1 Integrated Mechanical Electronic Systems

Integrated mechanical electronic systems emerge from a suitable combination of mechanics, electronics and information processing. Thereby, these fields influence each other mutually. First, a shift of functions from mechanics to electronics is observed and then 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.

In the following, first the development from mechanical to mechatronic systems is described and the systems concerned in mechanical engineering and in precision mechanics are considered. Several tasks arise and different forms of integration for mechanics and electronics can be distinguished. The integration may be performed, *e.g.*, by the components (hardware) or by the functions (software). Generally, a development to adaptive or intelligent overall systems shows up. The first chapter ends with a consideration of substantial design steps for mechatronic systems.

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 years. 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. A realization with added fixed wired (analog) devices turns out to enable only relatively simple and limited control functions. If these analog devices are replaced with digital computers in the form of, *e.g.*, on-line coupled microcomputers, the information processing can be designed to be considerably more flexible and more comprehensive. Figure 1.1 summarizes this development, beginning with the purely mechanical systems of the nineteenth century to mechatronic systems in the 1980s. The first digitally controlled machines were, *e.g.*, machine tools, where already in around 1973 fixed wired sequential control devices based on transistors were being replaced by digital storage programmable control systems. This was paralleled by the introduction of digital control systems for, *e.g.*, electrical drives, industrial robots and steam turbines and for automotive parts. About 10 years later, the first mechanical systems with integrated sensors, actuators and microcontrollers appeared, *e.g.*, as anti-lock braking systems (ABS) for vehicles or magnetic bearings and in the form of precision electro-mechanical devices as cameras, video recorders, printers and disk storage, thus forming the first mechatronic systems.

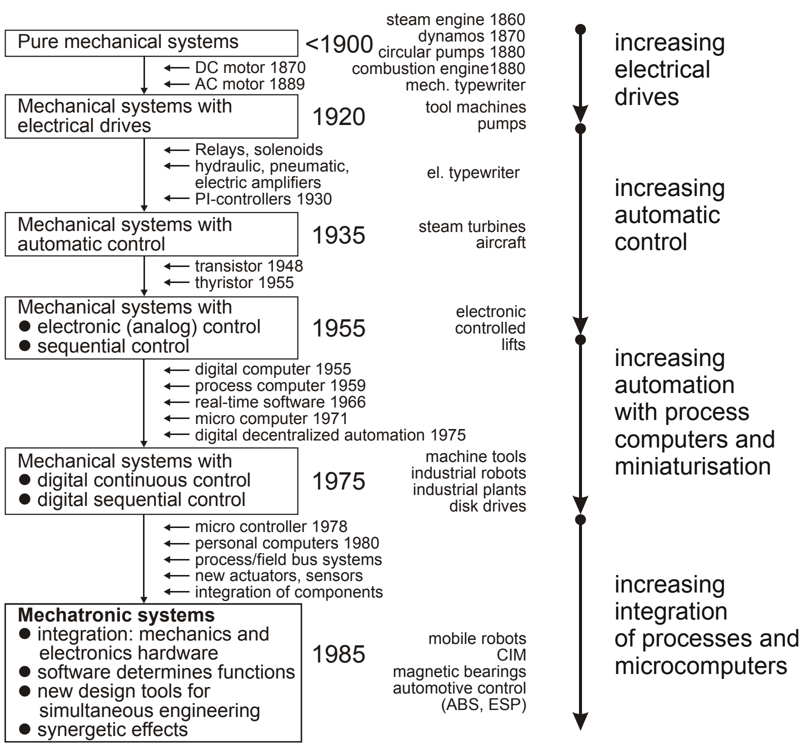

Figure 1.1. Historical development of mechanical, electronic and mechatronic systems

Figure 1.2 shows the example of a machine set, consisting of a power-generating machine (DC motor) and a power-consuming machine (circulation pump): (a) a scheme of the components, (b) the resulting signal flow diagram in two-port representation, and (c) the open-loop process with one or several manipulated variables as input variables and several measured variables as output variables.

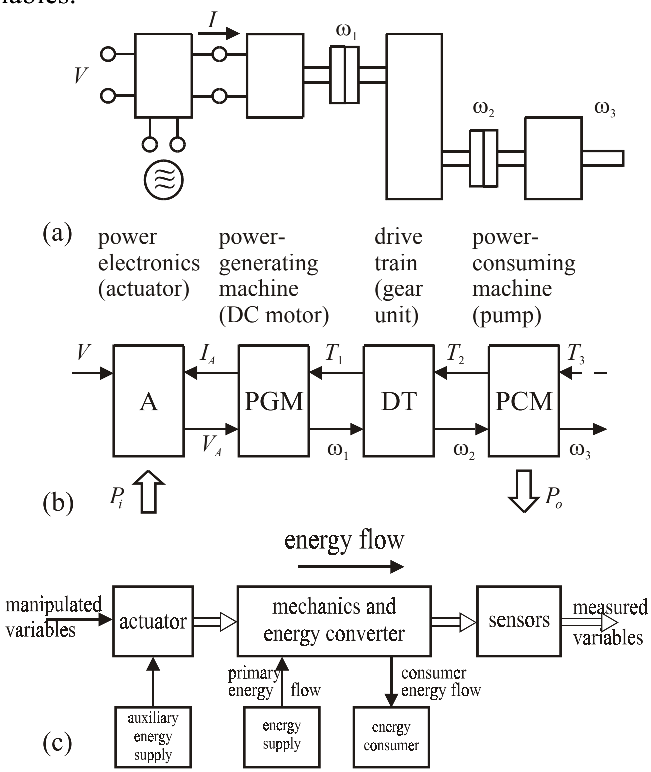

Figure 1.2. Schematic representation of a machine set: (a) scheme of the components; (b) signal flow diagram (two-port representation); (c) open-loop process
V voltage; V_A armature voltage; I_A armature current; T torque; ω angular frequency; P_i drive power; P_o consumer power

This process is characterized by different controllable energy flows (electrical, mechanical, hydraulic). The first and last flow can be manipulated by a manipulated variable of low power (auxiliary power), *e.g.*, through a power electronics device and a flow valve actuator. Several sensors yield measurable variables. For a mechanical-electronic system, a digital electronic system is added to the process. This electronic system acts on the process based on the measurements or external command variables in a feedforward or feedback manner, Figure 1.3. If then the electronic and the mechanical system are merged to an autonomous overall system, an integrated mechanical-electronic system results. The electronics processes process information, and such a system is characterized at least by a mechanical energy flow and an information flow.

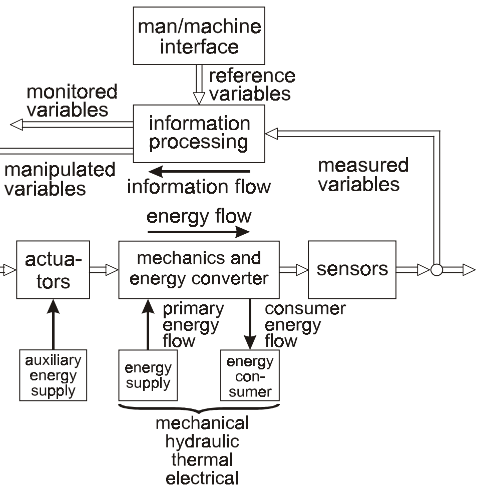

Figure 1.3. Mechanical process and information processing develop towards a mechatronic system

These integrated mechanical-electronic systems are increasingly called mechatronic systems.

Thus, MECHAnics and ElecTRONICS are conjoined. The word "mechatronics" was probably first created by a Japanese engineer in 1969, Kyura, Oho (1996). Several definitions can be found in the literature. The journal *Mechatronics* (1991) uses the following scope: "Mechatronics in its fundamental form can be regarded as the fusion of mechanical and electrical disciplines in modern engineering processes. It is a relatively new concept to the design of systems, devices and products aimed at achieving an optimal balance between basic mechanical structures and its overall control ." In the *IEEE/ASME Transactions on Mechatronics* (1996), a preliminary definition is given: "Mechatronics is the synergetic integration of mechanical engineering with electronics and intelligent computer control in the design and manufacturing of industrial products and processes." (Harashima, Tomizuka (1996)).

The IFAC Technical Committee on Mechatronic Systems, founded in 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."

