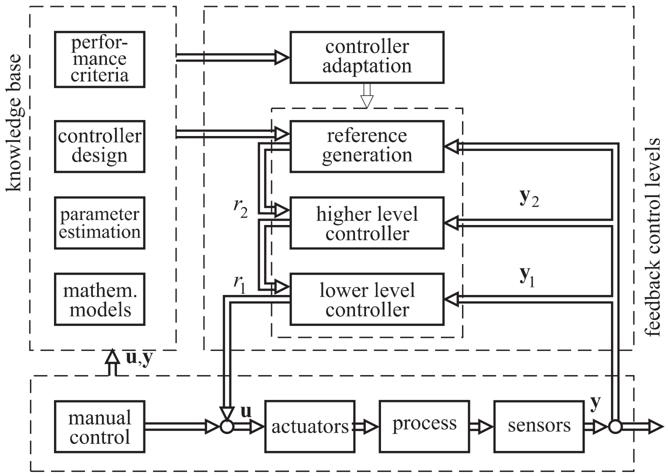

Fig. 8. Knowledge-based multi-level feedback control for mechatronic systems.

The goal of the *lower level feedback* is to provide a certain dynamic behaviour (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 proportional-derivative (PD) feedback.

Compensation of nonlinear static characteristics: nonlinear static characteristics are present in many subsystems of mechanical processes. Fig. 9 shows a typical example of 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 behaviour $F_D = f(U')$ 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_{Fv} the linear viscous friction coefficient which may be dependent on the motion

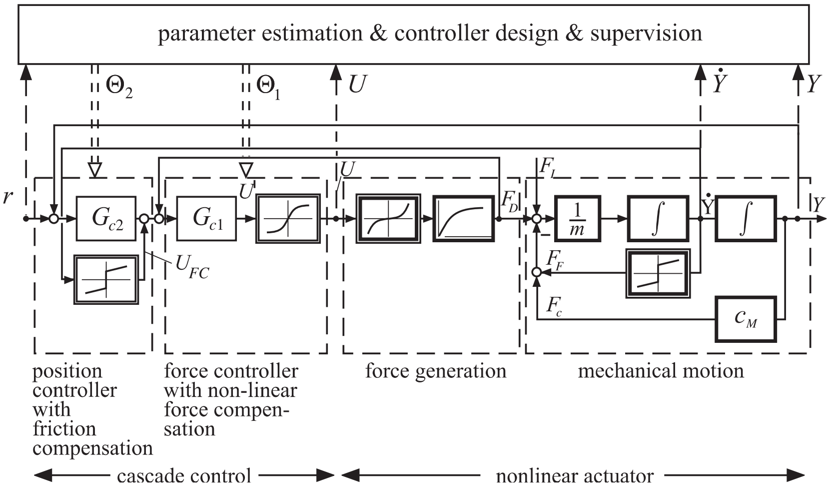

Fig. 9. Adaptive position control of a nonlinear electromechanical, hydraulic or pneumatic actuator (example).

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 Fig. 9, dithering, feedforward compensation and adaptive friction compensation are alternatives, see, e.g., Isermann and Raab (1993), Tomizuka (1995) and Canudas de Wit, Olsson, and Aström, Linschinsky (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 generates a dither signal. A comparison with a fixed PID-controller with friction compensation shows Pfeufer, Landsiedel, & Isermann (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 behaviour 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 behaviour 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 behaviour.

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 Figs. 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, and damping, see Isermann and Raab (1993), Isermann, Lachmann, and Matko (1992), Aström 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 shutdown (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 nonlinearities and especially the actuator behaviour have to be taken into the design. A big advantage is that the process and its control is designed and implemented from one manufacturer, such that optimal controllers can be realized and maintained. This is a special positive situation for mechatronic systems, which distinguishes the practical realizability of advanced control systems from other, e.g., industrial processes. However, considerable real-time constraints have to be mastered. A detailed description of control methods can be given only for concrete processes, actuation principles and measurement configurations.

4. Fault diagnosis, safety and fault tolerance

4.1. *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 ECUs, 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.

Fig. 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, Fig. 10.

These features are then compared with the features for normal behaviour, 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 (2006).

