Chapter 23
Mechatronics

Klaus Zeman

The term 'mechatronics' was first coined in 1969 by KIKUCHI in Japan [VDI-2206, HaTF-1996]. This artificial word merges the English terms *mechanism* ('mechanics') and *electronics* and thus primarily expresses the connection between mechanisms (mechanics or mechanical engineering) and electronics (including electrical engineering). Due to the progress in the field of microelectronics and microprocessor technology, information technology later became an essential part of mechatronics [VDI-2206]. This is not the only reason why the meaning of the term mechatronics has been subject to continuous change since its emergence. In line with the progress made in the various technical disciplines, it now encompasses significantly more areas than at the beginning and is still in a state of flux. This is proven by the numerous, partly different definitions and explanations in [Desi-2005, EhMe-2017, HeGP-2007, Iser-2005, Rodd-2006, VDI-2206, VWZH-2018].

One of the broadest definitions was initiated by TOMIZUKA and reads: '*Mechatronics is the synergistic integration of physical systems with information technology and complex decision-making in the design, manufacture and operation of industrial products and processes.*' [Tomi-2000, VDI-2206]. This definition allows not only mechanisms or mechanical systems as basic systems, but all physical (material) systems, for example, thermodynamic, chemical, biological, agricultural or economic systems. It includes not only the integration of such basic material systems including elements of information and communication technology (ICT), but also with complex decision-making processes, for the realisation of which computer-aided methods of artificial intelligence (AI) or machine learning (ML) from ICT have been used for some time. The inclusion of (automated) decision processes in the definition shows that, according to TOMIZUKA'S understanding, autonomous behaviour in the form of high adaptability to changing environments and situations,

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learning abilities or the capability for self-regulation [DGSC-2018] can be an essential property of mechatronic systems. TOMIZUKA's definition does not only refer to the development and design of such systems, but also to the production, realisation and operation of industrial products and processes. It requires only little imagination to extend this understanding to all phases of the product life cycle and to Product Service Systems (PSS) as well, thus achieving an even more integrated, holistic view.

Although a generally accepted definition of the term mechatronics has yet to be established, there is a largely uniform understanding of at least some key aspects of mechatronics and mechatronic systems today. According to this definition, mechatronics refers to the synergetic integration of Mechanical Engineering, Electrical Engineering/Electronics, Control Engineering and Information and Communication Technology (ICT) for the development, manufacture and operation of innovative products and processes. From its very beginning, mechatronics has denoted an interdisciplinary field of engineering sciences, whereby the extent of interdisciplinarity is constantly increasing, since more and more disciplines are to be integrated. The development of communication technologies can serve as an example of the permanent expansion of interdisciplinarity. With the introduction of the Internet towards the end of the twentieth century, completely new possibilities to interconnect any objects such as people, technical systems, things, animals or plants have opened up. Terms and abbreviations like Internet of Things (IoT), Internet of Humans (IoH), Internet of Systems (IoS), Internet of Animals (IoA), etc. account for this [AbHe-2016]. Analogous to the abbreviation CAx, which stands for 'Computer-Aided anything' [VWZH-2018], the abbreviation IoX, which stands for 'Internet of everything' or 'Internet of anything', is intended to express that everything can be networked with anything and anyone via the Internet.

Mechatronic systems have been using the possibilities of networking for quite some time as well; they increasingly interact among each other, with other technical systems and with their environment and must develop, accordingly.

Regardless of the further development of mechatronic systems, it is useful to distinguish between two different 'types' of integration [Iser-2005, VDI-2206, VWZH-2018]:

- The first type concerns the material components (hardware) from the different disciplines and denotes a physical, material and therefore also spatial integration. At the beginning of mechatronics, this spatial integration in the sense of 'miniaturisation' was in many cases the main focus. Due to the increasing ability especially of electronics to realise more and more memory, computing power and integrated circuits (and thus also functions, see next bullet point) within ever smaller space, the importance of miniaturisation is undergoing a certain change. This is becoming obvious, for example, when devices could be built much smaller than the market demands, which has long been the case with mobile phones. Technically, it would be possible to make a mobile phone much smaller than a matchbox, but then it would hardly be possible to operate it. In return, the 'surplus' space that might be gained through miniaturisation is used to integrate more and more functions or components within the available space. Regardless of spatial integration in the

sense of incorporation within the smallest or at least very limited space, the physical, material integration in the sense of a material 'interconnection' of components and parts by means of connecting elements and interfaces remains, which can be arbitrarily complex even if there is sufficient space available.
- The second type of integration refers to the (immaterial, intangible) functions that are increasingly information-driven (mainly by software). It is therefore often referred to as functional integration and has an immaterial character: Hence, in contrast to the material integration described above, it could also be called immaterial integration. Due to the progressing miniaturisation, it is becoming possible to accommodate more and more functions within the smallest space, which means that the functional density of mechatronic systems is constantly increasing.