All definitions agree that mechatronics is an interdisciplinary field, in which the following disciplines act together, Figure 1.4:

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

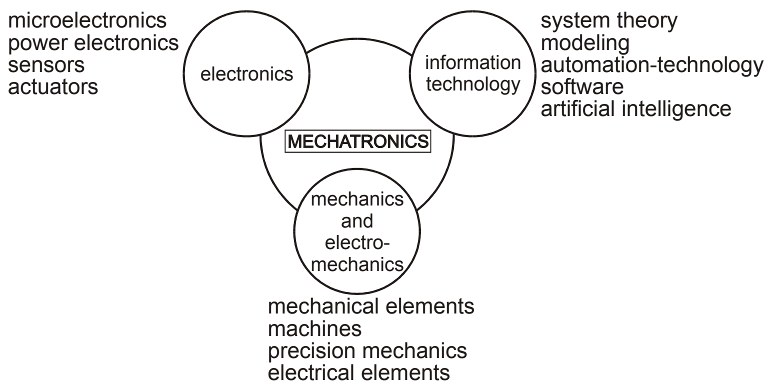

Figure 1.4. Mechatronics: synergetic integration of different disciplines

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, Figure 1.5. 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 developing with adaptive or even learning behavior which can also be called *intelligent mechatronic systems*, see also Section 1.5.

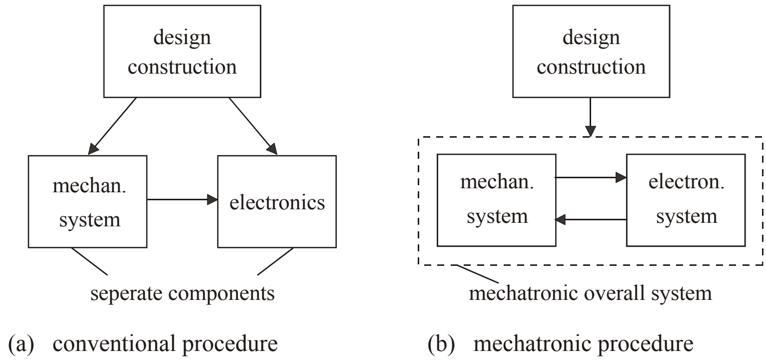

Figure 1.5. Interrelations during the design and construction of mechatronic systems

Descriptions of developments up until now can be seen in Schweitzer (1992), Gausemeiser *et al.* (1995), Harashima, Tomizuka (1996), Isermann (1996), Tomizuka (2000). An insight into general aspects are given editorially in the journals *Mechatronics* (1991), *Mechatronics System Engineering* (1993), *IEEE/ASME Transactions on Mechatronics* (1996), the conference proceedings of, *e.g.*, IEE, Mechatronics (1990), IMES (1993), DUIS (1993), ICRAM (1995), AIM (1999), IFAC (2000), the journal articles by Hiller (1995), Lückel (1995), and the books of Kitaura (1987), Bradley *et al.* (1991), McConaill *et al.* (1991), Isermann (1999).

1.2 MECHANICAL SYSTEMS

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 1.6. Another classification follows the discipline of *kinematics* according to the theory of engineering mechanics. One distinguishes between free (non-constrained) systems, where the elements can move without any constraints, and constrained systems, where elements have rigid joints. The joined systems can have holonomic constraints which restrict their position, or non-holonomic constraints, which restrict their position and velocity. Most mechanical systems in the frame of mechatronic systems belong to constrained systems.

In the following, examples of such systems are considered, for which an integration with electronics already took place or is to be expected. This is followed by a discussion of which systems may be considered to be mechatronic systems.

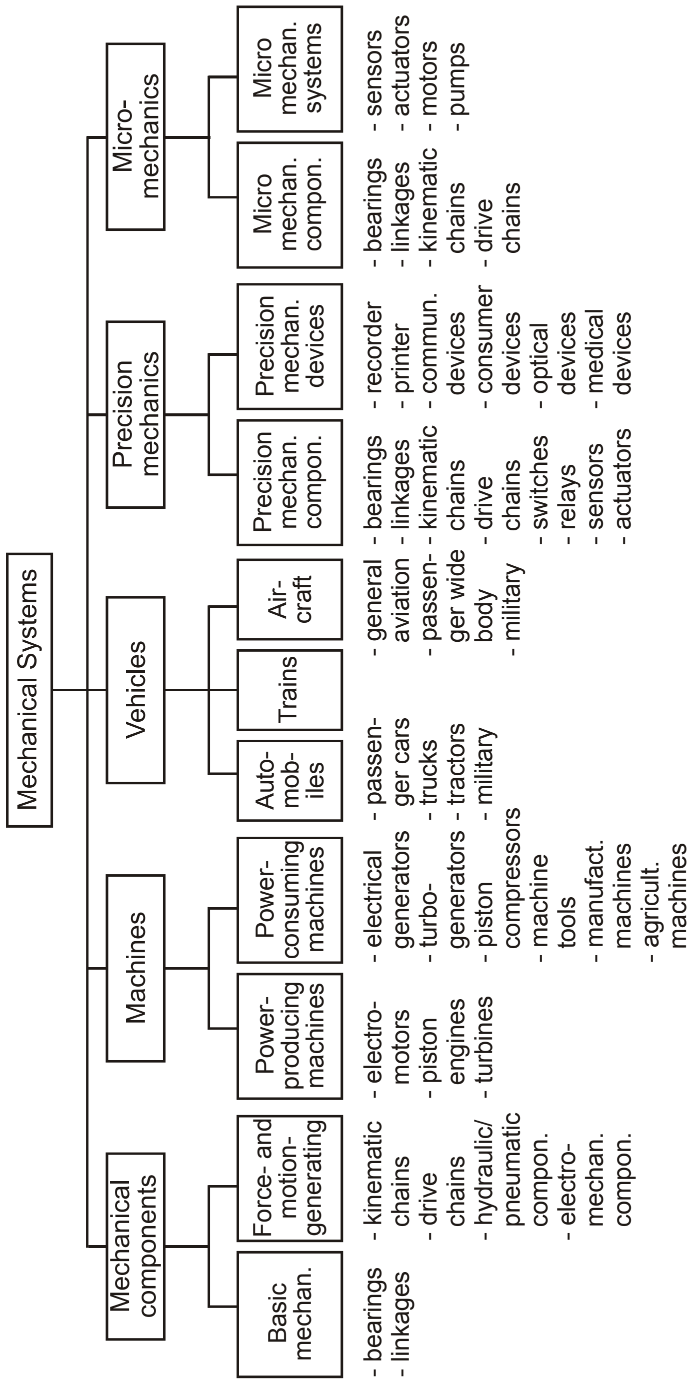

Figure 1.6. Mechanical systems and their classification, with examples

1.2.1 Mechanical Systems in Mechanical Engineering

The design of mechanical products is influenced by the interplay of energy, matter and information. With regard to the basic problem and its solution, frequently either the energy, matter or information flow is dominating. Therefore, one *main flow* and at least one *side flow* can be distinguished, Pahl, Beitz (1986).

The classification of machine elements as components in the engineering of machines, apparatus and devices was proposed by, *e.g.*, Beitz (1989), Roth (1982). The classification of machines according to systematic categories as, *e.g.*, economical branches, functions, operating principles, is given by Hupka (1973), see also Beitz, Küttner (1994). However, because of the manifold of possible classifications and the traditionally well-accepted terms, it is obviously not possible to classify all mechanical systems with a unique scheme, see also Green (1992), Smith (1994), Kreith (1998), Kutz (1998).

a) Machine elements

Machine elements are usually purely mechanical. Figure 1.6 shows some examples. Properties that can be improved by electronics are, for example, self-adaptive stiffness and damping, self-adaptive free motion or pretension, automatic operating functions like coupling or gear shifting, and supervisory functions. Some examples of mechatronic approaches are hydrobearings for combustion engines with electronic control of damping, magnetic bearings with position control, automatic electronic-hydraulic gears, and adaptive shock absorbers for wheel suspensions.

b) Machines

Machines show a particularly rich variability. Power-generating machines are characterized by the conversion of hydraulic, thermodynamic or electrical energy into mechanical energy and delivery of power. Power-consuming machines convert mechanical energy into another form, thereby absorbing energy. For example, vehicles convert mechanical energy into motion and absorb energy. Examples of mechatronic solutions for machines are: diesel engines with common-rail injection system and electronically controlled electromagnetic injection valves, spark-ignition engines with multidimensional look-up tables, knock control, exhaust oxygen control and misfire detection, spark ignition engines with combustion pressure feedback control and ignition timing, replacement of mechanical camshafts with electromagnetic actuated valves, turbojet engines with a multitude of control and supervisory functions, hydraulic piston motors and pumps with integrated control box, machine tools with integrated adaptive cutting force control and fault detection, and industrial robots with sensor-based grippers or tools in lightweight construction or command by sensor gloves.