4.2. *Safety and 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

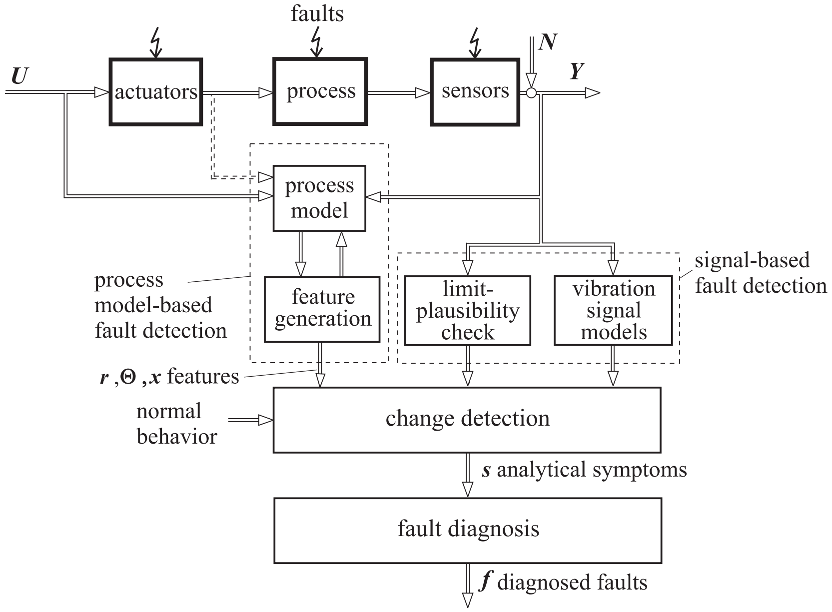

Fig. 10. Scheme for model-based fault detection (**r**: residuals; **Θ**: parameter estimates, **x**: state variable estimates).

measures like failure rates or mean-time-to-failure (MTTF) 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 Fig. 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:

- *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).

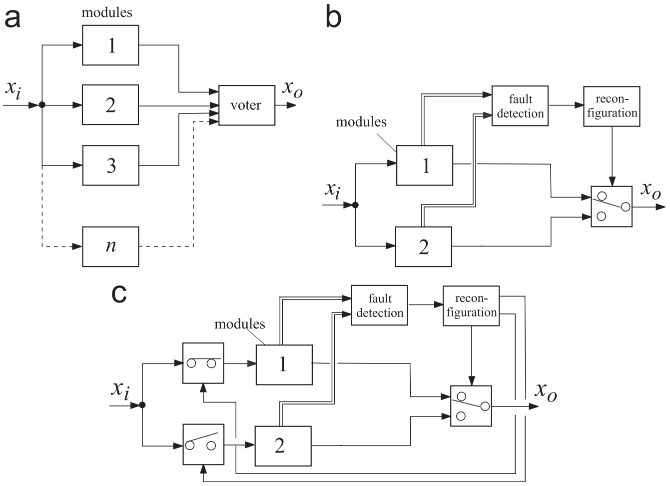

Fig. 11. Fault-tolerant schemes for electronic hardware: (a) static redundancy: multiple-redundant modules with majority voting and fault masking, m out of n systems (all modules are active); (b) dynamic redundancy: standby module that is continuously active, “hot standby”; (c) dynamic redundancy: standby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

5. Automotive mechatronics

Mechatronic products are especially advanced in the field of *automobiles*. Therefore, this area is considered to show some concrete examples. Fig. 12 gives a survey of presently realized mechatronic components and systems. The first mechatronic products for vehicles were antilock-braking (ABS, 1979) and automatic traction control (ATC, ASR, 1986) and the most recent are 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 with electronic fuel injection (analogue: 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), and 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 microECUs. 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 (2004).

