

Chapter 2

Brief Historical Overview of Control Systems, Mechatronics and Motion Control

The following Sects. 2.1 and 2.2 revisit notion and history of “feedback control”, “adaptive control”, “mechatronics” and “motion control” to provide some background on the evolution of control systems and mechatronic systems over the last centuries and decades.

2.1 Feedback Control and Adaptive Control

For engineers, “to control” means to alter, drive or direct a process or a plant (i.e. a “dynamical system”) in such a way that its behavior (i.e. its “dynamics”) is improved. The desired improvement is specified by “control objective(s)”: Certain quantities of the controlled system (i.e. “states” or “outputs”) should be kept close to prescribed values (i.e. “references”) even if the environment is changing (i.e. unknown “disturbances”, “loads” or “perturbations” affect the system behavior, see [253, Sect. 1.1]). A device controlling a system is called “controller”. It generates the “control action” or the “control input” to drive the system towards the reference(s).

To achieve “automatic control” (i.e. the system is controlled automatically by a controller) negative feedback of system quantities is essential. Therefore, these quantities have to be measured (or observed) and “compared” to their respective reference(s). The resulting “control error” or “tracking error” (for time-varying references) (i.e. the difference between actual measurement and reference) updates the control action in such way that the system is eventually driven towards its reference(s). The system is subject to “feedback control”. A system with controller and feedback is considered as “closed-loop system”.

Feedback is one of the fundamental ideas of engineering [253, Sect. 1.1].

The history of feedback control is mostly traced back to the “*governor*” introduced by James Watt (1736–1819¹) for speed control of steam machines. However, as it was shown by Otto Mayr in 1969, control systems were already known around 300 before Christ (BC) (see [238, p. 17–22]). These ancient controllers were used to assure accurate time keeping (by e.g. water clocks). For a chronological overview of the history of control systems from ancient times to 1955, the interested reader is referred to [238] (300 B.C.–1800), [29] (1800–1930) and [30] (1930–1955).

Not until 1868, the design of such (mechanical) governors was usually performed by trial and error. In March 1868, an article (see [237]) was published by James Clerk Maxwell (1831–1879) in which the dynamics of these “*regulators*” or “*modulators*” (as he called the governors) were analyzed concerning stability (in the sense of Linear Control Theory²).

In the early years of the 20th century, the use of feedback control was limited to some particular problems in mechanical engineering. Due to the development of electrical amplifiers in 1934 with (negative) “*feedback circuits*”, introduced by Harold Stephen Black (1898–1983) [44], more and more controllers were implemented to control electrical, mechanical and chemical processes by the 1940s [253, Sect. 1.1]. The applications were different, but the principle idea of feedback and the mathematical analysis tools were similar. Open-loop frequency response methods, introduced by Harry Nyquist (1889–1976) [259] and Hendrik Wade Bode (1905–1982) [46] (known from electronic circuits with feedback amplifiers) formed the basis for controller design and systematic stability analysis of linear time-invariant (LTI) closed-loop systems.

In 1948, Norbert Wiener (1894–1964) generalized the idea of feedback control to communication theory, biology, medicine and sociology. His newly founded discipline was called “*Cybernetics*” (see [338]). Not until 1961, “*Control Theory*” was considered an individual mathematical discipline (see [253, p. 2]).

In the 1950s, desire and need arose to cope with nonlinear control systems exhibiting changing dynamics (depending on the actual operating point) and varying disturbance characteristics (see [22, p. 3]). The control systems should have the capability to “*learn*”, “*adjust*” or “*self-tune*” themselves. Inspired by Biology where the notion of “*adaption*” is well known as

an advantageous confirmation of an organism to changes in its environment [253, p. 6],

Drenick and Shahbender [81] introduced the “*adaptive servomechanism*”³ to control theory in 1957. “*Adaptive control*” was born.

¹Years of birth and death are taken from en.wikipedia.org.

²J.C. Maxwell analyzed the roots of polynomials to have negative real parts; however, he was not able to formulate a general result. This was achieved nine years later by Edward John Routh (1831–1907) in 1877 [284].