Several mechatronic components have been introduced for automobiles (passenger cars and trucks), like anti-lock braking control (ABS) with first realization in 1967 and in series production since 1978, anti-slip control (ASR), electronic acceleration pedal with electrical throttle, active chassis control, electronic stability control (ESP), feedback-controlled suspensions with adjustable shock absorbers and pneumatic springs, see, *e.g.*, van Zanten (2000). Mechatronic developments for railway systems are active suspensions, tilting trains and actively steered wheelsets, Goodall, Kortüm (2000).

1.2.2 Mechanical Systems in Precision Mechanic Devices

Precision mechanic devices are characterized by the co-operation of, *e.g.*, precision mechanics, electromechanics, electronics and optics. Here of major interest are devices that are more dedicated to information processing than to energy transfer, Davidson (1968), Koller (1985), Walsh (1999). Figure 1.6 lists some examples. Also, actuators of automation technology belong to this class. Examples of mechatronic precision mechanic systems are brushless, electronically commutated DC motors, electromagnets (solenoids) with non-linear adaptive position control and fault detection, pneumatic cylinders with non-linear adaptive friction compensation, disk drives with precision position control and electronic controlled printers, automatic cameras, camcorders and video projectors. The integration of precision mechanics and microelectronics offers many possibilities for the basic design with integrating, mechatronic solutions. Except for the addition of sensors, actuators and decentralized drives, the digital sequence and feedback control has a considerable influence on the design of the devices. Also, the manual operation with keys and displays has a large impact on the design.

1.2.3 Micromechanics

Based on the continuous efforts of miniaturization, the field of microsystem technology could develop, consisting of, *e.g.*, microelectronic, microelectro-mechanical (MEMS) and micromechanic systems. The miniaturization began with microelectronics. Here, the first transistor in 1947, the first integrated circuit in 1958 and the first microprocessor in 1971 were important milestones. Steps in the direction of microelectromechanical systems were magnetic hard disk drives in around 1970, followed by, *e.g.*, sensors like accelerometers.

Microsystem technology is characterized by its production methods, including bulk micromachining, surface micromachining, fine-molding technologies and precision machining, Sato (2000). Bulk micromachining generates three-dimensional microstructures by etching materials, surface micromachining by layering thin films over the surface of a silicon substrate, fine-molding by a lithographic method for non-silicon structures like metals or polymers and precision machining by conventional cutting tools for metals, specially tailored for small dimensions in the 10 μm area.

Microsystem technology also includes microoptics, microfluidics, microheat-exchangers and microreactors. Based on microsystem components, like microactuators, microprocessors and microsensors, *micromechatronic systems* can be built up, including, for example, electrical micromotors, microgears and micropumps, Ehrfeld *et al.* (2000). This is an area where development is just at the beginning. First products, like yaw-rate and flow sensors, microelectronic gyros, ink-jet printer heads, piezoceramic actuators, micromotors with 2 mm diameter, planetary gears with 55 μm diameter, microscanners, micromirrors and micropumps, show the potential, Janocha (2000).

Further literature for this fast-progressing field includes Gad-el-Hak (2000), Madon (2001), Lyshevski (2001).

1.2.4 Mechanical Systems in Apparatus (Process Engineering)

Apparatus can be described as technical systems with a primary goal of processing materials and/or enabling material or heat flow, Koller (1985). Examples are mechanical apparatus like pipelines, valves, grinding machines, pneumatic sifters and filters, thermal apparatus like heat-exchangers, boilers and components for heating, ventilation and air conditioning, and burners, chemical reactors and stirring vessels. For these apparatus, an increasing integration with electronic control can also be observed. One example of simultaneous engineering is a design for fast-changing energy and material flows to follow fast load demands, thus saving large storage and investment costs (*e.g.*, for steam boilers, heating boilers, water supply systems). Digital adaptive control can compensate the partially very non-linear behavior, enabling a wide-range operation with high product performance. Also, the precisely adapted automation in the higher levels allows much progress, *e.g.*, in the frame of supervision, optimization and at the human – machine interface. Hence, several integrating design approaches and properties of mechatronic systems for machine elements and machines hold also for some apparatus. However, these partially mechanical systems are usually not considered as part of mechatronic systems.

1.2.5 Confinement of Mechatronic Systems

The previous discussion shows that the integration of electronics and information processing in the sense of mechatronic systems comprises many technical areas. Besides the mechanical process part, in many cases an electrical, thermal, thermodynamical, chemical or information-transferring part exists. One reason is that machines, devices and apparatus are often energy converters that contain energy forms other than just mechanical energy. Then, the non-mechanical process parts cannot be separated from the mechanical part with regard to the functions and the signal flow. Therefore, mechatronic systems can also include electrical, thermal, thermodynamical, chemical and information-carrying process parts. In addition to Section 1.1, this leads to an extended definition:

"Mechatronic systems in a wide sense can be considered as an interdisciplinary field in which the following disciplines are acting together, Figure 1.4:

- mechanical and coupled systems;
- electronic systems;
- information technology.

Herewith, the mechanical system should dominate with regard to the overall function. In addition, synergetic effects should be created, which contain more than the pure addition of the disciplines ."

The field of mechatronics therefore can be seen to comprise, except for the purely mechanical machine elements, the machines and the precision mechanical devices, and also a small part of apparatus, like transporting systems, mills, oil and gas burners. However, the border between mechatronic systems and electronics integrated systems, for which until now no special term exists, is not crisp, but gradual.

1.3 FUNCTIONS OF MECHATRONIC SYSTEMS

Mechatronic systems enable, after the integration of the components, many improved and also new functions. This will be discussed by using examples.

1.3.1 Design

The basic mechanical construction first has to satisfy the task of transferring the mechanical energy flow (force, torque) to generate motions or special movements, *etc*. Known traditional methods are applied, like material selection, calculation of strengths, manufacturing, production costs, *etc*. By attaching sensors, actuators and mechanical controllers, in earlier times, simple control functions were realized, *e.g.*, the flyball governor. Then gradually pneumatic, hydraulic and electrical analog controllers were used. After the advent of digital control systems, especially with microprocessors in around 1975, the information processing part could be designed to be much more sophisticated. These digitally controlled systems had been first added to the basic mechanical construction and their limitations were given by the properties of the sensors, actuators and electronics, *i.e.*, they were frequently not satisfying reliability and lifetime requirements under the rough environmental conditions (temperature, vibrations, contamination) and had a relatively large space requirement, cable connections and low computational speed. However, many of the initial drawbacks have been removed during time, and since about 1980 the electronic hardware is much more miniaturized, robust and powerful and connected by field bus systems. Hence, the emphasis on the electronic side could be increased and the mechanical construction could be designed as a mechanical-electronic system from the very beginning. The aim was to result in more autonomy, for example, by decentralized control, field bus connections, plug-and-play approaches, distributed energy supply, *etc*, such that self-contained units emerge.

1.3.2 Distribution of Mechanical and Electronic Functions

Mechatronic systems permit many improved and new functions. This will be discussed by considering some examples.

In the design of mechatronic systems, the interplay for the realization of functions in the mechanical and electronic part is crucial. Compared to pure mechanical realizations, the use of amplifiers and actuators with electrical auxiliary energy has already led to considerable simplifications, as can be seen from watches, electronic typewriters and cameras. A further considerable simplification in the mechanics resulted from introducing microcomputers in connection with decentralized electrical drives, *e.g.*, for electronic typewriters, sewing machines, multi-axis handling systems and automatic gears.

The design of lightweight constructions leads to elastic systems that are weakly damped through the material itself. An *electronic damping* through position, speed or vibration sensors and electronic feedback can be realized with the additional advantage of an adjustable damping through the algorithms. Examples are elastic drivetrains of vehicles with damping algorithms in the engine electronics, elastic robots, hydraulic systems, far-reaching cranes and space constructions (*e.g.*, with flywheels).