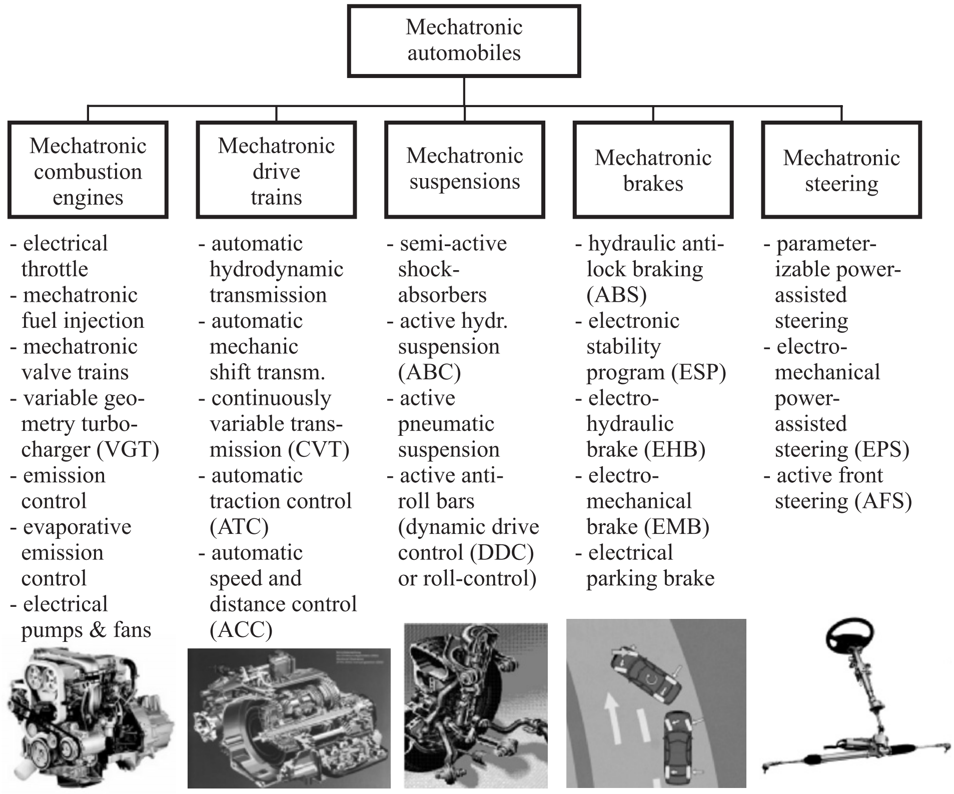

Fig. 12. Survey of mechatronic components and systems for automobiles and engines.

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 tyre load variation F_{zdyn} is a measure for *safety*, as it indicates the applicable forces between the tyre and the road. With fixed parameter suspensions usually a compromise is made within the $\ddot{z}_B(F_{zdyn})$ relation.

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

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 for passenger cars and an operating range is between 0 and 5 Hz about 1–2 kW and between 0–12 Hz about 2–7 kW. Fig. 14 shows one example of a hydraulic active suspension with a hydraulic piston in series with the steel spring, Merker, Wirtz, Hiller, and Jeglitzka (2001). This concept is designed to reduce low frequent body motions ($f<2$ Hz), due to rolling and pitching and to reduce higher frequent road excitations ($f<6$ Hz). It is controlled by a state-feedback controller with measurement of deflection z_{WB} between body and wheel and body acceleration $\ddot{z}_B$. A recent survey on mechatronic suspensions is given by Fischer and Isermann (2004) as well as a model-based fault detection of an active suspension by Fischer, Schöner, and Isermann (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 became more complex. In order to increase the functionality further, to save 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 brake (EMB), for which prototypes exist, see Fig. 15.

Fig. 16 shows the different stages for *brake systems* of passenger cars or lightweight trucks. In the case of the

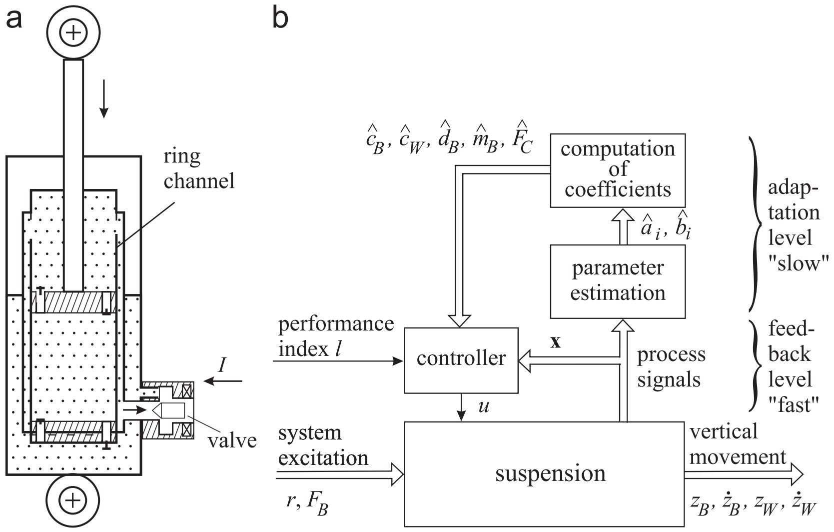

Fig. 13. Semi-active shock absorber (a) and its control (b).