³The term “*servomechanism*” was coined by the military while analyzing the problem of positioning a gun for aiming at the target [336, 337]. Later “*servomechanism*” became a description for the ability of feedback control systems to simultaneously track reference signals and reject disturbances, known as the servo (mechanism) problem (see [97]).

Several definitions of “*adaptive control*” or “*adaptive controllers*” can be found in the literature, for a collection see e.g. [253, Definitions 1.1.1–2, 1.2–1.4, p. 9–11]. Some authors even questioned the necessity of introducing the term “*adaptive*” in feedback control considering any feedback as adaptive (see [241]). For this monograph, the author follows the informal but pragmatical definition of adaptive controllers given by Karl Johan Åström (1934–):

An adaptive controller is a controller with adjustable parameters and a mechanism for adjusting the parameters [22, p. 1].

Note that this definition may also incorporate variable-structure adaptive controllers (see [22, Sect. 10.4]) with different dynamics for different operating points. In this book, solely adaptive controllers with fixed structure are considered.

First motivating examples for the need of adaptive control were flight control (of e.g. military supersonic aircrafts), process control (e.g. refineries in chemical engineering) or decision making under uncertainty (in e.g. economics). For more details on adaptive control around 1960, the reader is referred to the survey articles [15, 17, 188].

In the mid 1950s, inspired by the problem of designing autopilots for high-performance aircrafts, several adaptive control schemes were developed, such as gain scheduling,⁴ self-tuning regulators⁵ (STR), model reference adaptive control (MRAC)⁶ or dual controllers (see [22, p. 22–24]).

At this time the notions of controllability and observability, state space concepts and tools to analyze stability of nonlinear systems were still missing or not fully recognized. These concepts and tools were introduced in the seminal contributions [194–196, 230]⁷ by Rudolph Emil Kálmán (1930–) and Alekandr Mikhailovich Lyapunov (1857–1918), respectively. This

lack of understanding of the properties of the proposed adaptive control schemes [184, Sect. 1.3] *combined with* a lot of enthusiasm, bad hardware and non-existing theory [16]

lead to severe implementation problems and eventually to an accident during flight tests (see [184, p. 23]). As a consequence, the funding of research on adaptive flight control was cut and, additionally, it became obvious that the available computer hardware was not yet powerful enough for most of the adaptive control algorithms. Hence, the interest in adaptive control dropped again (see [17] or in great detail [22, p. 2–3] or [184, Sect. 1.3]). The flight control problem was finally solved by gain scheduling (see [17] or in more detail [22, p. 414–415]).

⁴It was severely discussed if gain scheduling is an adaptive controller or not. In view of the informal definition, gain scheduling is clearly an adaptive controller [22, p. 19].

⁵In [20], the authors avoided the use of the term “adaptive” for their controller, since the plant parameters were assumed constant but unknown (not varying). However, in the notion of the above definition, self-tuning regulators are also adaptive controllers.

⁶STR and (indirect) MRAC [184, Sect. 1.2.4] are nowadays considered as equivalent [22, p. ix].

⁷First French translation in 1907: “Problème Général de la Stabilité de Mouvement” in *Annales de la Faculté des Sciences de l’Université de Toulouse*, Vol. 9, pp. 203–474. Reprinted by Princeton University Press in 1949. First English book in 1966 [231], modern translation in [232] with biography and bibliography of A.M. Lyapunov.