The addition of closed-loop control, *e.g.*, for position, speed or force, does not only result in a precise tracking of reference variables, but also an approximate linear overall behavior, though the mechanical systems show non-linear behavior. By omitting the constraint of linearization on the mechanical side, the effort for construction and manufacturing may be reduced. Examples are simple mechanical pneumatic and electromechanical actuators and flow valves with electronic control.

With the aid of freely programmable reference variable generation, the adaptation of non-linear mechanical systems to the operator can be improved. This is already used for the driving pedal characteristics within the engine electronics for automobiles, telemanipulation of vehicles and aircraft and in the development of hydraulic actuated excavators and electric power steering.

However, with increasing number of sensors, actuators, switches and control units, the cables and electrical connections also increase such that reliability, cost, weight and the required space are major concerns. Therefore, the development of suitable bus systems, plug systems and fault-tolerant and reconfigurable electronic systems are challenges for the design.

1.3.3 Operating Properties

By applying active feedback control, the precision of, *e.g.*, a position is reached by comparison of a programmed reference variable with measured control variable and not only through the high mechanical precision of a passively feedforward-controlled mechanical element. Therefore, the mechanical precision in design and manufacturing may be reduced somewhat and more simple constructions for bearings or slideways can be used. An important aspect is hereby the compensation of a larger and time-variant friction by *adaptive friction compensation*, Isermann *et al.* (1992). Then also a larger friction on the cost of backlash may be intended (*e.g.*, gears with pretension), because it is usually easier to compensate for friction than for backlash.

Model-based and adaptive control further allow an operation in more operating points (wide-range operation), compared to fixed control with unsatisfactory performance (danger of instability or sluggish behavior). A combination of robust and adaptive control allows a wide-range operation to become possible, *e.g.*, for flow-, force-, speed-control and for processes involving engines, vehicles and aircraft. A better control performance allows the reference variables to be moved closer to constraints with improved efficiencies and yields (*e.g.*, higher temperatures, pressures for combustion engines and turbines, compressors at stalling limits, higher tensions and higher speed for paper machines and steel mills).

1.3.4 New Functions

Mechatronic systems also allow functions that could not be performed without digital electronics. Firstly, non-measurable quantities can be calculated on the basis of measured signals and influenced by feedforward or feedback control. Examples are time-dependent variables like the slip for tires, internal tensions, temperatures, the slip angle and ground speed for steering control of vehicles or parameters like damping and stiffness coefficients and resistances. The automatic adaptation of parameters, like damping and stiffness for oscillating systems based on measurements of displacements or accelerations, is another example. Integrated supervision and fault diagnosis becomes more and more important with increasing automatic functions, increasing complexity and higher demands on reliability and safety. Then, fault-tolerance by triggering of redundant components and system reconfiguration, maintenance on request and any kind of teleservice makes the system more “intelligent”.

1.3.5 Other Developments

Mechatronic systems frequently allow a flexible adaptation to boundary conditions. A part of the functions and also precision becomes programmable and fast changeable. Advance simulations enable the reduction of experimental investigations with many parameter variations. Also, a faster time-to-market is possible if the basic elements are developed in parallel and the functional integration results from the software.

A far-reaching integration of the process and the electronics is much easier if the customer obtains the functioning system from one manufacturer. Usually, this is the manufacturer of the machine, the device or the apparatus. Although this manufacturer has to cope intensively with the electronics and the information processing, they get the chance to add to the value of the product. For small devices and machines with large production numbers, this is obvious. In the case of larger machines and apparatus, the process and its automation frequently comes from different manufacturers. Then, special effort is needed to result in integrated solutions.

Table 1.1 summarizes some properties of mechatronic systems compared to conventional electromechanical systems and Table 1.2 shows practical examples for the corresponding rows of Table 1.1.

1.4 INTEGRATION FORMS OF PROCESSES AND ELECTRONICS

Figure 1.7a shows a general scheme of a classical mechanical-electronic system. Such systems resulted from adding available sensors and actuators and analog or digital controllers to the mechanical components. The limits of this approach were the lack of suitable sensors and actuators, the unsatisfactory lifetime under the rough operating conditions (acceleration, temperature, contamination), the large space requirements, the required cables and relatively slow data processing. With increasing improvements of the miniaturization, robustness and computing power of microelectronic components, one can now 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 capsuled units with touchless signal transfer or bus connections and robust microelectronics.

Table 1.1. Properties of conventional and mechatronic designed systems

conventional design	**mechatronic design**
added components	**integration of components**
1 bulky	compact
2 complex	simple mechanisms
3 cable problems	bus or wireless communication
4 connected components	autonomous units
simple control	**integration by information processing (software)**
5 stiff construction	elastic construction with damping by electronic feedback
6 feedforward control, linear (analog) control	programmable feedback (non-linear) digital control
7 precision through narrow tolerances	precision through measurement and feedback control
8 non-measurable quantities change arbitrarily	control of non-measurable estimated quantities
9 simple monitoring	supervision with fault diagnosis
10 fixed abilities	adaptive and learning abilities

Table 1.2. Realization examples for the properties given in Table 1.1

conventional design	**mechatronic design**
added components	**integration of components**
1 electromechanical typewriter	electronic printer
2 mechanically controlled injection pump with rotating piston	high pressure pump and magnetic injection valves (common rail)
3 many wiring	bus cable
4 belt-driven auxiliaries	decentralized driven auxiliaries
simple control	**integration by information processing (software)**
5 stiff drivetrain	elastic drivetrain with algorithmic damping through engine control
6 mechanical gas pedal	electronic non-linear throttle control
7 feedforward-controlled actuator	feedback-controlled actuator with friction compensation
8 manual steering of cars during spinning	feedback control of slip angle by state observer and individual wheel braking
9 monitoring of exhaust gases through maintenance or inspection	on-board misfire detection by speed measurement of engine crankshaft
10 rail vehicles	mobile vehicle with automatic navigation

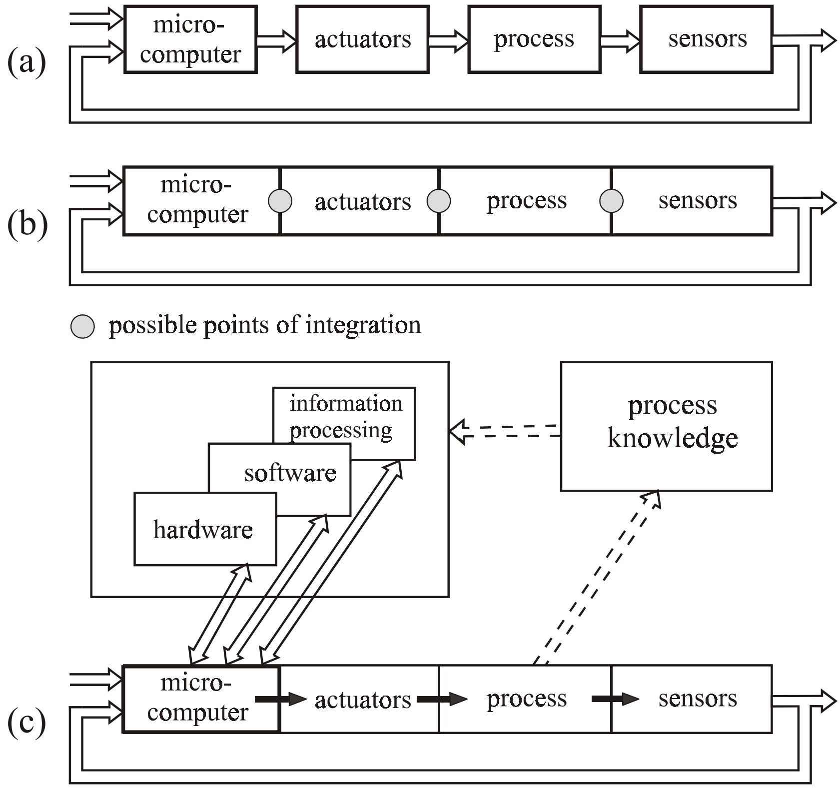

Figure 1.7. Integration of mechatronic systems: (a) general scheme of a (classical) mechanical-electronic system; (b) integration through components (hardware integration); (c) integration through functions (software integration)

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 1.7b. 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. Hence, there are several possibilities for building an integrated overall system by proper integration of the hardware.