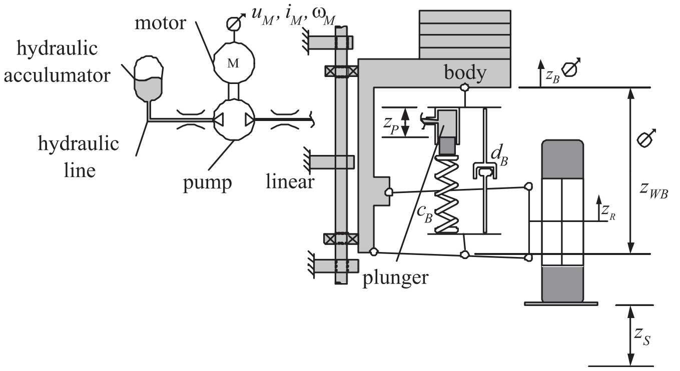

Fig. 14. Active hydraulic suspension system (ABC, Mercedes CL and S-class), ⌀̸ measured signals.

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 EHB, Figs. 16a and 15a, where the mechanical pedal has sensors for position and hydraulic pressure, Jonner, Winner, Dreilich, and Schunck (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 is released. Hence, a hydraulic back up serves to fail safe as for conventional hydraulic brakes.

The EMB according to Figs. 16b and 15b no longer contains hydraulics. 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 exists, a mechanical or hydraulic fail-safe is not possible. Therefore, the complete electrical path must be built with fault tolerance, see the architecture in Fig. 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. Fig. 18 shows an example for full braking with ABS functions based on continuous, proportional acting slip controlled EHB-brakes, Semmler, Isermann, Schwarz, and Rieth (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, high costs and missing 42 V-electrical board 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”. Fig. 19 shows some mechatronic steering

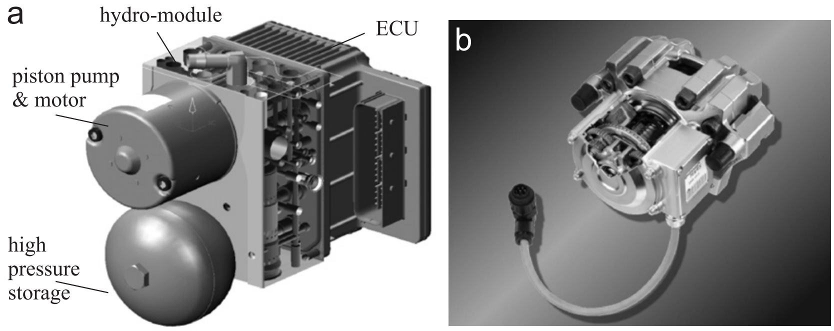

Fig. 15. Illustration of brake-by-wire-systems: (a) Electrohydraulic brake control (EHB), Bosch; (b) Electromechanical brake (EMB), Continental Teves.

