2 Mechatronic Product Development

The world of engineering is like an archipelago whose inhabitants are familiar with their own islands but have only a distant view of the others and little communication with them. A comparable near-isolation impedes the productivity of engineers, whether their field is electrical and electronics, mechanical, chemical, civil, or industrial. Yet modern manufacturing systems, as well as the planes, cars, and computers, and myriad other complex products of their making, depend on the harmonious blending of many different technologies.

Richard Comerford, 1994

In the quote above, Comerford (1994) tellingly depicts the situation which initiated the development of Mechatronics. Characterized by the cited blend of technologies, Mechatronic products have gradually emerged from electromechanical products through the addition of first electronics, later computer controls, and software. Ko Kikuchi, the former president of the Yasakawa Electric Company, introduced the term *Mechatronics* from *"mecha"* for mechanism and *"tronics"* for electronics in 1969, in order to use the term as trademark for such devices (Comerford 1994).

Precision mechanics was the initial field where Mechatronics emerged (Diehl 2009). These days, Mechatronics encompasses a much larger scope of applications. It ranges from mechatronic components (e.g. semi-active hydraulic shock absorber, integrated servo drive) over mechatronic machines (e.g. mechatronic combustion engines, integrated AC drive systems) to the omnipresent applications in the automotive area (e.g. anti-lock braking systems, electro-hydraulic brakes, active suspension systems) (Isermann 2008) and in the consumer goods industry (e.g. vacuum cleaners, washers, dryers, dishwashers, entertainment devices) (de Silva 2005).

2.1 Introduction and Terminological Understanding

Over the years, though, the usage of the term Mechatronics became increasingly heterogeneous (Zohm 2003). A rough analysis of the about 20 definitions on Mechatronics collected at the website of the Department of Mechanical Engineering at Colorado State University (Alciatore 2011), uncovers large differences on the contextual level of the definitions:

(a) Two thirds of the definitions refer to the context of design methodology and locate Mechatronics in between a design approach, design methodology, and design framework.
(b) The remaining third of the definitions views Mechatronics primarily as an engineering discipline.

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(c) Only one author perceives Mechatronics from the context of the conceived technical systems.

This controversy about substantial aspects of Mechatronics is reflected in the opinion of several authors who state that a generally accepted definition of Mechatronics does not currently exist (Buur 1990; Hewit 1993; cited in Wikander, Törngren, et al. 2001; VDI 2004; Bishop 2006; Felgen 2007; Vajna, Weber, et al. 2009). Moreover, Hewit (1993; cited in Wikander, Törngren, et al. 2001) argues that such a definition should not be desirable, as it would constrain the future development of this engineering field. Correspondingly, Bishop (2006) states that the lack of consensus on a widely accepted definition should be interpreted as a healthy sign for a vivid engineering field. He endorses a broad perception of Mechatronics as *"a natural stage in the evolutionary process of modern engineering design"* (Bishop 2006).

2.1.1 Contexts of Terminological Understanding

In spite of the ongoing debate on the nature of Mechatronics, the present thesis is in need of a clear terminological understanding of Mechatronics in order to conduct research on knowledge characteristics at the core of MPD, i.e. its knowledge bases, the used knowledge frame and the knowledge dynamics tightly associated with the manifold activities during the product development process.

The aforementioned analysis of the contextual levels used for definitions of Mechatronics (Alciatore 2011) indicates that Mechatronics is perceived within the scientific world from different points of views, including at least three distinct contexts:

(a) Mechatronics engineering science
(b) The approach and methodology practiced in MPD
(c) Mechatronic systems

When using the similar term *electronics* as analogy, it appears that this term likewise operates on at least two different contextual levels: Firstly, it designates a *"branch of physics and technology concerned with the design of circuits using transistors and microchips, and with the behavior and movement of electrons in a semiconductor, conductor, vacuum, or gas"* (Oxford Dictionaries 2010). Secondly, it describes the products of these design activities, i.e. *"circuits and devices using transistors, microchips"* (Oxford Dictionaries 2010).

