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Design of Mechatronic Systems

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Introduction

A decisive characteristic feature of mechatronics is a functional and spatial integration of components including synthesis of various technologies. The arrangement of these components ensures their function; specifically in terms of their reliability and reasonable costs. Designing of mechatronic systems needs therefore to start from functions and only then to decide which configuration of components and technologies would be the most appropriate for accomplishment.

1. Mechatronic approach to system design

We have already learnt that the conception of mechatronics arises from the integration of knowledge from different areas of physics and technical disciplines. The purpose of mechatronics is to use this integration in order to achieve a synergic effect, i.e. to obtain a product with highest possible technical and economical parameters. In this light, mechatronics can be considered as a new and innovative technology that can be divided into several areas:

- ***Design*****.** Here we deal with searching for and mastering of appropriate level of abstract tools and their interconnection with other levels of abstract tools, whereas these tools have to be able to appropriately conceive the tasks from mechanics, electrical engineering, electronics, control and data processing,
- ***Production.*** Here we deal with evaluation of product design in terms of its manufacturability under the respective conditions, namely with respect to mechanical and electrical components,
- ***Quality and reliability.*** Here we deal with development of methods and tools to ensure the quality and to predict reliability and implementation of these methods and tools into the process of product designing,
- ***Education.*** Here we deal with breaking through the barriers between a traditional conception of mechanical engineering and electrical engineering and a control including computer sciences. This area should be developed within the respective enterprises and also between the enterprises, and last but not least also in secondary and tertiary education.

This chapter will mainly be devoted to the development of methods, tools, and models that provide aid to the process of designing. This content is in full correspondence with the area of designing and in partial correspondence with the area of education.

The requirements laid upon the process of designing can be summarised as follows:

- ***Highest attention paid to the early stage of designing process,***
- ***Shared modelling of technical systems and the processes occurring therein,***
- ***Work in an interdisciplinary team interdisciplinary team.***

Shared modelling throughout the initial stage of designing process is a necessary condition for the work of interdisciplinary team. The reasons can be formulated as follows:

- ***A designer is provided with a possibility of virtual presentation of problem solving,***
- ***A shared model enables us to explain the core of the solution to the other fellow workers, and if needed by the management, also to other workers from manufacturing and marketing departments. It is also important that this model can be used in further stages of designing process,***
- ***A shared model is a condition that enables the designer to concentrate on the solutions to the problems that are decisive for the respective stage of designing process,***
- ***A shared model also allows an easy verification of completeness and quality of problem solving.***

It is necessary to point out that mechatronic systems are considered to be complex. They consist of a number of elements of various physical natures. The elements interact with each other but properties of the systems cannot be determined by describing the interactions. ***Therefore the system is more than a set of parts; the synergic effect is reached.***

1.1. Traditional methodology of machine design

A traditional design of machine systems, which ***seem to be mechatronic,*** is discussed in this paragraph. Considered systems consist of subsystems of different physical nature (mechanics, electrotechnics, electronic, control including software). The subsystems operate independently with ***limited interactions***. Even for these systems, the internal complexity has to be considered from the beginning of design process. A traditional methodology of design process is as follows:

- ***system is partitioned into individual homogenous subsystems according to the disciplines,***
- ***homogenous subsystems are designed by specialists from a design team,***
- ***each homogenous subsystem is designed by traditional way,***
- ***each product function is from the most part realized by only one homogenous subsystem,***
- ***interactions are minimized, emphasis is mainly laid on common interfaces of the subsystems.***

A common approach is as follows: first the mechanical parts are designed (skeleton) followed by electrical systems (muscles), electronic systems (sensors and nervous system) and finally a control system (brain). A resulting system that appears to be mechatronic is only a result of application of existing solutions and corresponding technologies. ***Research and development of new technologies and/or solutions is not needed*** if the traditional methodology is used.

1.2. Mechatronic methodology of machine design

Development of technology leads to a continuous increase in demands on properties of designed products:

- ***more functions,***
- ***higher efficiency and reliability,***
- ***lower demands on energy,***
- ***minimal size and weight,***
- ***lower cost.***

The following demands, brought about by development of technology, are increasing productivity of developers and designers. ***Shortening of development and design time*** is mainly desirable.

These demands cannot be fulfilled by traditional methodology. Main concern is that the development cycle of new product is too long, and the required or optimally achievable quality of the product is not guaranteed. It means that the individual homogenous subsystems form a barrier that does not allow us to increase the quality of system without increasing the price.

A mechatronic design is a tool which allows us to accomplish required changes. It can be understood as follows:

- ***mechatronic approach accepts usefulness of partitioning of solved problems to individual mechatronic disciplines,***

- ***it creates only one system with maximal functional and spatial integration instead of individual homogenous systems,***
- ***this system shows higher flexibility and intelligence without increased price.***

It is evident that the mechatronic design is mostly useful at the stage of search for solution conception. It is because the most of decisions about division of functions and their implementation including spatial integration to mechatronic system is accepted in this stage.