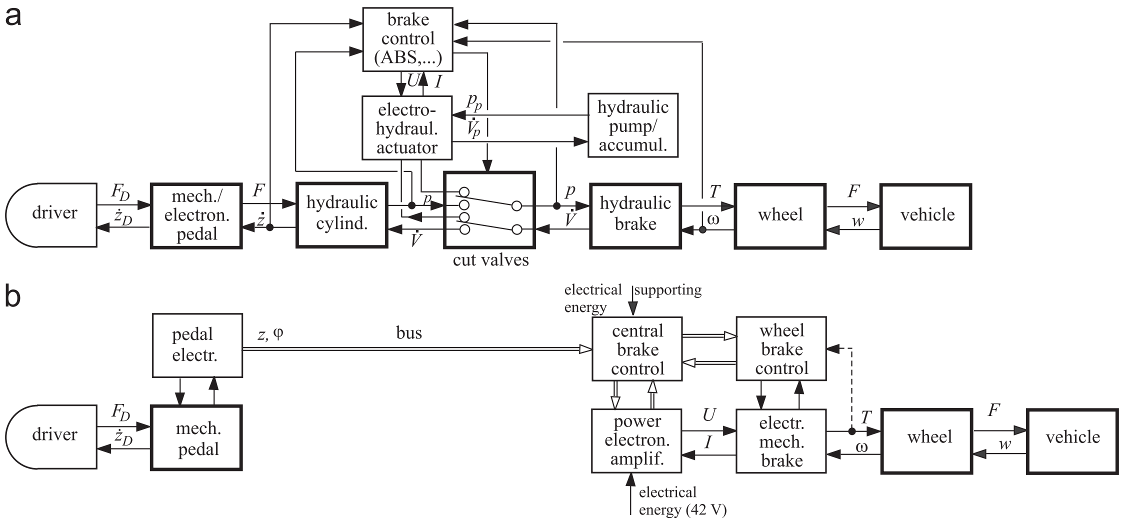

Fig. 16. Signal flow diagram for different mechatronic brake systems of passenger cars: (a) Electrohydraulic brake (EHB) with hydraulic brake; (b) Electromechanical brake (EMB) without mechanical backup.

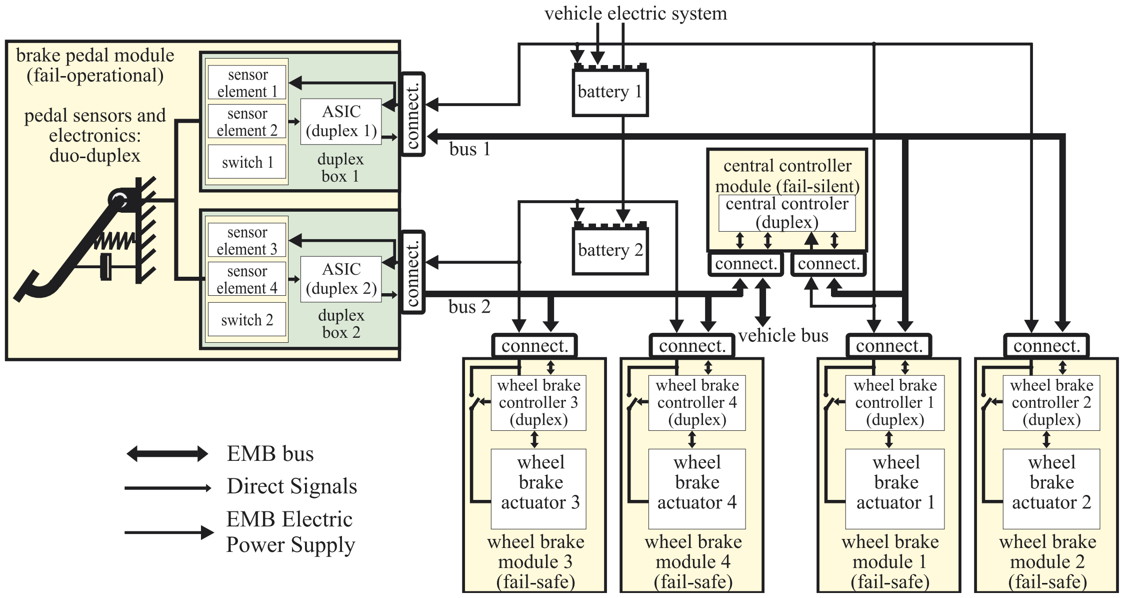

Fig. 17. Fault-tolerant electromechanical brake (EMB) system architecture (prototype).