Mechatronics, just like IDE, thus encompasses integration, interdisciplinarity, heterogeneity, complexity, but also communication, cooperation and teamwork, which is why a systematic approach to the development of such products is particularly important. The main differences between IDE and mechatronics are the human-centred nature of IDE and the use of equivalent attributes to describe and determine product behaviour.

Mechatronic systems usually consist of the following elements [EhMe-2017, Iser-2005, VDI-2206, VWZH-2018], Fig. 23.1.

- The *basic system* is often a mechanical, electromechanical, electrical, fluid-technical (hydraulic or pneumatic) or thermo-dynamical system. In a somewhat broader sense, however, any physical, chemical, biological, even economic system may be considered as a basic system.

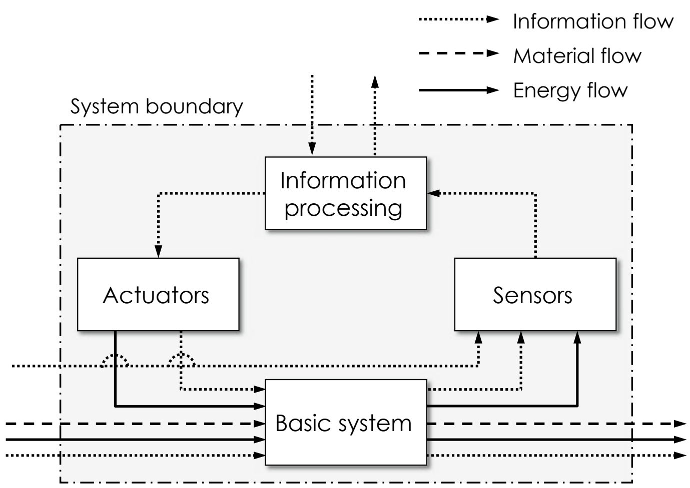

Fig. 23.1 Basic structure of a mechatronic system. Continuous line: energy flow. Dashed line: material flow. Dotted line: information flow. Dash dotted line: system boundary (based on [VDI-2206])

- The task of *sensors* is to provide information about the current properties of the basic system (e.g. its state), but also about the input and output variables (e.g. process variables such as heat or material flows) and the environment including the users of the system, for which purpose selected variables of the basic system or the environment are collected. This can be done directly by metrological detection (via sensors) or indirectly via so-called observers (state observers, estimators), with which the missing variables are reconstructed (estimated, reproduced) from the existing measured values using suitable models [HeGP-2007, Föll-1994, VDI-2206, VWZH-2018]. The signals formed by the sensors represent the input variables for information processing.
- By means of *Information processing*—using the sensor signals—control interventions for the existing actuators (see the following bullet point) are determined. This is performed with the target to influence both state and behaviour of the basic system just as it is actually intended—possibly depending on the environment, a super-ordinate system, a user of the system or other systems with which the mechatronic system is interconnected. The information processing unit can itself receive and process signals from the environment (again via sensors) as well as information from super-ordinate systems or from a network, and vice versa can send information to these systems. Thus, the mechatronic system can also be part (subsystem, system element or agent) of a super-ordinate system or a cyber-physical system (Sect. 23.2). Today, information processing is performed mainly digitally, i.e. by microprocessors and signals that are discrete in time and value. In special cases where, for example, signals have to be processed with particularly high speed, analogue technologies are still used because they enable the fastest possible processing. The determined control interventions represent output variables of the information processing and simultaneously input variables to the actuators.
- *Actuators* realise the control interventions (effects on the basic system) determined by information processing and intervene directly in the basic system or in the process running there. It makes sense to regard the actuators as parts of the basic system.