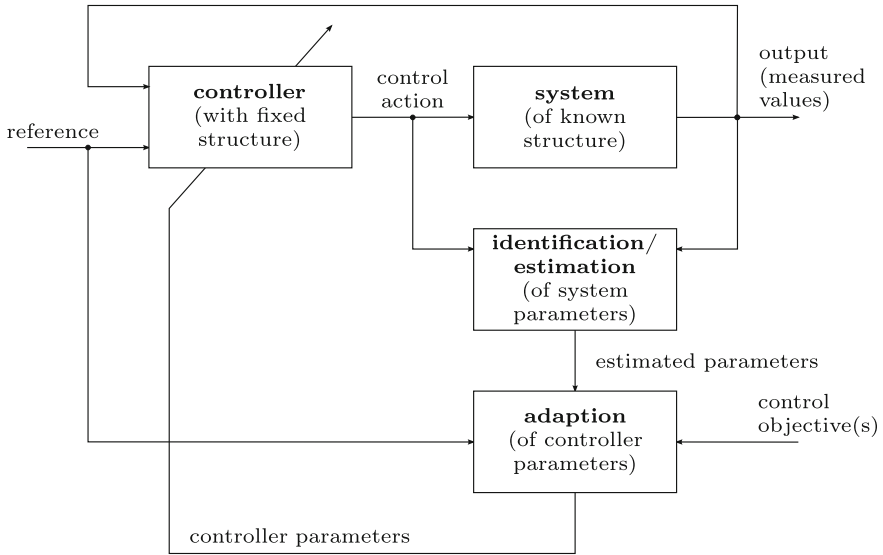


Fig. 2.1 Indirect adaptive control (based on Fig. 1.6 in [184])

A renaissance of adaptive control arose in the years around 1970, when first stability proofs were reported (see [22, p. 2–3] or [184, p. 24]). However, the adaptive schemes were sensitive to small perturbations resulting in potential instability of the closed-loop system. Not before the late 1980s and early 1990s, the field revived by breakthroughs in robustness analysis of adaptive control systems (see [184, p. 25]). Since then, research focused more and more on the “*transient and steady-state performance*” [184, p. 25] of adaptive control systems (mostly related to MRAC).

Loosely speaking, feedback control solves the problem of designing a controller with fixed structure and constant parameters for a system with *known structure and (at least roughly known) parameters* to meet given control objective(s) such as stability of the closed-loop system, asymptotic tracking and disturbance rejection. In contrast, imposing the assumption that such a controller exists, adaptive control solves the problem of designing a variable controller (in structure and/or parameters) for a plant with *known structure but unknown parameters* (see [184, Sect. 1.2.3]). Adaptive control may be classified into two categories: “*indirect*” and “*direct*” adaptive control. These adaptive concepts are illustrated in Figs. 2.1 and 2.2, respectively.

“*Indirect adaptive control*” relies on identification algorithms (e.g. recursive least square or gradient methods) to estimate the unknown system parameters. Assuming that these estimates converge to the true values, the controller parameters are adjusted by using the estimated system parameters and an adequate adaption rule (see Fig. 2.1). This approach is nowadays known as the “*certainty equivalence principle*”⁸ [17]. The

⁸The idea of neglecting uncertainties and using estimated values of system parameters as true values (for controller design) was introduced in [311] as “*certainty equivalence method*”.

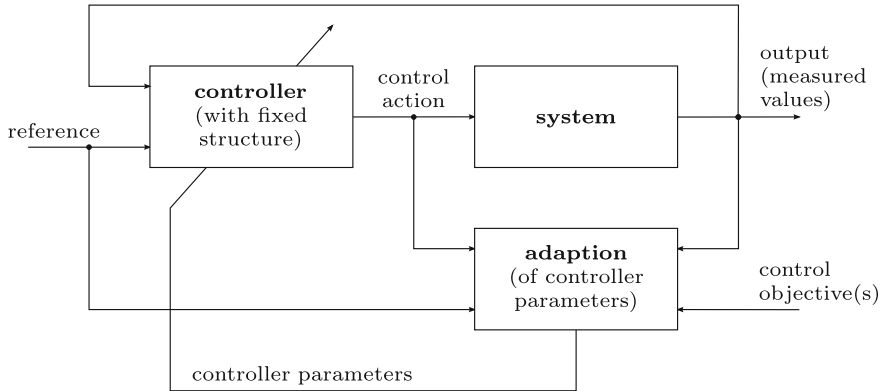


Fig. 2.2 Direct adaptive control (based on Fig. 1.7 in [184])

assumption on convergence is based on “*persistent excitation* [253, Chap. 6]”: to achieve ideal identification of a system (i.e. exponential/asymptotic convergence of estimation parameters to real parameters), excitation with a sufficiently large number of amplitudes and frequencies (incorporating all eigenmodes in the case of linear systems) is necessary. The order of the identification problem (number of estimates) at least increases with the order of the system: For example, for recursive least square methods, the number of estimation parameters grows quadratically with the system order (see [152]). A typical example for indirect adaptive control is model reference adaptive control (MRAC); even though there exist direct model reference adaptive controllers (see [184, p. 14]). For MRAC the control objective is prescribed in terms of a “*reference model*” which determines how the closed-loop system should behave.