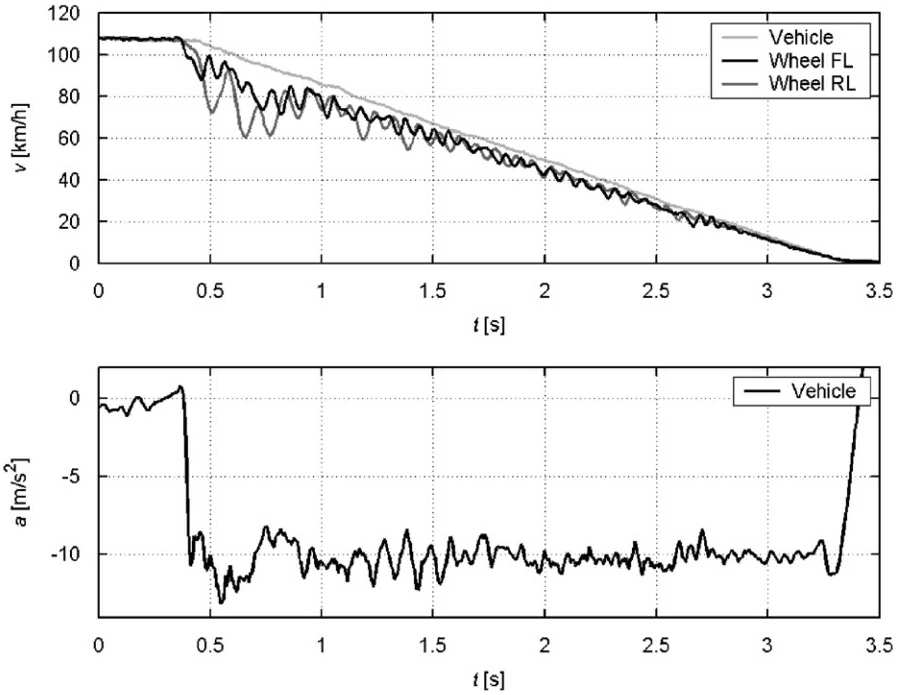

Fig. 18. Braking with model-based ABS- (anti-lock-braking system) functions, measured on dry asphalt. Continuous nonlinear, adaptive slip control with EHB (electrohydraulic brake) generates maximal brake froces (FL, RL: front, rear left).

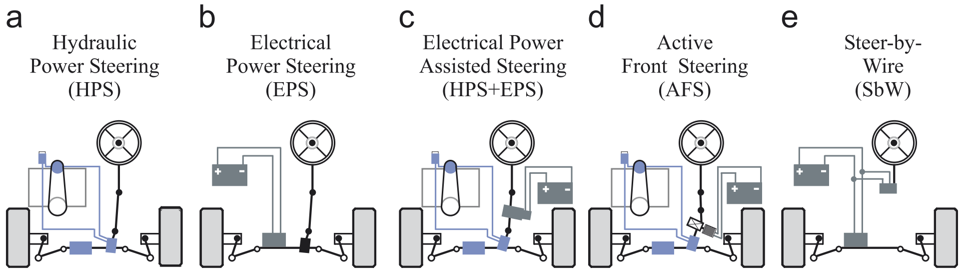

Fig. 19. Mechatronic steering systems: (a) conventional hydraulic power steering (HPS) (since about 1945); (b) electrical power steering (EPS) for smaller cars (1996); (c) electrical power assisted steering (HPS + EPS) for larger cars; (d) active front steering (AFS): Additional wheel angles generated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

systems. Since about 1996 electrically assisted power steering (EPS) has been on the market for smaller cars, Connor (1996). For larger cars the hydraulic power steering (HPS) is paralleled by EPS, allowing electrical inputs for, e.g., automatic parking. A recent development is the AFS introduced in 2003, where additional steering angles are generated with a DC motor acting on a planetary gear, Ackermann, Guldner, Sienel, Steinhauser, and Utkin (1995), Konik, Bartz, Bärnthol, Brunds, and Wimmer (2000). Fig. 20 shows an example. By this construction the mechanical linkage to the wheels is maintained and electrical inputs can be superimposed. This allows to increase the steering gain with lower speed, a higher dynamic steering and yaw rate damping and, e.g., sidewind compensation. In combination with active anti-roll bar stiffness variation at the front and rear axle the steering behaviour can dynamically be changed to become more understeering or more oversteering, thus making the vehicle more agile and better to handle in critical situations, Konik et al. (2000), Öttgen and Bertram (2002) and Börner and Isermann (2006), Schorn, Schmitt, Stählin, and Isermann (2005).

Fig. 21 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 the operating unit with the brakes or steer control system including 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, Schwarz, and Stölzl (2002). Redundant electrical power supplies (12 and 42 V), like two batteries and a generator are important.