In compliance with the results of the analysis of numerous definitions on Mechatronics and the aforementioned analogy to electronics, the present thesis regards Mechatronics as a concept appearing within a range of contextual levels (cf. Figure 2.1):

(a) The practice of mechatronic product development will be considered as the primary context for the definition of Mechatronics.
(b) In addition, Mechatronics engineering science will be taken into account as a second context because it acquires and supplies a large part of the knowledge applied within MPD and contributes therefore substantially to MPD's knowledge characteristics.
(c) Equally, a terminological understanding of Mechatronics in the context of mechatronic systems will be beneficial due to the tight relationships between (i) the product's

specific content and structure, and (ii) the characteristics of the product development process itself.

Figure 2.1: Contexts for the terminological understanding of Mechatronics (Neumann 2012)

In the following, these three contexts of terminological understanding will be explored to (a) extract key aspects shaping the nature of Mechatronics applicable to all of these contexts, (b) discover topics in each context closely connected to these paradigms, and finally (c) provide definitions of Mechatronics within each of the contexts comprising those specific topics.

2.1.2 Paradigms of Mechatronics

Zohm (2003) analyzed in his dissertation the scientific understanding of Mechatronics based on definitions given in text books, dissertations and journals, and arrived at the following insights:

(a) There is a large agreement between the authors on the interdisciplinary character of Mechatronics, which Zohm interprets plainly as *"collaboration of several disciplines"*.
(b) The majority of publications mention three disciplines as constituents of Mechatronics: mechanics, electronics, and computer science. Other authors subsume additional disciplines, e.g. control engineering, or perceive nearly all engineering disciplines as constituents of Mechatronics.
(c) Only a few publications provide a sufficient differentiation of the integration into functional and spatial aspects. Zohm emphasizes the distinction of functional and spatial integration as central element for the terminological understanding of Mechatronics.

In contrast to the findings of Zohm (2003), the analysis of the about 20 definitions listed on the aforementioned website (Alciatore 2011) confirms that control engineering is considered by most definitions as an essential contributor to Mechatronics. Therefore, the present thesis takes into account mechanical engineering, electrical engineering, and computer science with control engineering as one of its sub-disciplines, as the main constituents of Mechatronics as shown in Figure 2.2 (VDI 2004; Isermann 2008; Diehl 2009).

Other scholars consider Mechatronics rather as a *"design philosophy"* (Millbank 1993; Tomkinson and Horne 1996; cited in Grimheden and Hanson 2001). Certainly, that designation of Mechatronics as *"design philosophy"* collides with the established meaning of design philosophy within engineering design science where it is considered *"as a meta-theoretical framework for design theories"* (Love 2000; cited in Horváth 2004). In order to avoid this contradiction, the word *"design philosophy"* should be interpreted based on its second meaning[14] as a particular approach to engineering design combined with a specific mechatronic attitude.

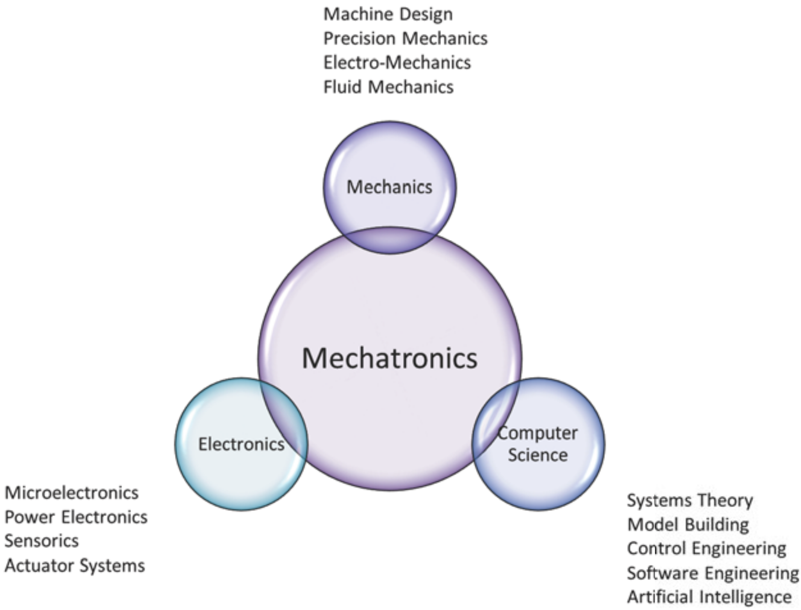

Figure 2.2: Main constituents of Mechatronics, adapted from (Isermann 2008)

What constitutes the essence of that specific mechatronic attitude or approach? Grimheden (2005) emphasizes in his dissertation on *"Mechatronics engineering education"* the central importance of the *"concept of synergy, or synergistic integration"* for the thematic identity of Mechatronics.