As we know mechatronics has substantial multidisciplinary and interdisciplinary character. It means we have to have access to suitable auxiliary tools – models – at stage of search for solution conception. These models:

- ***serve as tools to illustratively express developer's and designer's thoughts,***
- ***are essential communication tool in the team of developers and designers,***
- ***can serve to communication with people outside of team (e.g. management or marketing),***
- ***have to permit modelling of whole system at interdisciplinary level to reach independence of implemented technology.***

A general model describing each mechatronic system and its properties is required, but in reality it does not exist so several models have to be combined. An appropriate model has to be chosen at each design stage. A crucial condition for model selection is a compatibility of models, i.e. it has to be possible to ***switch from one model to another***.

According to [1] the following models have to be created in order to completely describe the technical system:

- ***model of technical process.*** The model should understandably describe the solved problem; clearly describe the relation between a mechatronic system and the user and the other mechatronic systems. It means the model has to incorporate an interface between the mechatronic system and the user and/or the other technical systems,
- ***model of process structure and its logical behavior.*** The model should describe transformation processes (transformation of material, energy and information) inside the mechatronic system. The effects (defined by target functions) are realized by the processes and the model is also characterized by control of the transformation processes based on a logical behavior. The model is technologically independent and can be applied to a large group of similar mechatronic systems,
- ***model of target functions and their logical behavior.*** The model should create function carriers or the mechatronic system's target functions (effects) capable to ensure fulfilling of requirements related to a technical process. A result is a description of the mechatronic system's functions including a logical behavior. The model is also technologically independent,
- ***model of function carriers.*** The model describes how the individual functions are realized. The function carriers are the used technical principles which create a required effect through their function.
- ***model of function carriers structure.*** The model describes a particular material realization of function carriers and so it is not interdisciplinary. It means that its content depends on a particular discipline (mechanics, electrotechnics, electronics, etc.).

The above mentioned various models are used to achieve the following:

- ***increasing number of possible solution variants***
- ***decreasing complexity of search for most suitable solution,***
- ***finding the most appropriate technology,***
- ***better control over the progress of the whole process,,***
- ***required quality (functionality/price) at a shortened development cycle.***

From the previous general description of a mechatronic approach to designing, it is evident that a more detailed analysis of these issues goes beyond the scope of this book. Therefore the methodology will be presented in a simplified way with appropriately chosen examples. An approach according to [2] is chosen to achieve a clear explanation.

2. Structure of mechatronic systems

There exist different approaches to the description of mechatronic systems. However the best approach to choose is the approach closest to shown structure of models.

2.1. Basic structure

A basic structure of the mechatronic system is created by ***a system*, *sensors*, *actuators* and devices for *information processing*. The surrounding environment**, in which the mechatronic system operates, is also important. A diagram of this structure is shown in fig. 2.1.

The system has usually a mechanical, electromechanical or hydraulic structure or it is a combination of these structures. It means that a given physical system can be generally understood as a respective system that can be represented by a hierarchically structured mechatronic system (see chapter 2.2).

A task of sensors is to determine a chosen state variable value of the system. Generally the state variables can be understood as the physical variables fully determined for a sampling interval by their values at a sampling time t_0. This ensures that the state variables for time $t > t_0$ are known. In this case, the sensors can be physically represented by the measured values or software sensors so called "observers". The sensors supply input variables for ***the information processing***, at present usually digital, i.e. discrete in terms of values and time. The information processing is usually done by a microprocessor although it can be also done by a fully analog electronics or combined (hybrid) analog/digital electronics. The information processing determines actions needed to affect appropriately the state variables of the system. An implementation of the actions is directly in the system by ***actuators***.