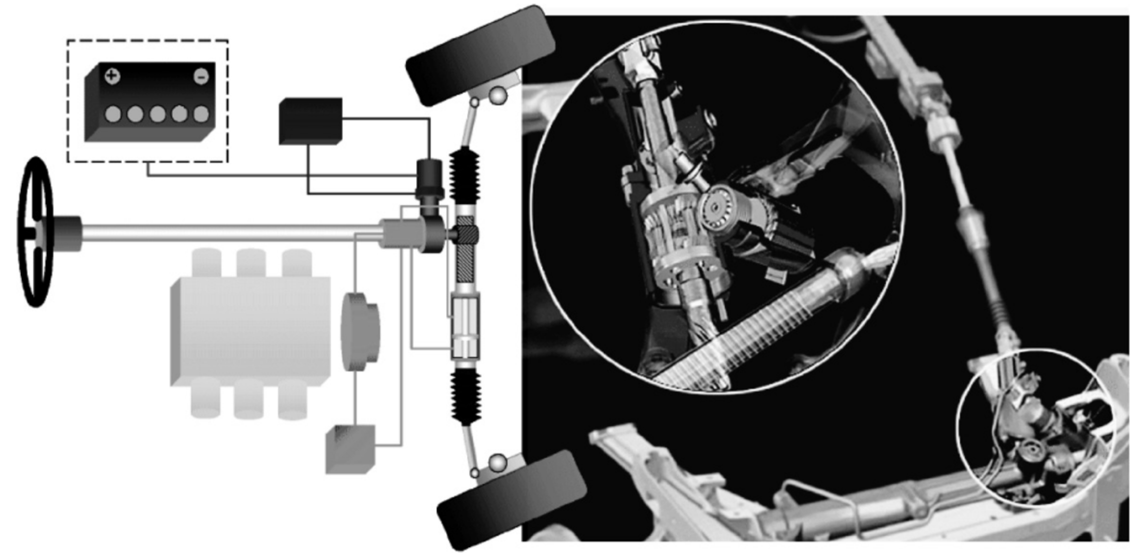

Fig. 20. Active front steering, generating additional steering angles through a planetary gear and brushless DC motor (BMW).

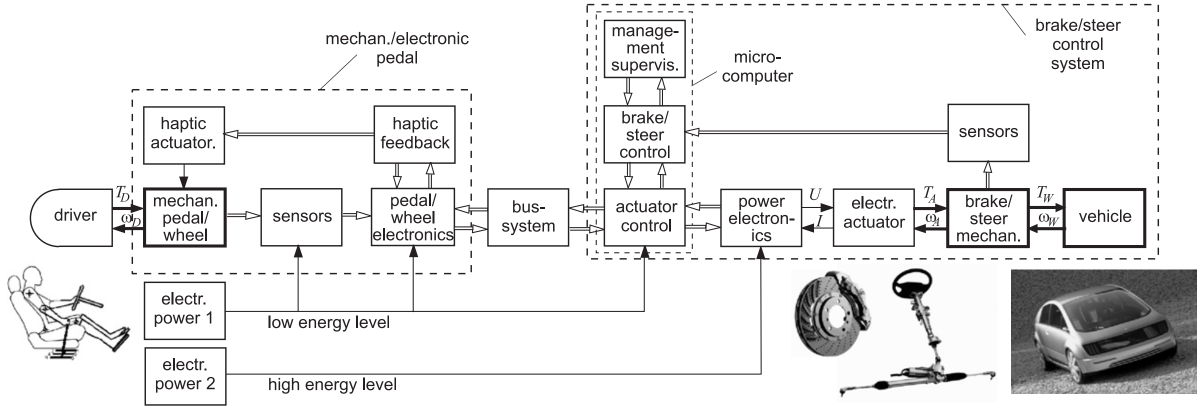

Fig. 21. Signal flow diagram of drive-by-wire systems.

6. Conclusions and outlook

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 include complex control algorithms, condition monitoring and fault-diagnosis methods and require fault-tolerant components for safety-related processes. These software-based functions are implemented and maintained by a designer team and are only accessible by these authorized experts. Therefore, they can be more involved as, e.g., compared to process industries. With increasing mechatronic design, systematic development chains, from modelling and design to implementation and testing will be developed.

The contribution gives an overview of the structure and design of mechatronic systems and considers various embedded control functions and fault tolerance. As one example of 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, robots, and automation components, etc. Thus, mechatronic development is an *emerging area for innovative engineering*.

Next steps of development are, e.g., more *intelligent mechatronic systems* with learning behaviour and decision-making, *fault-tolerant mechatronic systems* for highly reliable and safe systems (e.g., vehicles, production machinery, medical devices and aerospace systems) and *drive-by-wire mobile systems* (e.g., brake-by wire, steer-by wire, drive-by wire, autopilot-driver assistance, mobile robots for agriculture and production). A further development may be the *integration* of mechatronic systems with wire-bound and wire-less *communication channels* (audio nets, internet), e.g., with remote access for software updates, telemonitoring and telediagnosis, maintenance procedures, security measures, etc.

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