“*Direct adaptive control*” does not require system identification or estimation. The adaption of the controller parameters directly depends on measured system output, reference, control action and control objective(s) (see Fig. 2.2). Direct methods are, in general, not applicable to all systems but are restricted to certain “*system classes*” (e.g. minimum-phase systems, see [184, p. 10]).

A very simple form of direct adaptive control is non-identifier based adaptive control. “*Non-identifier based adaptive controllers*”—also known as “*high-gain adaptive controllers*” (see the survey [161] or the monograph [162])—exploit the so called “*high-gain property*” of minimum-phase systems with (strict) relative degree one and known sign of the high-frequency gain⁹: For simple proportional output feedback $u(t) = -k y(t)$ and a sufficiently large controller gain $k \geq k^* > 0$ (larger than a threshold gain $k^* > 0$), the closed-loop system is stable (see [170]). The threshold gain k^* (lower bound for k) depends on system data and must be known *a priori*. In the adaptive case, it is found *online* by (dynamic) adaption. The following non-identifier based adaptive output feedback controller

⁹The notions “minimum-phase”, “relative degree” and “high-frequency gain” are defined in Definitions 5.66, 5.54 and 5.61 for LTI SISO systems, respectively.

$$u(t) = -k(t)y(t), \quad \dot{k}(t) = y(t)^2, \quad k(0) = k_0 > 0 \quad (2.1)$$

“stabilizes” the closed-loop system. The controller gain $k(\cdot)$ is *bounded* but *non-decreasing*. Moreover, when measurement noise $n_y(\cdot) \in \mathcal{W}^{2,\infty}(\mathbb{R}_{\geq 0}; \mathbb{R})$ deteriorates the output, the adaption in (2.1) becomes $\dot{k}(t) = (y(t) + n_y(t))^2$ and, hence, the gain $k(\cdot)$ might diverge (see [170]). In this case or if unknown load disturbances perturb the system, adaptive λ -tracking control should be applied which introduces a dead-zone in gain adaption. Moreover, for reference $y_{\text{ref}}(\cdot) \in \mathcal{W}^{1,\infty}(\mathbb{R}_{\geq 0}; \mathbb{R})$, asymptotic accuracy $\lambda > 0$ and tracking error $e(\cdot)$ as in (1.1), the adaptive λ -tracking controller

$$u(t) = k(t)e(t), \quad \dot{k}(t) = d_\lambda(|e(t) + n_y(t)|), \quad k(0) = k_0 > 0,$$

with $d_\lambda(\cdot)$ as in (N.7), achieves *tracking with prescribed asymptotic accuracy* (see [170]). The gain $k(\cdot)$, albeit *bounded*, is still *non-decreasing*. In [177], funnel control is introduced. It has a “time-varying” gain

$$k(t) = \frac{1}{\psi(t) - |e(t) - n_y(t)|} \quad (2.2)$$

where $\psi: \mathbb{R}_{\geq 0} \rightarrow [\lambda, \infty)$ is a prescribed continuous “*boundary function*” (the funnel boundary) and $\lambda > 0$ is the prescribed asymptotic accuracy. If the initial error $e(0)$ “starts” within the boundary, i.e. $\psi(0) > |e(0) - n_y(0)|$, funnel control assures *tracking with prescribed transient accuracy*, i.e. $\psi(t) > |e(t) - n_y(t)|$ for all $t \geq 0$. Most important, funnel control allows for gain *increase* and *decrease*.