Mechatronic systems thus represent technical systems (object systems). The interaction of the various components typically results in control loops with the aim of improving the behaviour of the basic system so that it can be regarded as optimal in the respective context. For this purpose, sensors are used to collect information about the basic system (for example, its state, input and output variables) and about its environment. An environmental system can, for example, be a user of the mechatronic system, a super-ordinate system in which the mechatronic system is embedded, or even the environment (also user) of the super-ordinate system. Processors analyse this information and determine control interventions for the actuators in such a way that the basic system behaves as it is currently intended to [VDI-2206]. In [HeGP-2007] it is aptly formulated: 'It is typical for mechatronic systems that a change of the system states is actively desired. For this purpose, the input variables is used to influence the system[1]'. Therefore, a significant feature of mechatronic systems is that their behaviour is influenced in a targeted manner so that the function of the system is realised in the best possible way. According to [Hubk-1984, HuEd-1996], the function of a system is understood as the desired behaviour of the system. Behaviour, in turn, is the conversion of the input variables to the output variables of the system. A distinction is made between static and dynamical systems: In dynamical systems (e.g. torsional vibration system of a drive train), the conversion of input variables (e.g. external torques) to output variables (e.g. rotational movements) depends not only on the input variables but also on the state of the system itself. To determine the output variables, a time integration is necessary which, in addition to the input variables, also has to consider the dynamics of the system itself including its initial state at the beginning of the time integration (at time $t = 0$) in the sense of initial conditions. For static systems (e.g. massless levers), however, no time integration is required; the inputs are quasi 'directly' converted into the output variables without 'eigendynamics' of the system. The targeted influencing of the system behaviour is inseparably connected with the temporal change of system variables (e.g. state variables, input variables, output variables), which is why mechatronic systems always represent dynamical systems.

23.1 Objectives of Mechatronisation

The objectives of mechatronisation are primarily support functions that are integrated into devices, machines and systems in order to support the user in application, usability, operation, maintenance, etc., to relieve him, increase safety, release him from tiresome or dangerous tasks, by taking over these tasks and fulfilling them better through the device or machine. There are numerous examples of this, such as autofocus and automatic exposure systems for photo cameras, ABS (anti-lock braking systems), airbags, anti-skid control systems, ESP (Electronic Stability Program), automatic operation of the windscreen wiper ('rain sensors'), automatic dipped beam control ('light sensors'), automatic differential gears, engine management, tyre pressure sensors, driver assistance systems, navigation systems for motor vehicles, autopilots for airplanes, automatic roasting, etc. Sub-functions or subtasks are performed by machine equipment, thus establishing the *functional integration* within mechatronic systems [ZeHS-2006].

For many devices, which the customer wants to be small, handy and light, the new functions sometimes have to be integrated within a very small space, so that, as described above, *spatial integration* is achieved.

At the same time, components can be massively reduced in size, making miniaturisation possible. Some products are unique simply because they are particularly small, light or compact (see digital cameras, mobile phones, memory cards, GPS transmitters, music players, etc.). With such miniaturised products, however, it is

[1] Here, the basic system is meant.

usually only possible to realise functions with very low power (e.g. sensor functions or control interventions).

In the past, the packing density and thus the functional density of electronic circuits was limited by the size of the individual components. With microelectronics, a radical change in electronics occurred. Components were no longer manufactured and joined mechanically, but were optically transferred and copied by photolithography onto the work piece, the silicon wafer. This led to an exponential decrease in the cost of computer processing power and storage capacity of hard discs. Studies show that since about 1960, CPU costs have been decreasing by a factor of at least 10 within 5 years, i.e. they have decreased to less than $1/10^{12}$ within 60 years. This shows the enormous increase in available CPU power. For data transfer rates in the Internet and storage capacities of hard discs, the cost developments are very similar (exponentially decreasing).

23.2 Mechatronic Products

Compared to conventional products, mechatronic products are characterised by extended, improved and new functions, which can only be achieved through the interaction of methods, technologies, functions, solutions and components from the various disciplines of mechatronics, resulting in enormous innovation potential. Heterogeneous components and knowledge from the various disciplines of mechatronics are thus integrated in mechatronic products to form an optimised solution for the overall product. These products often differ from conventional products by a higher number of heterogeneous, coupled elements and an associated higher complexity, which is not always apparent at first glance, as is shown by numerous products of daily use. Examples are photo and video cameras, hearing aids, mobile phones, copiers, TV sets, DVD players, PCs, cars, motorcycles, active wheel suspensions in Formula 1, airplanes, household appliances, ski lifts, etc. Figure 23.2 shows some mechatronic products for whose realisation the accommodation in a very limited space is a decisive prerequisite, which is why miniaturisation is an important objective for these products.