Harashima et al. (1996) introduced a closely associated definition of Mechatronics, which serves as the central reference within the VDI guideline 2206:

"[Mechatronics is]… the synergetic integration of mechanical engineering with electronic and intelligent computer control in the design and manufacturing of industrial products and processes."

Bradley (2010) discusses in his article *"Mechatronics – More questions than answers"* the numerous open questions on the nature of Mechatronics after 40 years of its evolution and the future potential of Mechatronics. He questions the uniqueness of the MPD approach given the fact that now the majority of engineering systems are integrated and interdisciplinary and concludes *"that mechatronics has to a significant degree been integrated with and incorpo-*

[14] The Oxford Dictionaries (2010) support this interpretation by providing a second meaning of philosophy as *"a theory or attitude that acts as a guiding principle for behavior".*

rated within mainstream engineering design methods and strategies" (Bradley 2010). In addition, he raises the question whether Mechatronics today should rather be considered as a systems oriented design approach.

The key aspects of Mechatronics described in the definitions given by Harashima et al., the dissertations of Buur, Zohm and Grimheden, i.e. synergy, spatial and functional technology integration, interdisciplinary character, and the understanding of Mechatronics as a systems oriented approach to engineering design (as shown in Figure 2.3), provide the input for the overall terminological understanding of Mechatronics within the present thesis.

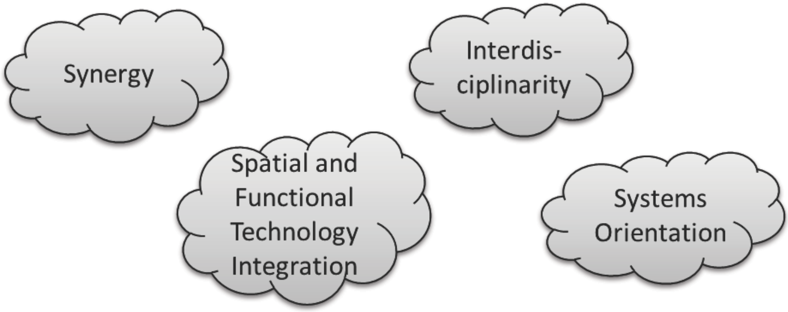

Figure 2.3: Key aspects shaping the nature of Mechatronics

2.1.3 Definitions of Mechatronics

Based on the described paradigms of Mechatronics, the sections 2.3, 2.4 and 2.5 will elaborate on specific fields of activities in the contexts of mechatronic systems, MPD and Mechatronics engineering science, which will then serve as the foundation for a definition of Mechatronics in each of these areas.

2.2 The Evolution of Mechatronic Products

Eversheim et al. (2000) introduced an evolutionary model describing the gradual changes from purely mechanical, through electro-mechanical, to mechatronic products in four phases. This model was later refined and extended by Zohm (2003) and finally consists of five development stages. It depicts in detail the basic activities of technological change, e.g. substitution, functional and spatial integration, leading to upgraded technical solutions for the initially purely mechanical product. The model allows for a flexible description of change, as it permits the omission of specific development phases not applicable for particular types of products. In the following, the evolutionary model is presented based on the descriptions given in Zohm's dissertation (Zohm 2003).

Figure 2.4 depicts the evolution of an automotive window-lifting system as an example illustrating the activities and phases of the evolutionary model. The initial product consists of purely mechanical components that realize all product functions (*Phase I*).