Since only “structural system knowledge” is required, non-identifier based adaptive control is inherently robust and makes it attractive for industrial application. For systems with a relative degree higher than one, non-identifier based adaptive control is still feasible, however the controllers become quite complex due to (i) backstepping [181, 346] or (ii) the use of high-gain observers [57]. Otherwise, the non-identifier based adaptive controller might incorporate controller gains with high powers (e.g. $k(t)^7$ for the relative degree two case [181]). Such controllers are not suitable for industrial application. In Part II, the Chaps. 8 and 9 present *simple* (in the sense of non-complex and of low order) non-identifier based adaptive controllers for the relative degree two case which achieve tracking with prescribed asymptotic accuracy and with prescribed transient accuracy, respectively.

Besides the theoretic evolution of adaptive control, it partly became popular in industry. Several applications in industry were published for e.g. chemical reactor control, autopilots for ship steering or speed control of electrical drives (see the surveys [16] or [342] for adaptive control in general and [170] for non-identifier based adaptive control in particular). However, research activities on adaptive control theory by far exceed the number of industrial applications: in 1997 the application/theory ratio ranged between 0.02 and 0.1 (see [342]). Adaptive control still lacks widespread industrial acceptance.

2.2 Mechatronics and Motion Control

The term “*Mechatronics*” was coined by Ko Kikuchi (see [70])—an electrical engineer of Yaskawa Electric Cooperation—in 1969 (see [213]). The company secured the trademark rights in 1972 (Japan Trademark Registration no. 946594). Since the term “*Mechatronics*” was soon widely adopted in industry, Yaskawa released its rights in 1982 (see [213]).

In the late 1960s and the early 1970s, innovations such as electronic amplification (e.g. operational amplifiers (op-amps) on the signal side and power electronics on the actuation side) and micro-processors lead to more and more usage of electronic components in combination with mechanical systems and paved the way for Mechatronics (see [24, 213]). For increasingly complex systems, the design process became more and more modular (see [24]), which helped to develop “*mechatronic products*” offering enhanced functionality and improved performance (see [24, 213]).

Although the word “*Mechatronics*” is simply the composition of “*mecha*” (from mechanism or mechanics) and “*tronics*” (from electronics, see [159, 213]), the concept is nowadays considered in a broader sense. The term is used in numerous ways and its definition(s) changed over the passed 40 years (see [24, 70, 159, 213, 329]). Some authors even state that a definition is not possible or even desirable (see [147]). A Year 2000 definition of “*Mechatronics*” was given in [329]:

The synergetic integration of physical systems with information technology [...] and complex-decision making in the design, manufacture and operation of industrial products and processes.

Note that the definition above is still not completely accepted in all fields of research or industry. The understanding of “*Mechatronics*” severely depends on the background of engineers and scientists, which influences the language and the focus on what is “*Mechatronics*” and even how it is taught (see [52]). Even the most important societies in mechatronics such as the International Federation of Automatic Control (IFAC), the American Society of Mechanical Engineers (ASME), the Institute of Electrical and Electronic Engineers (IEEE) and the Mechatronics Forum do not use a common language (e.g. session titles of mechatronic conferences differ significantly, possibly leading to misunderstanding among the several “*Mechatronic dialects*”, see [52]). For this book, the Year 2000 definition seems adequate.

By using the notion “*physical system*” instead of “*mechanical system*”, the Year 2000 definition emphasizes that not only (single) mechanical systems are treated as mechatronic systems but also large-scale distributed systems (e.g. automated highway systems, see [329]). Typical examples of nowadays mechatronic systems are microelectro-mechanical systems (MEMS), computer hard disc drives (HDD, see [329]), car braking systems (see [70]), machine tools with computerized numerical control (CNC), automated teller machines (ATM), automated baggage handling systems at airports (see [24]), manufacturing and process automation systems, automotive and aerospace vehicles, thermal and environmental control systems and vibrational control systems for buildings (see [24]).