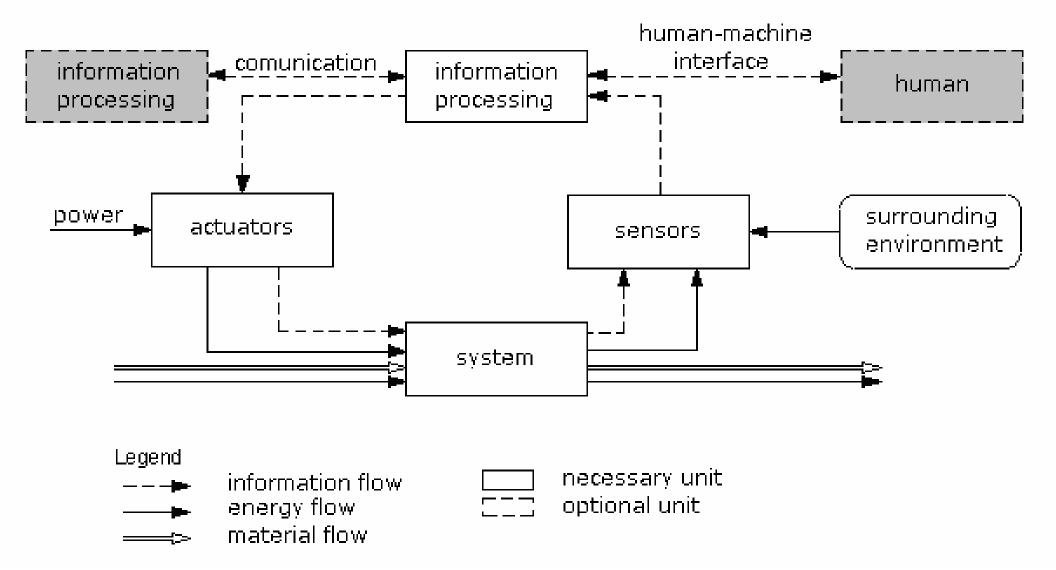


Fig. 2.1: Base structure of the mechatronic system

The present goal is a spatial integration with other functional elements in the area of sensors as well as in the area of actuators. It would create an "intelligent" unit, i.e. an ***intelligent sensor*** (integration of a measured values sensor, an analog/digital converter and a microprocessor) and an ***intelligent actuator*** (an integration of a digital/analog converter, an adapter circuit or a power amplifier, or even a microprocessor). The intelligent sensor measures analog physical quantities, for example pressure, temperature, velocity, it digitalizes measured values and transfers the signal – suitably adjusted – to information processing devices. The intelligent actuator is directly activated by the digital signal coming from the corresponding information processing device. Signals are converted to analog variables, amplified and then handed over, e.g. to create force or movement.

A closer look at relations between the system, the sensors, the information processing and the actuators shows that a description of the relations using flows is useful. In principle, there are three different types of flows:

- ***material flow,***
- ***energy flow,***
- ***information flow.***

Material flow: examples of material flow between mechatronic system units are solid bodies, tested objects, processed objects, gases or liquids.

Energy flow: energy is in this context understood as a different form of energy, for example mechanical, thermal or electrical energy but also action variables (e.g. force or current).

Information flow: it means the information transferred between the units of the mechatronic system, for example measured variables, pulse control or data.

The mechatronic system, shown in fig. 2.1, consists of units connected by three types of flows. The most visible are energy and material flows. Flows connecting the base system and environment with sensors and actuators have a character of energy flow as well as information flow – energy "flows" for measurement requirements (sensors) as well as for action execution (actuators) but energy is transferred as well – control signals of actuators and measurement signals of sensors. Tools for information processing use the information flow from sensors and also generate the information flow for the actuators. One main energy flow affecting, directly or indirectly, the system can be noticed in case of energy flows shown in fig. 2.1. Units for the information processing of a mechatronic system are often connected to the other units for information processing via a communication system. Communication with a human or a system user is usually realized by a special human-machine interface. The connection is represented by the information flow in both cases.

2.2. Modularization and hierarchization

Complex mechatronic systems are usually made by synergetic integration of different mechatronic ***modules***, i.e. elements of system or components connected to groups, jointly executing a certain function. It is not recommended to make the integration at one level but it is necessary to separate the configuration according to the principle of ***hierarchization*** because the modules contain and constitute different functions. A basic structure of the mechatronic system described in chapter 2.1 is understood as a basic module.

A higher-level system is made if more basic modules are connected together by its functional mechatronic structure and mechanic supporting structure. At this higher level, the other tasks are realized according to the events monitored by a sensor system and evaluated by the information - processing unit. A target value for the subordinate basic mechatronic modules is generated at this level of hierarchic structure as well as error diagnosis and algorithm monitoring.

Another hierarchic level, at which the basic modules and already grouped systems are simply connected by the information processing units, is suitable if the mechatronic system would do other tasks, for example process of learning or adaptation.