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, see Figure 1.7c. This means a processing of available signals in higher levels, as to be discussed in the next section. This includes the solution of tasks like supervision with fault diagnosis, optimization and general process management. The respective problem solutions result in real-time algorithms, which must be adapted to the mechanical process properties, *e.g.*, expressed by mathematical models in the form of static characteristics, differential equations, *etc.* 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, Figure 1.8.

In the following, mainly the integration through information processing will be considered further.

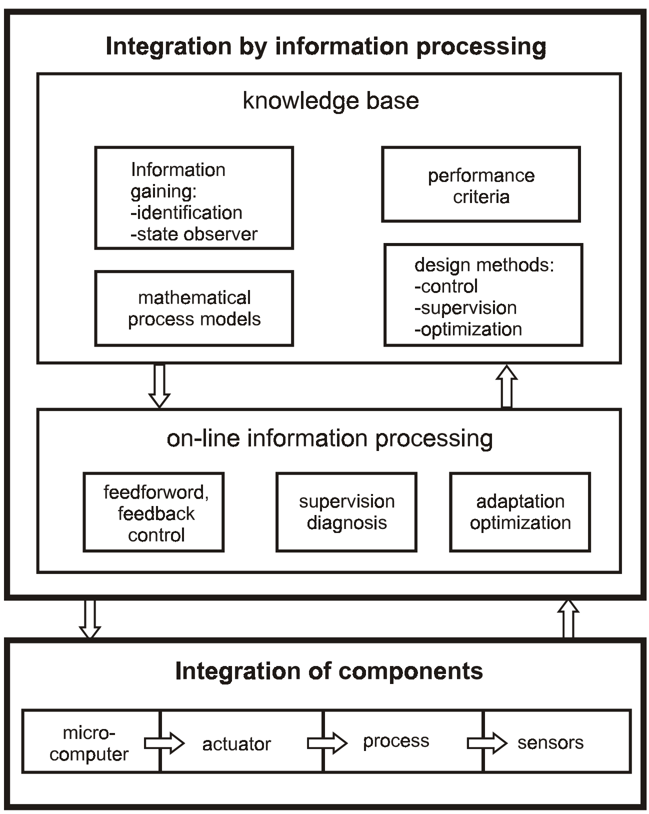

Figure 1.8. Integration of mechatronic systems: integration of components (hardware integration); integration by information processing (software integration)

1.5 WAYS OF INFORMATION PROCESSING

The governing of mechanical systems is usually performed through actuators for changing of positions, speeds, flows, forces or torques, and voltages. The directly measurable output quantities are frequently positions, speeds, accelerations or forces and currents. The different ways of information processing methods can be subdivided into multi-level process automation, special signal processing, model-based and adaptive control and intelligent systems.

1.5.1 Multi-level Control Systems

The information processing of direct measurable input and output signals can be organized in several levels, compare Figure 1.9:

level 1a: low-level control (feedforward, feedback for damping, stabilization, linearization);
level 1b: high-level control (advanced feedback control strategies);
level 2: supervision including fault diagnosis;
level 3: optimization, coordination (of processes);
level 4: general process management.

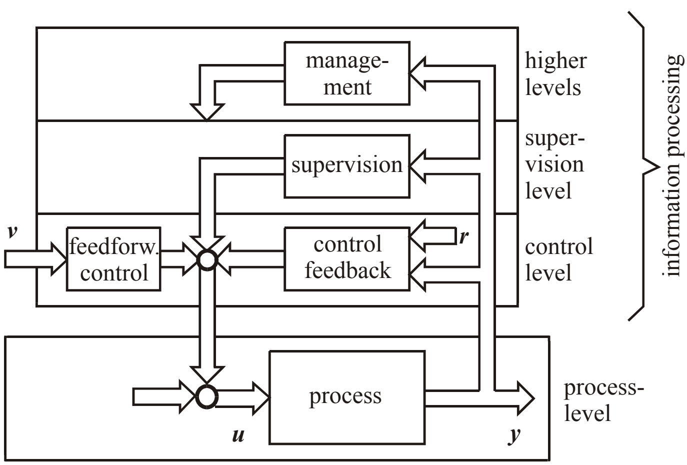

Figure 1.9. Different levels of information processing for process automation
u: manipulated variables; ***y***: measured variables; ***v***: input variables; ***r***: reference variables

Generally, it can be observed:

- lower levels: react fast, act locally,
- higher levels: react slowly, act globally.

Recent approaches for mechatronic systems mostly use signal processing in the lower levels, *e.g.*, damping or control of motions or simple supervision. Digital information processing, however, allows the solutions of many more tasks, such as adaptive control, learning control, supervision with fault diagnosis, decisions for maintenance or even fault-tolerance actions, economic optimization and coordination. The tasks of the higher levels are sometimes summarized as "process management".

1.5.2 Special Signal Preprocessing

The methods described above are partially also applicable to non-measurable quantities that are reconstructed by using mathematical process models. In this way, it is possible to control, *e.g.*, damping ratios, material and heat stress and slip or to supervise quantities like resistances, capacitances, temperatures within components, or parameters of wear and contamination. This signal processing may require special filters to determine amplitudes or frequencies of vibrations, to determine derived or integrated quantities, or state variable observers, compare Figure 1.10.

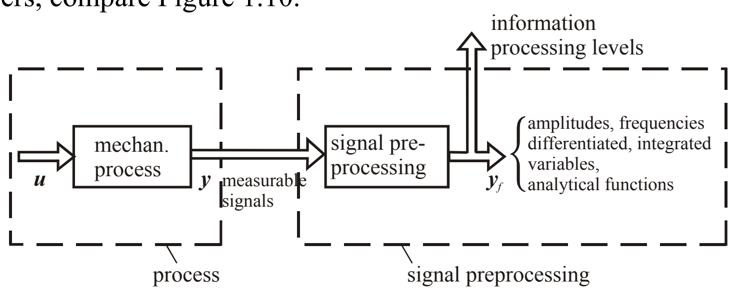

Figure 1.10. Special signal processing to obtain non-measurable quantities (signal preprocessing)

1.5.3 Information Gaining

A precondition for precisely adapted algorithms for feedforward and feedback control, for damping by electronic feedback, for fault detection, *etc.*, is the knowledge of mathematical process models for static and dynamic behavior. In the case of mechanical processes, the model structure and some model parameters can frequently be obtained through theoretical modeling. Based on this model structure in the form of linear and non-linear differential equations, the measured input and output variables can be brought into their causal relationships and information on the internal process behavior can be obtained.

Parameter estimation

The output error $e(t)$ between the measured output signal $y(t)$ and the output signal $y_M(t)$ of a virtual parallel model (or the equation error) is formed, Figure 1.11a. The parameters $\hat{\Theta}$ of the model are then estimated by searching for the minimum of the sum of the squared errors (method of least squares). Well-proven algorithms and software modules in non-recursive or recursive form exist, also for continuous time, discrete time and slowly time-variant parameters and some non-linear models, see Chapter 7.

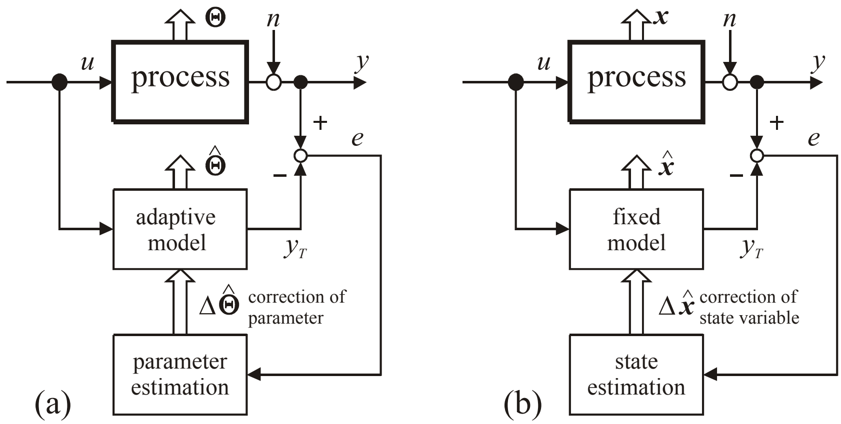

Figure 1.11. Model-based methods to obtain information of dynamical processes
output error: $e(t) = y(t) - y_M(t)$

(a) parameter estimation
$\boldsymbol{\Theta}$: real process parameters
$\hat{\boldsymbol{\Theta}}$: estimated process parameters

(b) state estimation
$\boldsymbol{x}$: real process state variables
$\hat{\boldsymbol{x}}$: estimated process state variables

State estimation

If the parameters Θ or ***a***, ***b***, ***c*** of a state variable model are known, the output error $e(t)$ can be fed back and the time-variant state variables $\boldsymbol{x}(t)$ can be corrected by $\Delta\boldsymbol{x}(t)$, Figure 1.11b. With a design for deterministic signals, a state observer is obtained and for stochastic signals a state estimation (Kalman filter) results. Then, non-measurable, internal process variables can be estimated, Föllinger (1992), Ogata (1997), Franklin *et al.* (1998), Dorf, Bishop (2000), see Chapter 7.