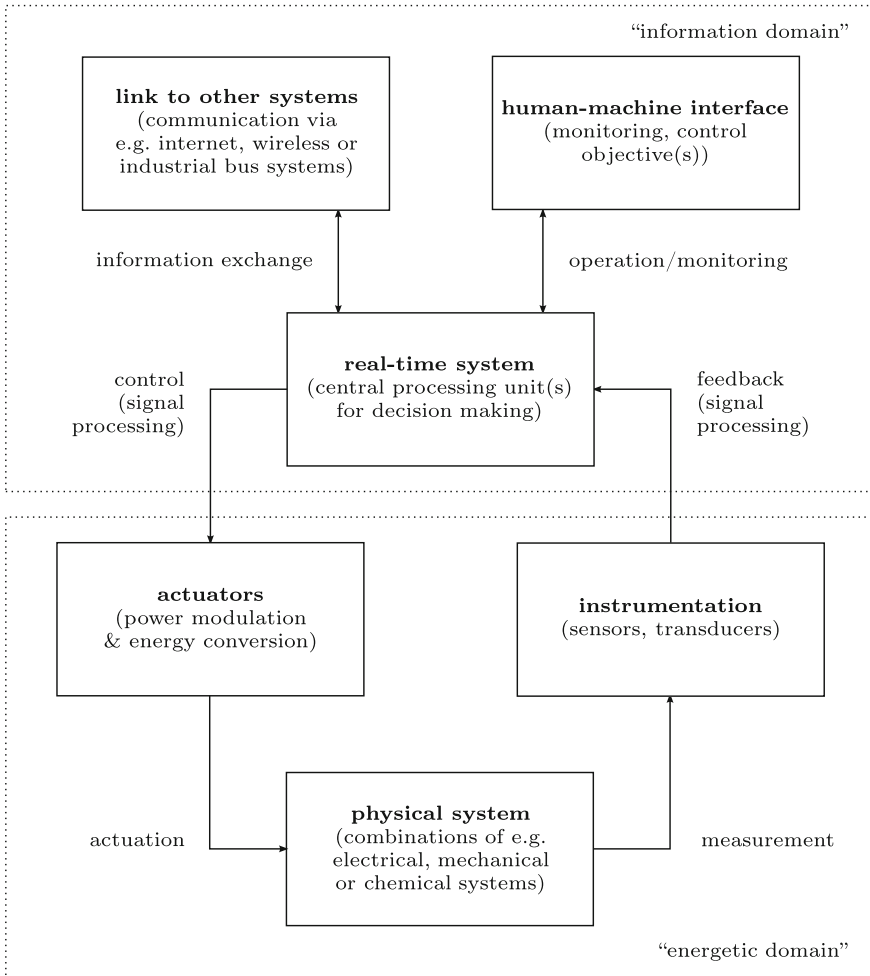


Fig. 2.3 Components of modern mechatronic systems (based on figures in [24, 52, 329])

The terms “*synergetic integration*”, “*information technology*” and “*complex-decision making*” in the definition attribute to the holistic, synergistic and interdisciplinary nature (see [339]) of “*Mechatronics*” as several science and engineering disciplines—e.g. electronic (electrical), computer, mechanical and software engineering and chemistry, biology and mathematics (systems and control theory)—equally contribute to the design, manufacture and operation of mechatronic products (see [24, 52, 159, 329, 339]).

Mechatronics is well established in many branches of industry such as automotive, manufacturing, aerospace and building/construction industry, electrical drive engineering, robotics and automation, (bio)medical engineering and even consumer