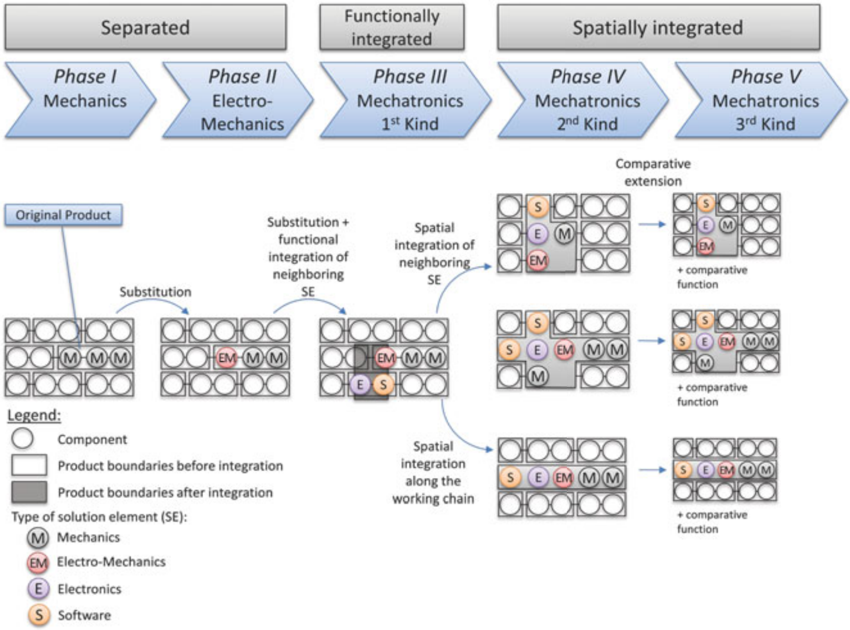

Figure 2.4: Evolutionary model of mechatronic products applied to the evolution of an automotive window lift system, according to (Zohm 2003)

In the next phase (*Phase II*), electro-mechanical components, e.g. relays, electric motors and other electric actuators, complement or replace the existing mechanical elements. In the case of the automotive window-lifting system, an electric motor controlled by a switch replaced the previous manual crank handle in the early 1940s in a few luxury car models (Society of Automotive Engineers 1940).

The addition of electronic components, e.g. microprocessors, transistors, thyristors and sensors, allows for new and upgraded product features in the subsequent evolutionary phase (*Phase III*). Typically, a separate printed circuit board contains these electronic components. Wired connections link the board with functionally related components. Due to demanding constraints on durability toward mechanical loads and thermo-dynamic conditions, electronics cannot yet be integrated spatially with the neighboring electro-mechanical and mechanical components.

Programmable electronic components, typically a microprocessor, permit the execution of a dedicated software implementing functions such as information processing, decision making and control of the actuators. As a result, embedded software becomes part of the mechatronic product. The development of this first kind of mechatronic systems requires therefore the contributions of all main engineering disciplines constituting Mechatronics (cf. section 2.1.2).

As this stage primarily aims at achieving a functional integration of the solution elements, an optimization of the system reaching over all involved disciplines is not yet in scope. The collaboration of the involved engineering disciplines may therefore remain on the multidisciplinary level. In the 1980s, such so called *"first kind of mechatronic systems"* allowed for new features within automotive window-lifting systems such as pinch protection (Brose Fahrzeugteile 2006).

Phase IV focuses on the spatial integration of the already functionally integrated components, which requires a closer, interdisciplinary collaboration addressing the challenging mechanical, thermo-dynamic and spatial conditions for the integration of the heterogeneous components. In the example of the window-lifting systems, the spatial integration of the electric motor, the gearbox, position sensors, and the connector for the associated control unit within one casing increased the density of functions per volumetric unit, simplified the assembly process, and allowed for a flexible usage of different types of control units fitting into an appropriate slot. As a next step in the integration process, so called *"door systems"* integrated most of the components equipping a vehicle door, e.g. the window lift, the door-locking system, loudspeakers, the wiring harness, and the control unit. As of 2006, door systems already comprised 85% of the functional components of a vehicle door (Brose Fahrzeugteile 2006).

The fifth development stage of mechatronic products (*Phase V*) focuses on the further optimization of the already functionally and spatially integrated solution elements toward the generation of additional synergistic effects. At this stage, these spatially integrated products may permit the realization of upgraded and new functions not achievable in earlier development phases of the evolution process. In case of the window-lifting system, the fifth stage resulted for instance in a more reliable and cost-effective pinch protection system based on the spatial integration of two hall sensors into the electric motor (Reif 2009). Zohm (2003) argues that these new functions of spatially integrated mechatronic systems may permit companies to achieve a comparative advantage[15] over their competition. Therefore, he introduces the term "*comparative functions*" to indicate functions enabling such comparative advantage.