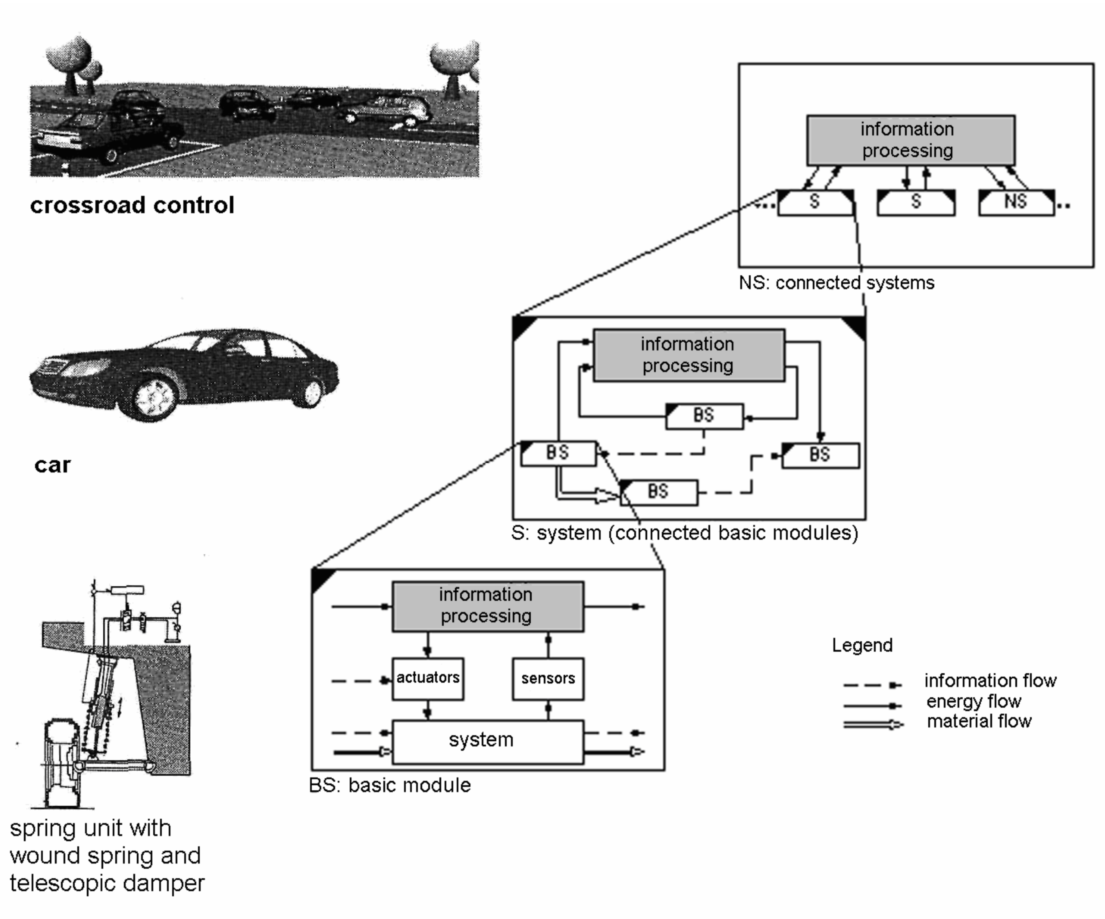


Fig. 2.2: Example of mechatronic system separation according to [3]

A sample of mechatronic system’s hierarchical structure is shown in fig. 2.2. The basic modules at the first level (e.g. a spring unit with wound spring and telescopic damper) are connected to the second level (e.g. car) by the information processing. The created systems are connected together by information processing (e.g. crossway control) at the third level.

A spatial integration of related equipment is also an important task as well as functional integration of the mechatronic modules. Modules of equipment have to be integrated through defined interfaces to create a whole system with individual hierarchical levels (mechatronic units). A simultaneous considering of both integration tasks leads to the optimally constructed mechatronic systems.

3. Useful properties of mechatronics

Useful properties of mechatronics are obtained from an innovative potential of technology and techniques and their functional and spatial integration. The first source of innovation arises from ***dynamical development of electronic and software-technical components*** and their systematic integration into a previously purely mechanic products. Innovation cycles of electronics and information technology are much shorter than the ones in mechanics. The dynamics brings about a number of opportunities. Their integration can be used to create mechatronic products. Furthermore a ***new combination of known production technologies*** gives rise to the second source of opportunities. Technical progress allows incorporation of electronic components and software to a purely mechanical or electro technical products. This leads to integration of functions previously realized elsewhere into the product or creates new functional possibilities.

A basic assumption required for full use of the two possibilities is ***modularization*** of product functions and ***interface*** definition (see chapter 2.2). Modularization means to form a modular structure of products in which connections between modules are less different than relations inside the modules. It allows us to reduce the interaction between modules to minimum. The interface between modules is created so that compatibility is ensured even if innovation dynamics of components differ, e.g. hardware components of different product generations or software update of unchanged hardware, etc.

3.1. Innovation potential of information technology and electronics

A contribution of the potential to the mechatronic products emerges from dynamics of information technology and electronics. The innovation dynamics has commercial and technical dimension.

Commercial dimension: The electronics area is commercially characterized by a stable decrease of price of electronic components. The reached price decrease can be directly used to decrease market prices and technical innovations are also directly brought to the market. Companies integrating microelectronic circuits to their products can profit directly from the commercial dimension and use the price decrease of their own products to improve a ratio price/performance.