Another characteristic of mechatronic products is that their properties are determined to a considerable extent by non-material elements (software) [HeGP-2007, VDI-2206]. This in the first instance leads to a shift in functions from the physical (often mechanical) 'basic product' to electronics or information processing. Subsequently, products (systems) are enabled that have a certain ability to adapt, learn and decide. Accordingly, they are called 'intelligent products'. Such products can, for example, autonomously optimise processes, adapt to changing conditions (e.g. changing environments), recognise critical operating states, or stop or start certain processes depending on the current product state or on events that have occurred. They, therefore, have intelligent or autonomous (self-contained) functions [Desi-2005, GGSA-2004, HeGP-2007, Iser-2005, VDI-2206, DGSC-2018].

Fig. 23.2 Mechatronic products where miniaturisation is an important goal [ZeHS-2006] (using free available images from Apple, Bartels, Canon, Nokia, Phonak, Visotech)

A logical (further) development of mechatronic systems leads to so-called *Cyber Physical Systems*, which arise when material systems (physical systems) are connected to each other via a local or global network in order to communicate with each other, to jointly perform tasks in a network and to make decisions on the further procedure (control) by evaluating feedback (cybernetics). In the case of cyber-physical systems, the material (physical) systems can also be other than mechatronic systems (e.g. living beings), which is why this approach is even more general than if only mechatronic systems are networked with each other [Lee-2006, Lee-2008, GeBr-2012]. The integration of physical (material, real) systems and virtual systems (computers) into cyber-physical systems is shown in Fig. 23.3.

To capture, describe and map the physical systems in the virtual world (in computers, in 'cyber space'), models and measurements of the physical systems are required. Networking enables a variety of desirable but also questionable possibilities of influencing the physical (material, real) systems, including humans and animals.

A new feature of cyber-physical systems is the emphasis on the fact that the resulting system, similar to the Internet, can have a previously unknown number of subsystems ('participants', 'agents') that change over time during operation. The definition of TOMIZUKA [Tomi-2000, VDI-2206] (see the beginning of this chapter) already includes such systems.

Examples of cyber-physical systems include traffic control systems, modern production systems, logistics systems, energy distribution systems or driver assistance systems in their gradations up to fully autonomous driving, etc. if the systems involved are able to perform tasks much more efficiently in a network than would be possible with isolated solutions.

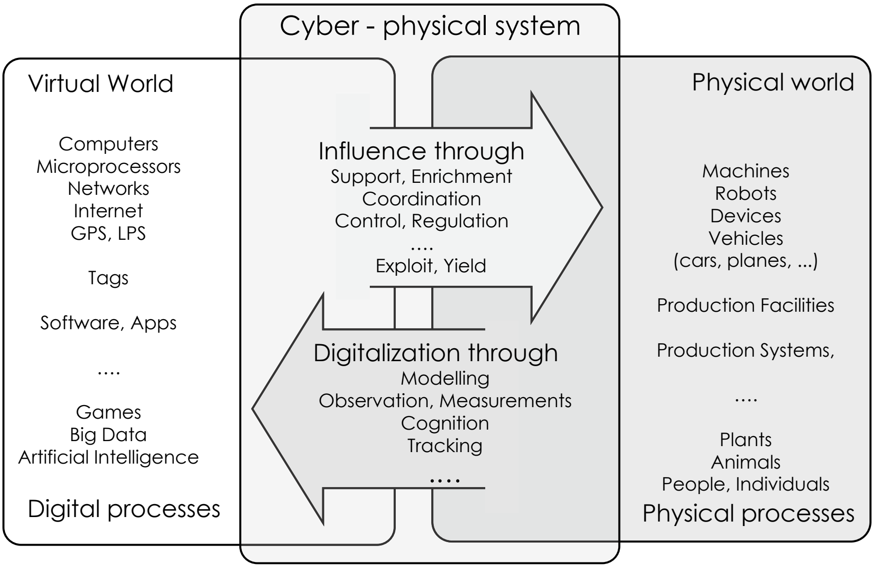

Fig. 23.3 Cyber-physical system: Integration of physical (material, real) systems and virtual systems (computers); modelling for computer-internal acquisition and implementation, possibilities for influencing physical (material, real) systems

It is above all the interactions between the individual product elements from very different areas that have a significant influence on the functionality of the overall product. Interactions are used specifically to create innovative products such as machines, devices, systems, etc. by combining (interconnecting, linking) elements from the disciplines of mechanics, mechanical engineering, electrical engineering, electronics, information technology, communication technology as clever as possible. Finding, designing and creating such solutions is a synthesis process that can be aptly summarised under the term *mechatronic design.*[2]

In conclusion, it should be noted that mechatronics is penetrating more and more areas of automotive engineering, production technology and the entire field of mechanical and plant engineering, but also medical technology and biology (e.g. exoskeletons). This can be seen from the fact that most of today's products from these areas represent more or less complex mechatronic systems and would hardly be conceivable without mechatronics.