The results of the parameter estimation can, for example, be used for adaptive control or damping or for model-based fault detection. State variable estimates are the basis for state feedback to control and stabilize systems with difficult behavior, or for the control of non-measurable variables and fault detection with state observers.

1.5.4 Model-based Methods of Control

The information processing is, at least in the lower levels, performed by simple algorithms or software modules under real-time conditions. These algorithms contain free adjustable parameters, which have to be adapted to the static and dynamic behavior of the process. In contrast to manual tuning by trial and error, the use of mathematical models allows precise and fast automatic adaptation.

The mathematical models can be obtained by identification and parameter estimation, which use the measured and sampled input and output signals. These methods are not restricted to linear models, but also allow the identification of several classes of non-linear systems. If the parameter estimation methods are combined with appropriate control algorithm design methods, adaptive control systems result, which can be used for precise controller tuning permanently or only for commissioning, Åström, Wittenmark (1994), Isermann *et al.* (1992), Figure 1.12.

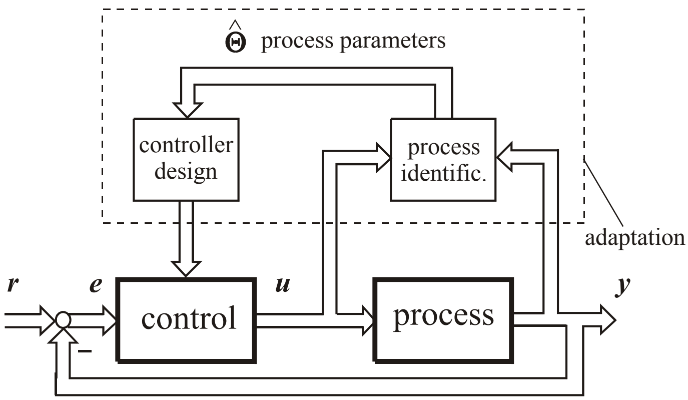

Figure 1.12. Adaptive control through permanent process identification and controller design

1.5.5 Supervision and Fault Diagnosis

With the increasing number of automatic functions (autonomy) including electronic components, sensors and actuators, increasing complexity and increasing demands on reliability and safety, integrated supervision with fault diagnosis becomes more and more important. This is, therefore, a significant natural feature of an intelligent mechatronic system. Figure 1.13 shows a process influenced by faults. These faults indicate unpermitted deviations from normal states and can be 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 method for fault detection is the limit value checking or plausibility checks of a few measurable variables. However, incipient and intermittent faults cannot usually be detected and an in-depth fault diagnosis is not possible with this simple approach. Therefore, 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 (1999), Chen, Patton (1999). Based on measured input signals $\boldsymbol{U}(t)$, output signals $\boldsymbol{Y}(t)$ and process models, features are generated by, *e.g.*, parameter estimation, state and output observers and parity equations, Figure 1.13.

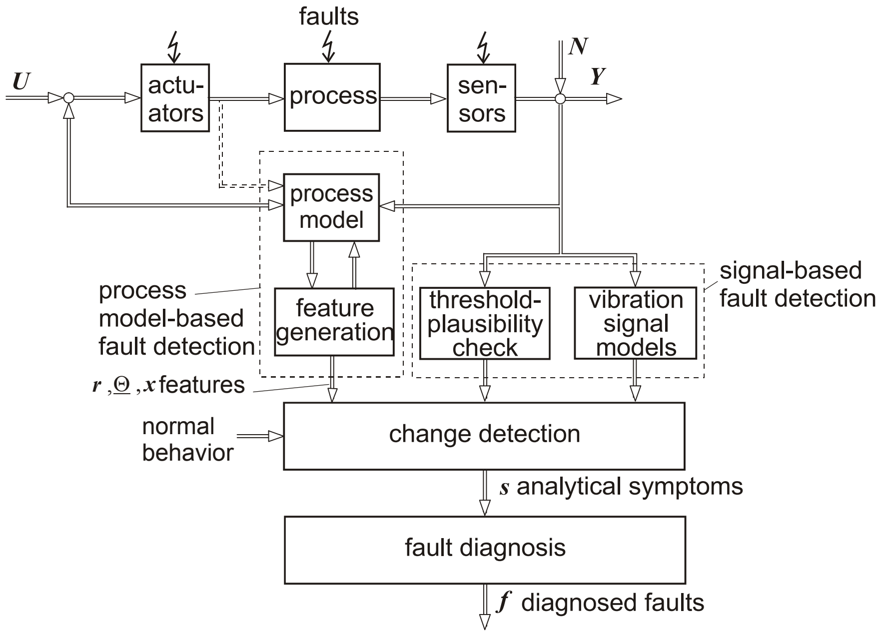

Figure 1.13. Scheme for a model-based fault detection

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. For fault detection with parameter estimation, state estimation and also parity equations discrete time models can also be used.

Advanced supervision and fault diagnosis is a basis for improving reliability and safety, state-dependent maintenance, triggering of redundancies and reconfiguration for fault-tolerant systems, Isermann (2000).

1.5.6 Intelligent Systems

The information processing within mechatronic systems may range between simple control functions and "intelligent" control. Various definitions of intelligent control systems do exist, see, *e.g.*, Saridis, (1977), Saridis, Valavanis (1988), Åström (1991), White, Sofge (1992), Antsaklis (1994), Gupta, Sinha (1996), Harris (1994). An intelligent control system may be organized as an on-line expert system according to Figure 1.14 and comprises:

1. multi-control functions (executive functions);
2. knowledge base;
3. inference mechanisms;
4. communication interfaces.

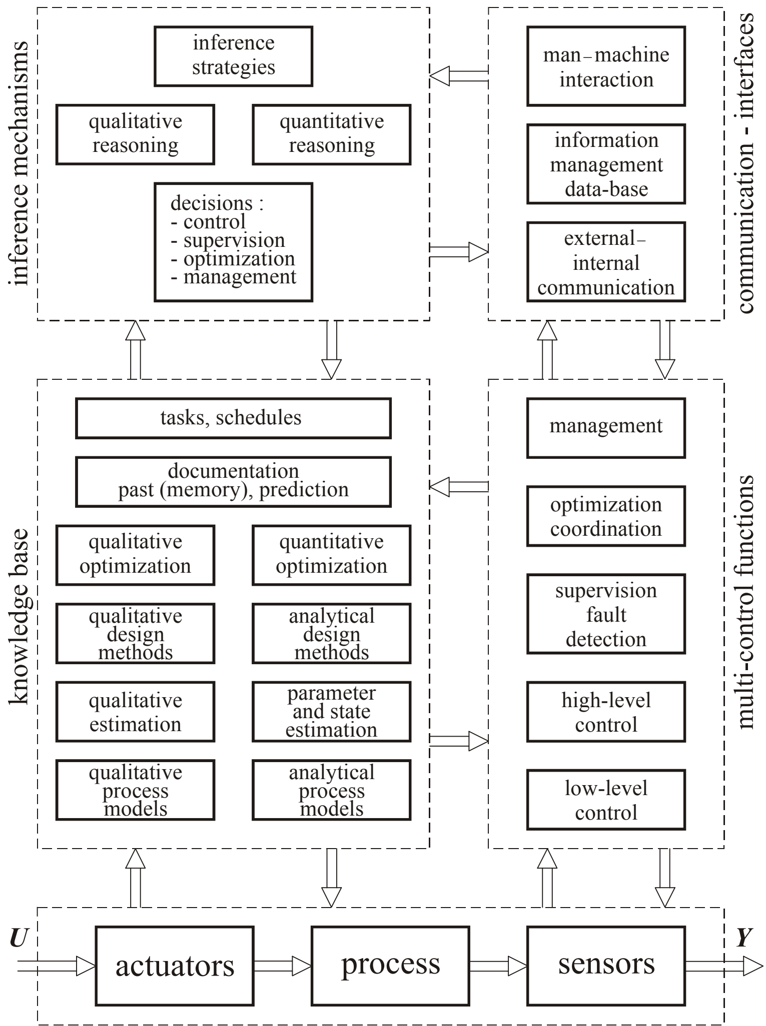

Figure 1.14. Advanced intelligent automatic system with multi-control levels, knowledge base, inference mechanism and interfaces

The on-line control functions are usually organized in multi-levels, as already described. The knowledge base contains quantitative and qualitative knowledge. The quantitative part operates with analytical (mathematical) process models, parameter and state estimation methods, analytical design methods (*e.g.*, for control and fault detection) and quantitative optimization methods. Similar modules hold for qualitative knowledge, *e.g.*, in the form of rules (fuzzy logic and soft computing). Further knowledge is the past history of events and the possibility of predicting the behavior. Finally, tasks or schedules may be included.