Technical dimension: An innovation dynamics of electronic and software technology can be illustrated by the Moore law, which says that abilities of microprocessors can double every eighteen months. A technical progress is not limited only by abilities of microelectronic components. Advances in technology for a component production decrease the requirements to environment characteristics where electronic circuits can be used.

Technical and commercial dimensions are connected together. So prices can be decreased simultaneously with increasing capabilities of products. A furthermore described procedure with consideration of electronic components capabilities allows the use of more complicated software programs. The result is possibility of reaching a completely new function or targeted replacement of mechanical, electrical or electronic components.

3.2. Innovation potential of functional and spatial integration

A functional and spatial integration of different components brings about the following advantages:

- ***improvement of ratio price/performance,***
- ***improvement of performance (e.g. increase in energy efficiency, speed, acceleration),***
- ***increase in functionality (e.g. operational comfort) or even possibility of implementation of new functions (e.g. automatic test and diagnosis),***

- ***reaching of behavior improvement (e.g. improvement of accuracy, compensation of disturbances).***

Many examples of the purely mechanical or electromechanical products from different industry areas, which can be improved in this way or even profitably made with use of functional integration of electronic or software, can be shown. Some examples are shown in table 1.

Table 1:

Area	**Product example**
Motor vehicles engineering	Window lifters, traction performance control, keyless start up, automatic air-conditioning control, engine control, seat adjustment, component function control through data bus
Mechanical engineering	Image processing system for automatic positioning, manipulators, robots
Consumer electronics	CD players (laser and accurate mechanic), digital cameras

Functional integration of mechanical and electrical/electronic components is done by its connection through material, energy and informational flow. The components can be separated from each other in this case.

Spatial integration means that mechanical and electrical/electronic components create a structural unit in means of a common entity. It means another technical complication in many cases. The problem is how to adjust electronic components to an operational environment of mechanical components. The operational environment is not often suitable for electronic components because of high temperatures, variation in temperature, dampness, mechanical impacts and vibrations, strong electromagnetic fields and so on. The problems can be overcome only by suitable precautions as encapsulation, usage of cooling systems or special construction of connecting technologies, which allow us to carry out spatial integration of electronic components.

The integration of mechanics and electronics in the mechatronic modules and components redefines the traditional interface not only at a product and development level but also at production level. The parameters of interfaces between separate manufacturers are also newly defined. The changes can be done only if they allow the equivalent use of technical and commercial potential.

Main technical and commercial potentials are shown in fig. 3.1 as corresponds to the evaluation by car industry companies. A smaller installation space achieved by elimination of covers and connecting elements (82%), higher reliability, exclusion of plug connections and connecting conductors (81%) and higher dynamics (64%) are introduced as the most important within the scope of technical potential. Companies agree that the most important commercial potential lies in the possibility to test a whole system with the providers. This is suitable because the tested system is, in this case, installed in the workshop of Original Equipment Manufacturer (OEM) or a costumer (with 88% significant potential). Another significant potential is a lower need for manpower for OEM throughout assembling that is achieved by decrease of number of components to assemble (82%). Further, a decrease in price of logistics is reported, which is achieved by a decrease in number of units (components/modules) and by its transportation or installation, if software is changed (80%).

However, these potentials have the following main disadvantages; higher costs of spare parts in case of repair, insufficient experience with new production and test technologies and also the use of pioneering procedures in construction and communication technologies.

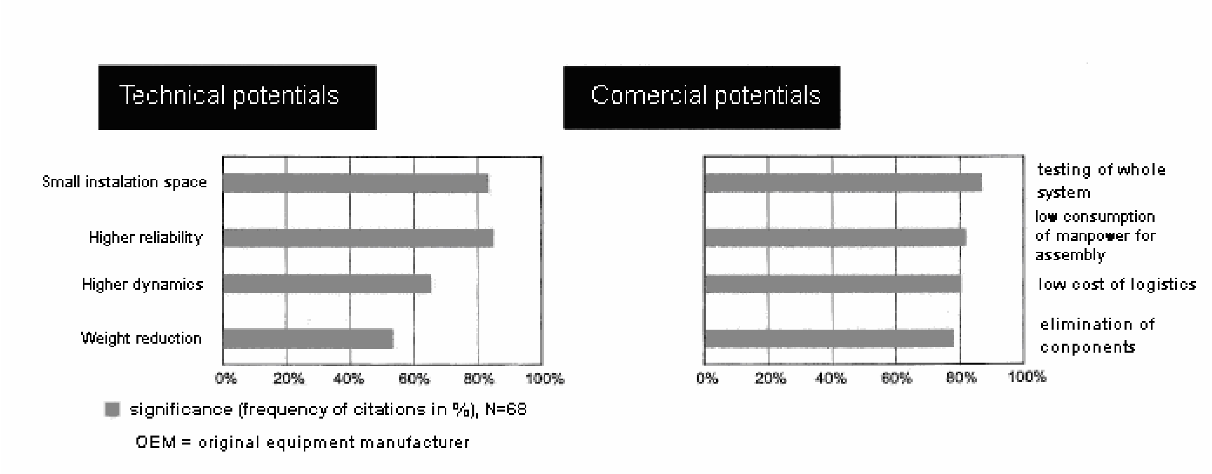


Fig. 3.1: Important technological and commercial potentials according to [4]