2.3 Mechatronic Systems

2.3.1 Characteristics and Definition

The preceding section clarified how technological activities shaped the characteristics of mechatronic products during an evolutionary process. In the following, the specific impact of these technological activities on the content, the structure, and the capabilities of mechatronic systems will be described and utilized to define the essence of mechatronic systems.

[15] Comparative advantage: The ability of an organization to perform an economic activity more efficiently than others (Oxford Dictionaries 2010).

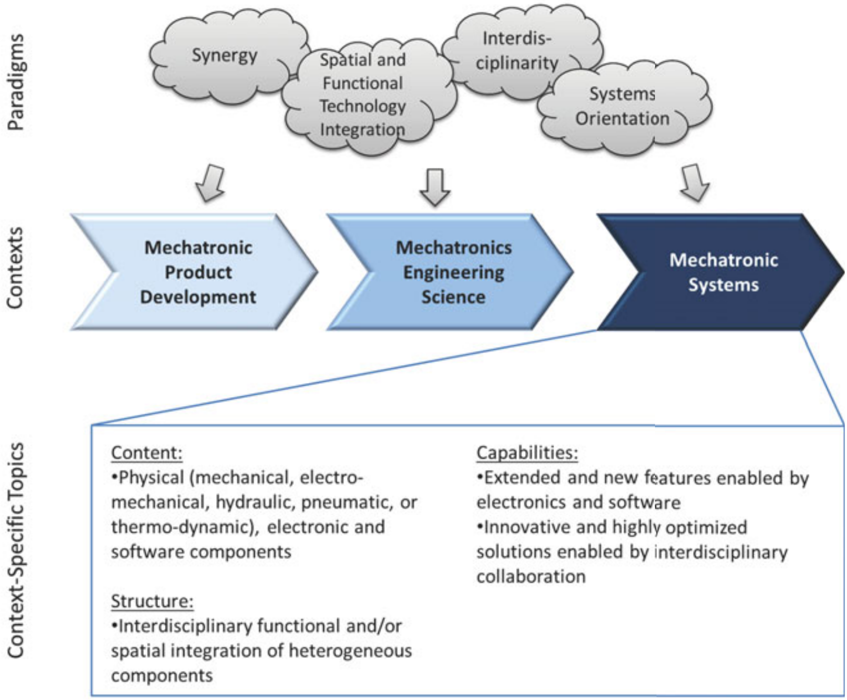

Figure 2.5: Manifestations of the overall mechatronic paradigms in the context of mechatronic systems

Figure 2.5 depicts the resulting characteristics of mechatronic systems:

(a) Their content became technologically heterogeneous.
(b) Due to functional and/or spatial integration, their structure is characterized by the high number of relations between items belonging to different disciplines.
(c) Their capabilities were extended under the influence of electronics and software.
(d) All together, they have the potential to constitute innovative and highly optimized solutions.

These characteristics of mechatronic systems, the understanding of a mechatronic system as a specialized technical system according to the definition given by VDI guideline 2221 (1993), and the definition of mechatronic systems provided by Isermann (2008) present the essential inputs for the conceptual understanding of mechatronic systems. The following definition integrates these different contributions into the terminological concept adopted by the present thesis:

Definition 2.1: Mechatronic system

A mechatronic system is a technical system that consists of functionally and/or spatially integrated physical (mechanical, electro-mechanical, hydraulic, pneumatic, or thermo-dynamic), electronic and software components. The integration of these heterogeneous components is achieved first by a multidisciplinary and later by an interdisciplinary collaboration of the relevant engineering disciplines (typically: mechanical engineering, electrical engineering, and computer science with control engineering as one of its sub-disciplines) that enable synergistic effects resulting in innovative and highly optimized solutions.

2.3.2 Structure of Mechatronic Systems

2.3.2.1 Basic Structure

In principle, four main components integrated with each other will form the basic structure of a mechatronic system (VDI 2004; Gausemeier and Feldmann 2006).

The *basic system* constitutes in the most general sense a physical system, whose state is continuously observed and controlled. Using the example of an automotive window-lifting system (cf. section 2.2) using cables, a so called *"cable window-lifter"*, the basic system contains only mechanical components. Here, a gearbox, the cable, and the lifting arms moving the window glass form the basic system. In more general terms, the basic system may comprise *"a mechanical, electro-mechanical, hydraulic or pneumatic structure or a combination of these"* (VDI 2004).