The inference mechanism draws conclusions either by quantitative reasoning (*e.g.*, Boolean methods) or by qualitative reasoning (*e.g.*, possibilistic methods) and takes decisions for the executive functions.

Finally, communication between the different modules, an information management database and the man–machine interaction has to be organized.

Based on these functions of an on-line expert system, an intelligent system can be built up with the ability "to model, reason and learn the process and its automatic functions within a given frame and to govern it towards a certain goal". Hence, intelligent mechatronic systems can be developed, ranging from the "low-degree intelligent" such as intelligent actuators, to "fairly intelligent systems" such as self-navigating automatic guided vehicles.

An intelligent mechatronic system can adapt the controller to mostly nonlinear behavior (adaptation) and store its controller parameters dependent on the position and load (learning), supervise all relevant elements and perform a fault diagnosis (supervision) to request for maintenance or if a failure occurs (decisions on actions). In the case of multiple redundant components, supervision may help to switch off the faulty component and to perform a reconfiguration of the controlled process, thus making the mechatronic system fault-tolerant.

1.6 DESIGN PROCEDURES FOR MECHATRONIC SYSTEMS

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. Figure 1.15 shows a general procedure and the summary below lists some typical design steps, summarizing the discussion before. This compilation shows again that it is the integration of engineering across traditional boundaries that is typical of the development of mechatronic systems. As many of these design steps are treated in the various chapters of this book, they are not further commented on here.

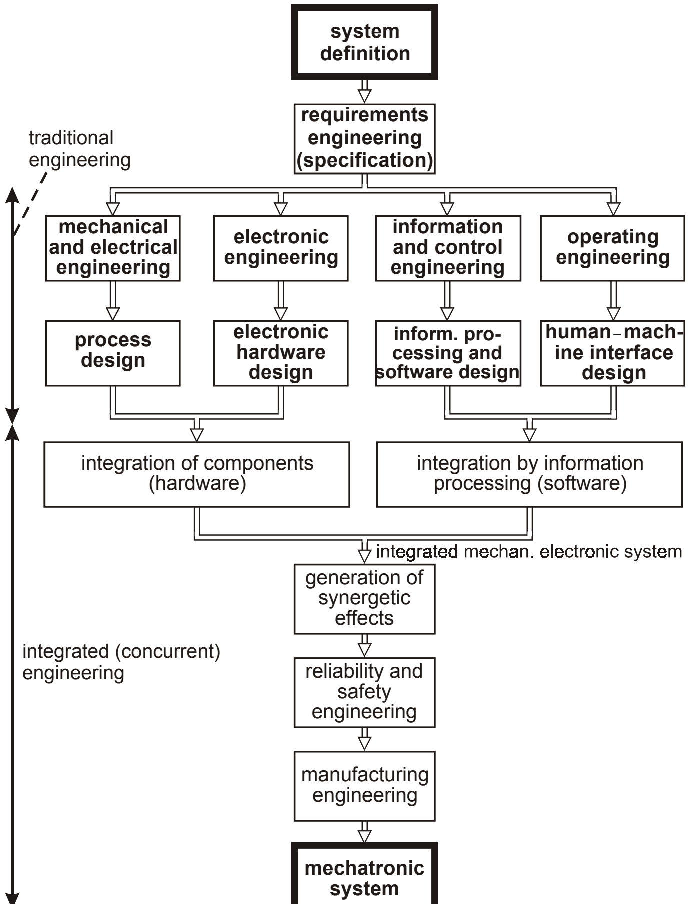

Figure 1.15. Design procedure for mechatronic systems (iteration steps are not indicated)

Integrated engineering for mechatronic systems (summary)

1. *System definition and requirements engineering*
   - definition of general functions and data of the process or product or system;
   - traditional solutions;
   - new functions;
   - sources, limitations;
   - costs;
   - time schedules.
2. *Solutions by traditional engineering (review)*
   - mechanical, hydraulic, pneumatic, electrical, thermal... components;
   - electronic components, sensors, actuators;
   - information processing and automatic control;

– operator's console.

3. *First mechatronic design*
   – simultaneous mechanical, electrical, electronic, information;
   – control and operating engineering;
   – design of modules;
   – task distribution between mechanical, electrical and electronic modules;
   – addition of sensors and actuators;
   – addition of information processing;
   – electronic hardware architecture (microprocessors, bus systems, plug systems);
   – software architecture (structure, language, real-time solutions);
   – control engineering;
   – modeling and simulation.
4. *Human–machine interface*
   – electronic buttons, pedals, sticks or wheels;
   – haptic force or torque feedback;
   – graphic displays, instruments, screens;
   – operator supervision and emergency assistance;
   – teleoperation with visual or tactile feedback.
5. *Integration of components (hardware)*
   – spatial integration of process and electronics;
   – embedding of sensors and microcomputers in mechanics;
   – integration of actuators;
   – integration of cables by bus systems;
   – sophisticated plug systems.
6. *Integration by information processing (software)*
   – model-based computation of non-measurable variables;
   – compensation of non-linearities by algorithms;
   – damping of oscillations by proper feedback algorithms;
   – wide operating conditions through adaptive control algorithms and state observation;
   – special control algorithms for start-up, warm-up, normal operation and shut-down;
   – automatic fault detection and diagnosis;
   – fault-tolerance through analytical redundancy (see 8.);
   - learning behavior.
7. *Redesign of mechanical and electrical construction*
   – simplification of mechanical and electrical design;
   – generation of special kinematic functions through servo-drives and control algorithms;
   – replacement of linearization by mechanical or electrical design through non-linear control algorithms;
   – lightweight construction with damping through electronic feedback;

   - proper design of dynamics to improve control performance;
   - redesign of intermediate energy or mass storages through improved control performance.
8. *Reliability and safety engineering*
   - failure mode effect analysis (FMEA);
   - hazard analysis;
   - fault- tolerance through hardware redundancy and analytical redundancy (process model-based);
   - fault detection and reconfiguration;
   - fail operational, fail-safe, fail-silent design.
9. *Generation of synergetic effects*
   - use of some components for different tasks;
   - use of mathematical process models for control and fault detection;
   - use of actuator signals as measurements for the driven mechanical system ("actuator as sensor principle");
   - improvement of precision and dynamics through electronic feedback control (*e.g.*, actuators or automobiles);
   - use of the masses of submodules for the absorption of vibrations of the main module (*e.g.*, front end part of a car);
   - improvement of comfort and safety (automotive suspensions).
10. *Use of special design tools*
   - computer-aided design (throughout for all elements);
   - mechatronic design platform;
   - modeling, identification, control algorithm design, simulation (hardware-in-the-loop);
11. *Experimental verification*
   - all individual components;
   - subsystems;
   - overall systems;
   - human–machine interplay.

Figure 1.16 shows five important development steps for mechatronic systems, starting from a purely mechanical system and resulting in a fully integrated mechatronic system. Depending on the type of mechanical system, the intensity of the single development steps is different. For precision mechanical devices, fairly integrated mechatronic systems already exist. The influence of the electronics on mechanical elements may be considerable, as shown by adaptive dampers, anti-lock system brakes and automatic gears. However, complete machines and vehicles show first a mechatronic design of their elements and then slowly a redesign of parts of the overall structure as can be observed in the development of machine tools, robots and vehicle bodies.