4. Special aspects of development process

The following special points of view are focused mainly in interdisciplinary and highly complex tasks and are necessary for virtual modelling throughout development of mechatronic systems.

4.1. Communication and cooperation between domain – specific experts

More specialized knowledge, mainly from the area of engineering, electrical engineering and information technologies, is required for development of mechatronic systems. The domains have their own language, experience, methods and tools for descriptions that have been developed for decades. In the past there often was only one domain involved in the development of the product. The base was represented by machine structures. A basic mechanical structure was the base of the product, while electrotechnics, electronic and information technology were added only later. This ***sequential procedure*** led to partial optimization of product by a gradual development but the demands on costs and time were higher.

The mechatronic systems have to be solved in terms of ***simultaneous engineering***. To achieve this, the product conception has to be worked out by integrally participating specialists. Individual system components can be solved – if are compatible – on the basis of approach of different domains or, if possible, mainly on the basis of interdisciplinary cooperation. An interdisciplinary approach requires tools to ensure communication and cooperation between the concerned technical disciplines because methods related to the individual domains were usually developed for specifically defined tasks and cannot be easily extended to or interconnected with other methods. Specialists from different technical disciplines (e.g. mechanical engineering, electrical engineering or information technology) are required to have knowledge of their own discipline as a basis for cooperation between them. Ability and willingness to acquire the knowledge necessary for understanding of other disciplines is a basic requirement needed for team cooperation at interdisciplinary level. Because of heterogeneity of mechatronic systems, in practice there is a possibility to divide the development between departments of a company or more companies. Demands on a ***distributed development*** (early replacements, access to the latest and consistent database or state of knowledge independent of place and time, various changes of model, etc.) result in extraordinary widespread of mechatronics.

4.2. Higher complexity of system

Heterogeneity and the fact that coherence of several physical principles, different technologies and materials should be considered mean that a lot of space can be devoted to problem solving. First, we will focus on the solution space that can be adapted to a defined object. The following points can help:

- ***define an object as exactly as possible,***
- ***distinguish the requirements at all phases of development,***
- ***use a set of verified and tested functional structures and a set of complex tasks by means of which the original task can be partitioned into simpler and clearer subtasks. These subtasks then support a systematic expansion of different variants and considerations related to functional incorporation with the aim to find the first functional structure more easily.***

A goal is to carry out segmentation, selection of parts and integration so that an overall optimum is reached and a number of necessary designs are limited to a minimum. The complexity of mechatronic products lead to other considerations that have to be taken into account: exact determination of functions cannot be accomplished separately as it is in the case of traditional construction approach. Therefore when describing the functions, physical, geometric and technological aspects have to be considered, being of the same importance. This leads us to such methods as modularization, hierarchization, segmentation and integration.

An increased integration of functions and principles of an operation/solution of basic components and technologies lead to mutual influence, which has to be considered early and appropriately. The procedure of integrating separately developed and optimized sub assemblies into a resulting system (***down to up design***) is not any more fully sufficient. Repeated procedural steps are necessary to acquire the first knowledge about the basic structure and then to accomplish more specific determination of system parts. A refinement is a step - by - step process (***up to down design***). More detailed knowledge of system properties can lead to changes in higher - level elements so an upward change is done. Advanced phases of design are usually characterized by a variation between both development strategies (yo-yo effect).

4.3. Virtual prototypes production

An important part of the development process is the use of experimental models and prototypes, which allow us to test the product for a possible future mass production. An effort to minimize the number of prototypes exists because a prototype development and testing is time and finance consuming. Virtual prototypes (i.e. computer models) to be developed can be very beneficial. In addition to ***digital model of product*** (3D model + product structure), kinematic, dynamic, strength and other characteristics are also considered in a virtual prototype. The possibilities of virtual approach can be demonstrated e.g. on Boeing 777, which is the first airplane fully developed by 3D-CAD system containing even virtual assembling. The virtual modelling is very convenient for the development of mechatronic systems. A mutual influence and a growth of complexity achieved through joining the previously independent subsystems (e.g. joining the engine control and the brake system within the electronically controlled system for control of direction stability ESP) requires modelling and simulation of the system behavior at the early stage of design because a large number of possible configurations have to be investigated with minimal possible costs and development time. New safety requirements are imposed on the systems with separation of a direct link between user and machine, e.g. a brake booster system or electrical hand brake. The main focus is to predict failure of the individual parts and its effects within the system as a whole. These states can be indicated by simulations of safety-critical situations, which can immediately simulate a real situation for different operating states and parameters of designed system. The simulation means a transfer of an object with its functional processes to an experimental model to acquire knowledge about this real object. Alternatives of control and safety concepts can be therefore compared under identical conditions without complicated modifications of the prototype.