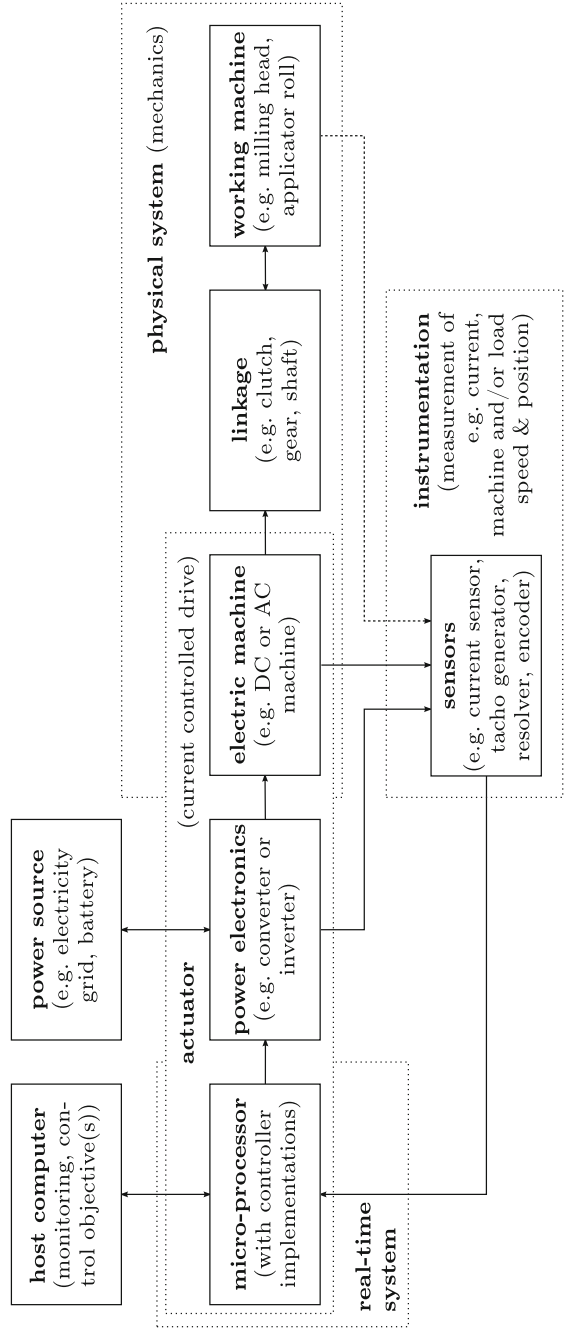


Fig. 2.4 Components of one-axis servo-systems in industry

electronics (see [159, 329, 339]). Mechatronics is (still) a growing market with increasing revenues, e.g. in 2010 the profit margins of the business segments “Industry Automation” and “Drive Technologies” of SIEMENS were 16.8 and 12.3%, respectively (see SIEMENS financial report 2010, p. 3).

The widespread use of increasingly powerful computers (e.g. micro-processors, digital signal processors (DSP), field programmable gate arrays (FPGA)) with real-time operating systems and software controllers (“*software servo-systems* [213]”) made the design process of complex-decision making algorithms “*versatile and flexible* [339]”. Decision making became more and more complex, e.g. neuronal networks, fuzzy logic, optimal and predictive control strategies and high dimensional (nonlinear) controllers could easily be implemented (see [301, Chaps. 5–9, 12–14, 16–17 and 18]). Mechatronic systems gained “*built-in intelligence* [339]”.

Figure 2.3 shows the components of modern mechatronic systems, though a clear delimitation among the components is often not possible. At its center, there is the real-time system connected to the human-machine interface. It exchanges information with other mechatronic systems. The implemented decision algorithms (e.g. controllers) generate the control input(s) to the actuator(s) which provide adequate actuation of the physical system by appropriate energy conversion (e.g. from electrical to mechanical). The installed instrumentation assures measurement of the necessary system states and allows for feedback to the real-time system. Note that a mechatronic system may be split into two domains: the “*information and energetic domain* [52]”.

This book focuses on motion control of industrial mechatronic systems such as “*one-axis servo-systems* [213]”. A typical one-axis servo-system is depicted in Fig. 2.4. It consists of electrical drive (power electronics & electrical machine) fed by a power source and linked to a working machine (to be driven). The electrical drive with current controller (torque generation) is considered as actuator, whereas rotor of electrical machine, linkage and working machine represent the physical (here: mechanical) system. Note the overlap between actuator and real-time system and physical system, respectively. Several sensors provide measurement signals which allow for feedback control. The controllers are implemented on the real-time system with human-machine interface to a host computer for monitoring and/or specifying reference or command signals.

Motion control is considered as the “*key technology in mechatronics* [260]” with the following—rather vague—control objectives:

- load position or load speed reference tracking and
- disturbance rejection (of e.g. unknown load torques and friction).

Depending on the requirements, the motion control objectives are formulated more precisely, e.g. in terms of maximum rise time, maximum overshoot and maximum settling time (see (mco_1) – (mco_4) or Fig. 1.2 on p. 4).

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Theory and Application

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