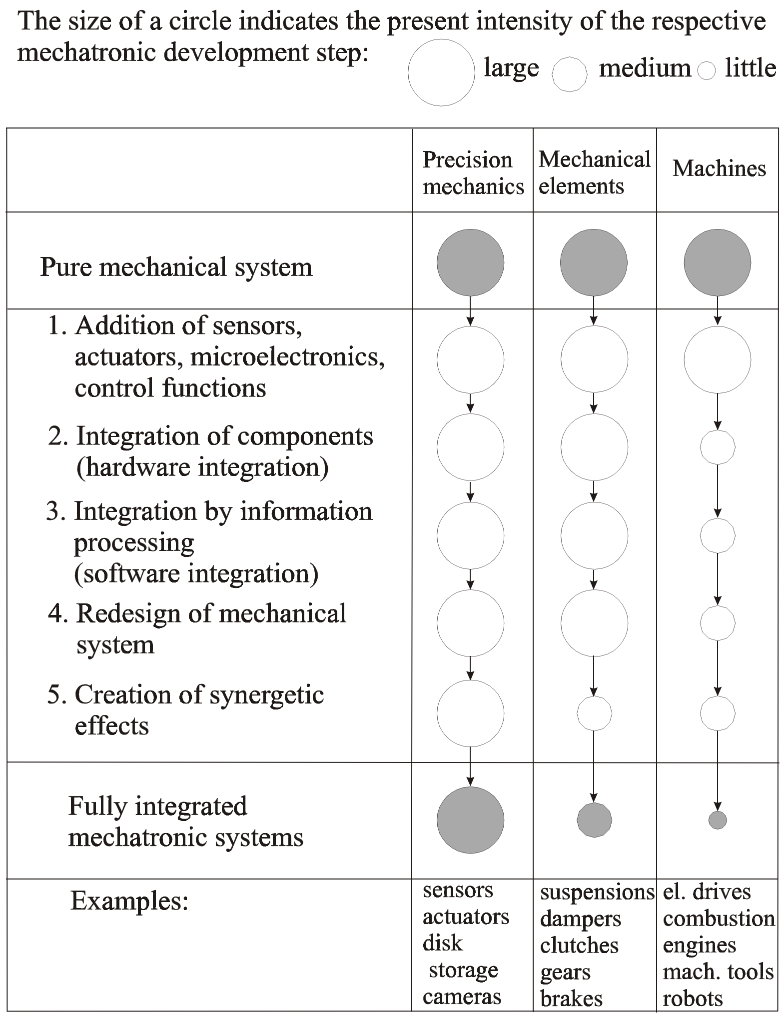

Figure 1.16. Typical steps in the design of mechatronic systems

The computer-aided development of mechatronic systems comprises:

1. constructive specification in the engineering development stage using CAD and CAE tools;
2. model building for obtaining static and dynamic process models;
3. transformation into computer codes for system simulation;
4. programming and implementation of the final mechatronic software.

Some software tools are described, for example, in Otter, Gruebel (1993). A broad range of CAD/CAE tools is available for 2D and 3D mechanical design, such as AutoCAD with a direct link to CAM (computer-aided manufacturing);

PADS for multi-layer printed circuit board layout, *etc*. However, computer-aided modeling has not advanced as much, see Section 2.1. Object-oriented languages such as DYMOLA, MOBILE and MODELICA for modeling of large combined systems are described in Otter, Gruebel (1993), Elmqvist (1993), Hiller (1995). These packages are based on specified ordinary differential equations, algebraic equations and discontinuities. A recent description of the state of computer-aided control system design can be found in James *et al*. (1995). For system simulation (and controller design), a variety of program systems exist, like ACSL, SIMPACK, MATLAB/SIMULINK. These simulation techniques are valuable tools for the design, as they allow the study of the interaction of components and the variations of design parameters before manufacturing. However, they are in general not suitable for real-time simulation.

1.7 CONTENTS OF THIS BOOK

The previous general considerations on mechatronic systems show that for the design, the start-up and the operation of mechatronic systems, the following aspects are important:

- *systematic description of the processes,* consisting of the mechanical, electrical, thermal and thermodynamic process parts;
- *systematic description of the information-transferring components,* as sensors, actuators and microelectronics;
- *modeling and simulation* of the static and dynamic behavior of the components and the overall mechatronic system;
- *architecture* of the digital computers and buses;
- *methods of information processing* for control, supervision, optimization, *etc*.;
- *software design tools* for modeling, simulation, mechanical design, computer-aided design, implementation, experimental test procedures, *etc.*;
- *operating engineering* (human–machine interface design);
- *entirely and unified treatment* in all development phases.

For many of the sub-areas there exists much literature, books and handbooks. First representations in its entirety appeared mainly in the frame of control engineering as, *e.g*., Oppelt (1953, 1972), Töpfer, Kriesel (1977, 1983). A first, more comprehensive, book on mechatronics was published by Bradley *et al.* (1991). It mainly considers the information-transferring components and system aspects.

In this book, the basics of modeling for the static and dynamic behavior of technical processes are treated in the first part. After classification of process elements, the fundamental equations for processes with energy and matter flows are stated in unified form for processes with lumped parameters in Chapter 2. Herewith, the equations are subdivided into balance equations, constitutive equations, phenomenological equations and connection laws. The resulting causalities are described and a general procedure for theoretical modeling is given. This is followed by the principles of mechanics for systems with many mobile masses in Chapter 3. One goal for the unified systematic treatment of modeling is the possibility of a unified representation of mechanical, electrical and thermal processes in the form of differential equations, state space equations and for the development of transparent block diagrams or for object-oriented software tools.

Then, frequently appearing models of mechanical elements, such as linkages and different machine elements (bearings, gears), and one-mass and multi-mass oscillators are considered in Chapter 4. This is followed in Chapter 5 by a survey of the most important electrical drives as electromagnets and electromotors in the form of direct current and alternating current motors for use in mechatronic systems. Basic models for the dynamic behavior of electromagnets, DC motors and inductance motors are described, and for several types the main characteristics of the static and dynamic behavior are given.

Modeling of machines is based on the previously established elementary models and leads to equation systems, preferably stated in state space representation, in Chapter 6. Then, the general behavior of machines is considered through the interaction of the characteristics of power-generating and power-consuming machines. Of special interest are the stability, the resulting dynamics and the dependency on the operation point.

In addition to theoretical modeling, a survey of the most important methods of experimental modeling or *identification* is given for continuous and discrete time, in Chapter 7. Of main interest are on-line methods for parameter estimation and artificial neural networks. Also, models for harmonic oscillations and their identification are considered, especially Fourier analysis and spectral estimation in Chapter 8.

The components for information transfer in mechatronic systems are considered in the second part of the book. This begins with a survey of the most important sensors and measurement devices for mechanical and thermal systems in Chapter 9. After a discussion of signal types and sensor properties, different measurement principles for displacements, velocities, accelerations, forces, *etc.*, are briefly described. Different types of actuators are considered for electrical, pneumatic and hydraulic auxiliary energy in Chapter 10. Basic structures of controlled actuators, consisting of a motor and an actuating element, are treated. This is followed by a systematic survey of electromagnetic, fluidic and unconventional motors. The advantages and disadvantages and their application areas and properties as system components are discussed. Finally, Chapter 11 gives a brief survey of microcomputers from an application viewpoint as embedded computers in mechatronic systems. Standard processors, microcontrollers, signal processors and bus systems are considered and some technical data, relevant for the application, are shown.

One goal of the book is to describe the single components with unified principles and to represent them in mathematical models for the design of integrated mechatronic overall systems. A suitable compromise between the multiplicity and details of the components, their models and the length of the book had to be made. Therefore, the main focus is the systematic description and representation of selected components with regard to their behavior within a mechatronic system. The modeling of the components could therefore be performed only exemplarily and had to be restricted to selected cases. However, to facilitate ease of reading, many tables and graphic representations are given throughout the book.

In designing mechatronic systems, traditional borders of the various disciplines have to be passed. This means for the classical mechanical engineer that frequently knowledge on the electronic components, information processing and systems theory has to be deepened, and for the electrical/electronic engineer that knowledge on thermodynamics, fluid mechanics and engineering mechanics has to be enlarged. For both, more knowledge on modern control principles, software engineering and information technology may be necessary. The book is addressed to students of electrical engineering, mechanical engineering and computer science and to practicing engineers, and tries to add to the respective knowledge.

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