When simulating the mechatronic systems, it is important to consider not only behavior of the subsystem itself but also and its influence on the other subsystems. It is more difficult because the basic elements of the system cannot often be ascribed to a particular knowledge domain, i.e. these basic elements usually contain functional dependences from at least two domains and create an interface between appropriate subsystems (e.g. hydraulic cylinder or electric DC motors). Because of heterogeneity of these systems, simulations of the whole mechatronic system are usually done by different tools of the information technology

(IT tools, computer application that helps the engineers throughout the product development) These are e.g. tools covering as many domains as possible, tools used to import models created in other tools into the simulation program, or tools solving the simulation of subsystems separately in different tools with a follow – up delivery of results. A difficult task is to interconnect the respective IT tools with the aim to create a joint overall development environment and to support a mutual interaction between the tools of the model, system, process and technology (see chapter 7).

5. Development of mechatronic methodology

The experience acquired recently from industrial practice and from the results of empirical search for a design clearly shows that this approach is not an optimal form of design process for a designer to rigidly stick to. Therefore the following is recommended:

5.1. Procedure

A more flexible process model, basically based on the following three points, is designed to create a methodical guideline for mechatronic design realization.

- ***design cycle at micro level***
- ***design cycle at macro level***
- ***pre - defined procedure modules of recurrent working tasks throughout mechatronic system design to be followed by the operator***

Design cycle at micro level: A segmented procedure of development process is carried out; in this case through a basic general solution of problems arising from these development cycles as it is known e.g. from system engineering. A flexible adjustable plan of the design process, according to characteristic properties of any development task, can be reached by arranging the cycles in a gradual sequence. The above micro cycle is mainly intended to support a designer of the product dealing with expected and therefore foreseeable sub - problems but also to solve sudden unexpected problems throughout a design process.

Design cycle at macro level: A V- model offers guidelines for basic procedures and it is taken from software development and modified to meet the requirements of mechatronics. The model describes a logical sequence of important procedures of mechatronic system development. If this model is used in practice, we have to consider the fact that the time sequence of the individual tasks cannot diverge from the logical sequence. E.g. minimization of development risks has to ensure that a problematic system with a critical subsystem cannot be recommended for mass production before a full development of the whole system dependent on this subsystem starts.

Development modules for recurrent working tasks: Processing of the individual steps of a planning method solved by the basic V-model is controlled by the above mentioned problem solution of the development cycle. However for some mechatronic systems developed for recurrent tasks, more particular units in the form of partially predefined development modules can describe the control. This chapter deals with development modules for system design, modelling and model analysis, specific areas of construction, system integration and assurance of individual properties.

A functional and spatial integration of mechanic, electric and electronic components in the mechatronic system often needs to consider possible industrial technologies and also planning of the corresponding industrial process. Therefore the product and its development are accomplished in a close relation.

5.2. Design cycle at micro level (micro cycle)

The organization of micro cycle operation, shown in fig. 5.1, was developed in system engineering and was adopted in a modified form by other branches, e.g. business management or software engineering. It contains the following steps:

Analysis of state or choice of goal: At the beginning of basic design cycle there is either the analysis of state or the choice of goal. A selected group or a single person can select an exogenously determined goal, which follows after the analyses of state (procedure led by desired state) or the following analysis of initial or indefinite state formulates the goal (procedure led by current state).

Analysis and synthesis: search for solution to given problems follows the original analysis of state and goal. This approach creates the procedure of persistent alternation between the synthesis steps and the analysis steps carried out by the designer partially on purpose and partially unconsciously. A goal of this step is to create alternative solution variants. It is possible, throughout the phase of search for solution that additional viewpoints of the problem would arise, and then it is necessary to return to the analysis of state or goal or a subsequent step representing the evaluation has to be done as additional criterion.