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[2]This term refers to the development process in the sense of a procedure and not to its result, the mechatronic system or the mechatronic product.

23.3 Development Methodology for Mechatronic Products

Design, development and realisation of mechatronic products—and thus mechatronics in general—require an integrative approach and interdisciplinary thinking as well as thinking in systems. This also places new demands on communication and cooperation between representatives of the various disciplines, on a common language and on integrated, computer-aided development environments [VDI-2206, Desi-2005]. Especially the last point mentioned above cannot be regarded as satisfactorily solved at present.

Numerous practical experiences prove that the composition of the development team is essential for the success of mechatronic design. Interest in and basic understanding of the respective 'foreign' disciplines, respect for the other disciplines, knowledge of inter-disciplinary relationships and the effects of definitions and changes of 'common', inter-disciplinary parameters and the identification with the 'common task' are critical factors for the success of mechatronic design. The equal treatment of all involved disciplines represents a high value and is established as a culture. It goes without saying that this also places increased demands on the ability of the people involved to work in a team (see also Sect. 15.6).

The development of a mechatronic product or system is, therefore, a complex process due to the different participants and the interacting disciplines of mechatronics. Therefore, before such a product or system can be developed, the reasons and objectives of mechatronic product development must be critically questioned. Typical questions include:

- Do requirements on the performance of the product contain such content that can no longer be realised merely mechanically?
- Should a product be reduced in size for reasons of space limitations (miniaturisation, spatial integration) or should additional functions be accommodated in a product if space is available, so that the behaviour of the product can be adapted to new requirements (functional integration)?
- How can new or extended functions, special features or a particularly low price be achieved for a product in general through mechatronisation in order to differentiate it from competing products and make it particularly attractive to the market? Are certain components, effects and functions of a product to be 'hidden' for reasons of, for example, knowledge protection by realising them with a non-mechanical technology?
- Should performance be made possible that requires materials with flexible or adjustable material properties (smart materials) (e.g. an adjustable modulus of elasticity that can be specifically influenced by actuators attached to the surface of the component)?
- If mechanical functions are to be taken over by electrical or software functions, the type and number of components now required must be clarified (space requirement? Ease of assembly?). What is the energy requirement and where are

sensors, actuators and energy sources placed? Can the energy source be a standard solution or must a customised solution be used? Should the energy source be interchangeable?
- What are the mutual influences of the new partial solutions? Is the respective fulfilment of the attributes safety, reliability and quality still given?
- What should the user interface look like? Which interventions should be enabled and which should be prevented?
- Which operating modes should be provided for the expected operating conditions?
- What is the economic balance of the mechatronisation of a product?

The VDI Guideline 2206 'Design methodology for mechatronic systems' [VDI-2206] was created for the development of mechatronic products and systems, which claims to be an integrated development methodology, i.e. spanning all disciplines involved (i.e. mechanical engineering, electrical engineering/electronics, information technology), Fig. 23.4.

This process model is formally based on the V-model from Software Engineering [IABG-2013]. In terms of content, it is based on the approaches originating from mechanics and mechanical engineering (see Chap. 1), so that the core of development activities remains discipline-specific. Accordingly, the mechanical or mechanical engineering activities (including pneumatics and hydraulics), the development activities in the fields of electrical engineering and information and communication technology run in parallel, each of them individually and in series. A layer is superimposed on these, which on the one hand ensures the integration of the subsystems into a heterogeneous overall system, and on the other hand, ensures ongoing system

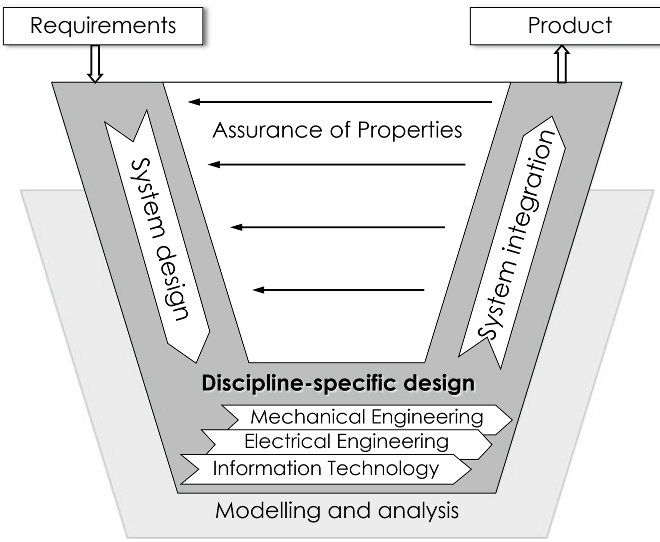

Fig. 23.4 Process model for the development of mechatronic products and systems according to [VDI-2206]