Sensors measure the state variables of the basic system and transform the measured values into electric quantities serving as input for the information-processing unit. With the automotive window-lifting system, a simple pinch protection system may be realized solely based on software sensors – the monitoring of the alternating component of the motor current permits the calculation of the current window position. A more reliable pinch protection approach requires physically present sensors: Two hall sensors measure the motor's rotation speed and direction permitting the calculation of the current displacement force (Reif 2009).

The *information processing* handles the data supplied by the sensors and decides on this basis how the actuators have to be controlled in order to influence the basic system in the preferred direction. These days, a microprocessor which only handles digital data constitutes this information-processing unit. For the automotive window-lifting system, the microcontroller is spatially integrated with other electronic components (e.g. EEPROM, voltage regulator, analog-digital converter, LIN-transceiver) on a single application specific integrated circuit (ASIC) (Reif 2009).

Controlled by electric actuating variables issued by the information-processing unit, the *actuator* influences the basic system typically by mechanical energy toward the desired state. In the example of the automotive window-lifting system, an electric motor constitutes the actuator.

Figure 2.6 depicts the three types of flows (Roth 1994; VDI 2004) linking the mechatronic system's main components:

(a) *Information flows* (I) carry different forms of information between the system's components, e.g. values measured by sensors, signals issued by switches and control information driving the actuators.
(b) *Energy flows* (E) transport the different types of energy (e.g. mechanical, electrical, thermal, and magnetic) between the units of the mechatronic system.
(c) *Material flows* (M) realize the exchange of material between the components of the mechatronic system, e.g. solid bodies, liquids, and gases.

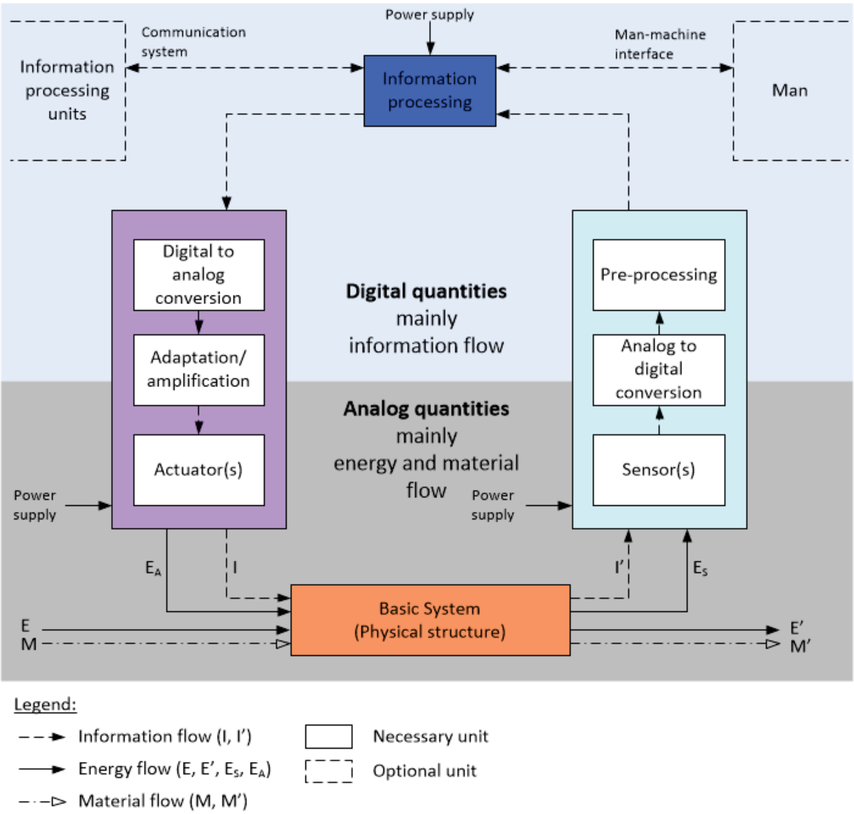

Figure 2.6: Basic structure of a mechatronic system, adapted from (Gausemeier, Ebbesmeyer, et al. 2001; cited in Krause, Franke, et al. 2007)

In the upper area of Figure 2.6, the information-processing unit, sensors and actors exchange mainly information typically based on digital quantities. In addition, optional components such as a man-machine interface and external information-processing units may be connected http://www.springer.com/978-3-658-11091-8

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