analysis (especially for the transient or dynamic behaviour). The system analysis also takes over the role of feedback in the development process and is, therefore, its decisive control mechanism (assurance of properties, performance checks, verification and validation).

The process model according to [VDI-2206] is more a framework concept than a directly applicable development method for mechatronic products and systems. However, the model provides indications of how the existing methods and tools can be used in the corresponding processes how they are interlinked with each other. Furthermore, it reflects the role of computer-based methods and tools in the development process, but here again without going into the questions of product modelling or product models in more detail (for more details see [VWZH-2018], Chap. 4 and Sect. 5.4).

Structures and procedures from the process model according to [VDI-2206] can be mapped without difficulty by the IDE procedure model (Chap. 16), consistently detailed and holistically realised.

- By describing the desired performance of the product (consisting of the performance of the product and its behaviour when providing this performance) via the six product attributes and their respective fulfilments (Chaps. 3 and 13), which do not prejudge any particular solution, the different mechatronic disciplines and their interaction are taken into account at a very early stage so that they no longer have to be processed separately (as in the V-Modell) during the actual genesis of the product.
- By means of the genesis of the attributes, the integration of possible subsystems into a heterogeneous overall system is also carried out at the earliest possible points in time.
- Comprehensive simulation and evaluation options in the activity group Evaluate/Compare/Select in the IDE procedure model (Chap. 16) ensure ongoing system analysis and necessary feedback during product development. This applies in particular to the assurance of properties as a control loop, which is carried out permanently in the IDE procedure model.

The serial structures implicit in the V-Modell (especially in the discipline-specific design) can be completely resolved with the IDE process model and arranged and designed according to requirements.

23.4 Mechatronisation of Processes

The mechatronisation of processes [ZeHS-2006] means the use of mechatronic concepts to improve the performance of industrial processes. These comprise, for example, manufacturing processes and their output, in order to minimise undesirable effects (such as environmental pollution through noise or pollutants) and to improve the utilisation of operating personnel and economic efficiency. A core element in this context is the targeted intervention with the aid of electronic control equipment for better control of the process, i.e. for its guidance and for the correction of control deviations if any are detected. This requires suitable sensor systems in order to detect control deviations at all, suitable actuators in order to intervene in the process in a targeted manner, and suitable control devices that dose the control intervention in such a way that the desired process result is ensured.

Mechatronisation of processes is understood as a mean of those mechatronic measures that have an effect on the process. There may, of course, be further ones, such as for maintenance, rapid and low-error commissioning, cost tracking, error detection and diagnosis, etc.

Rolling mill technology can serve as an example of machines and processes whose mechatronisation is already well advanced. However, mechatronisation has long since taken hold of many other applications (for example paper machines, combustion engines, agricultural machinery, cutting machine tools, spinning machines, storage and retrieval systems, parcel sorting systems), while some areas have hardly been touched at all (many manufacturing processes in construction technology). The reasons for these differences include the following: The various technical processes are differently suited for mechatronisation from a technical point of view (measurability of states, availability of technically and economically suitable sensors and actuators, sufficient understanding of the processes for successful automation). In many cases, however, the cost/benefit ratio plays a decisive role. While in some processes very high, monetary values are processed due to enormous throughput rates (material throughputs), and thus even small relative process improvements result in large benefits, in other processes the cost of mechatronisation far exceeds the economic benefit.

The benefit of mechatronisation of processes is achieved most quickly in those with the properties listed below, which is why mechatronisation is most advanced in these processes [ZeHS-2006]:

- Continuous processes with primarily high throughput, i.e. high monetary value of the material throughput, because even small relative improvements result in high benefits.
- Fast processes because there is a great potential for improvement in comparison to manual operation.
- Complex processes because their guidance and control often require non-linear multi-variable controls, which are, however, hardly controllable manually. Here, too, there is great potential for improvement through computer-aided process control in conjunction with fast control systems.

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