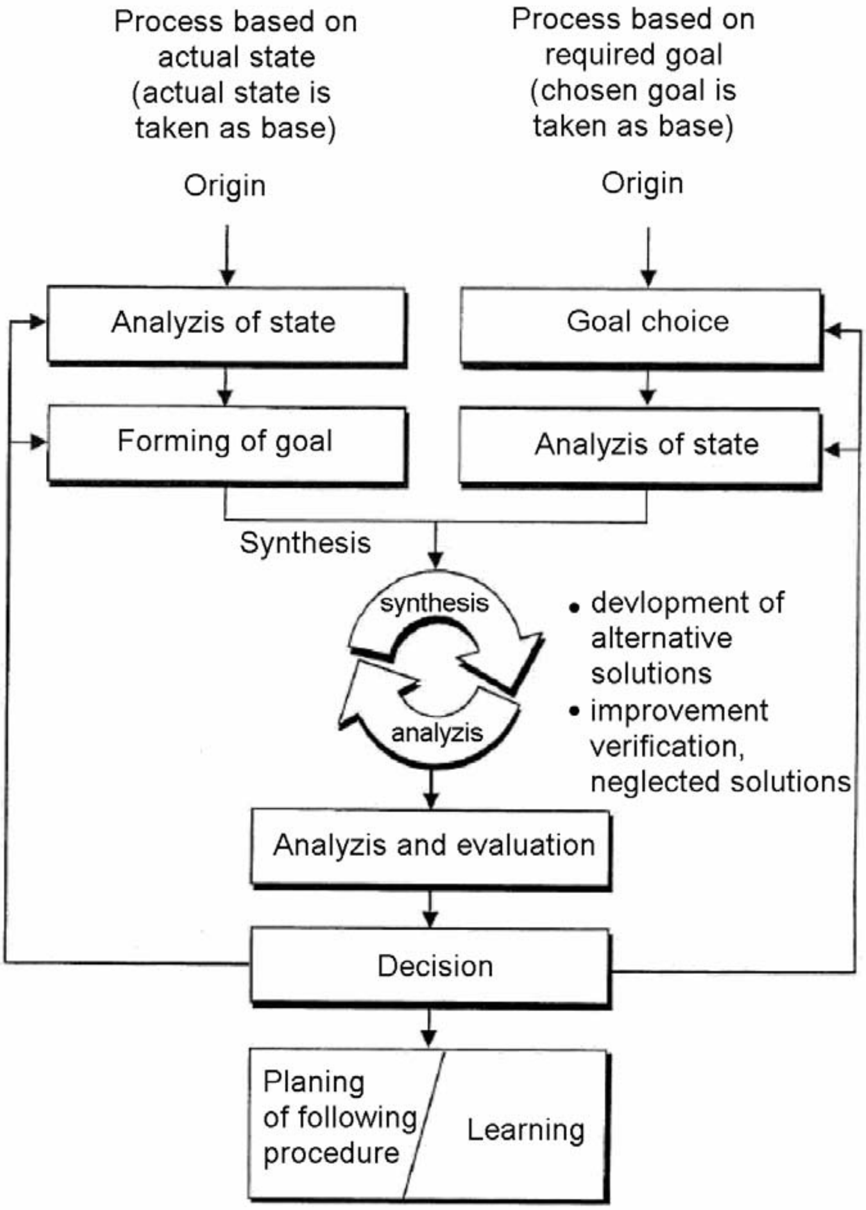


Fig. 5.1: Design cycle at micro level (micro cycle)

Analysis and evaluation: the particular solved variants are supplied by a detailed computation during the search for solution. The properties of individual variants of the partial or full solutions are analyzed on the basis of given requirements for this concept. The analysis can, for example, be done by computation, simulation, experiment, etc. A comparative evaluation is done if the individual steps of solution differ by orders in its degree of concretization. An evaluation of solved variants is, in this case, based on evaluative criteria defined during the goal formulation and search for solutions. A result of evaluation is a suggestion or recommendation of one or more variants of the solution. It should prepare the path to accept a decision about the evaluation result.

Decision: if previous solution procedure leads to satisfactory results, we can make a decision. If this is not the case, the analysis of state and goal formulation has to be resumed. In other words, a decision is based on a possible solution (possibly on more of them than on a single one) made on the basis of the following planning.

Planning of subsequent procedures or learning: the planning of subsequent procedures will, in many cases, progress more or less smoothly to the following cycles of problem solutions and this path leads to an effective development progress of such modified state. A short delay at the end of each cycle can follow, fully out of evaluation of reached results; during this delay, the requirement to display two subsequently reached results in a process of a general critical evaluation is satisfied. The knowledge, which can be used for the following development tasks, is acquired by inspection of how good the process step and its result were. In this way, the following steps of process can be improved.

5.3. Design cycle at macro level (macro cycle)

This cycle, according to fig. 5.2, describes a commonly used procedure for the mechatronic system design and has the case by the case, a different shape. The concept ***designing*** is understood as “to understand the whole unit, concept solution, identification or search for required and acceptable solutions; the model based on the interconnection between these elements creates a realizable unit”.

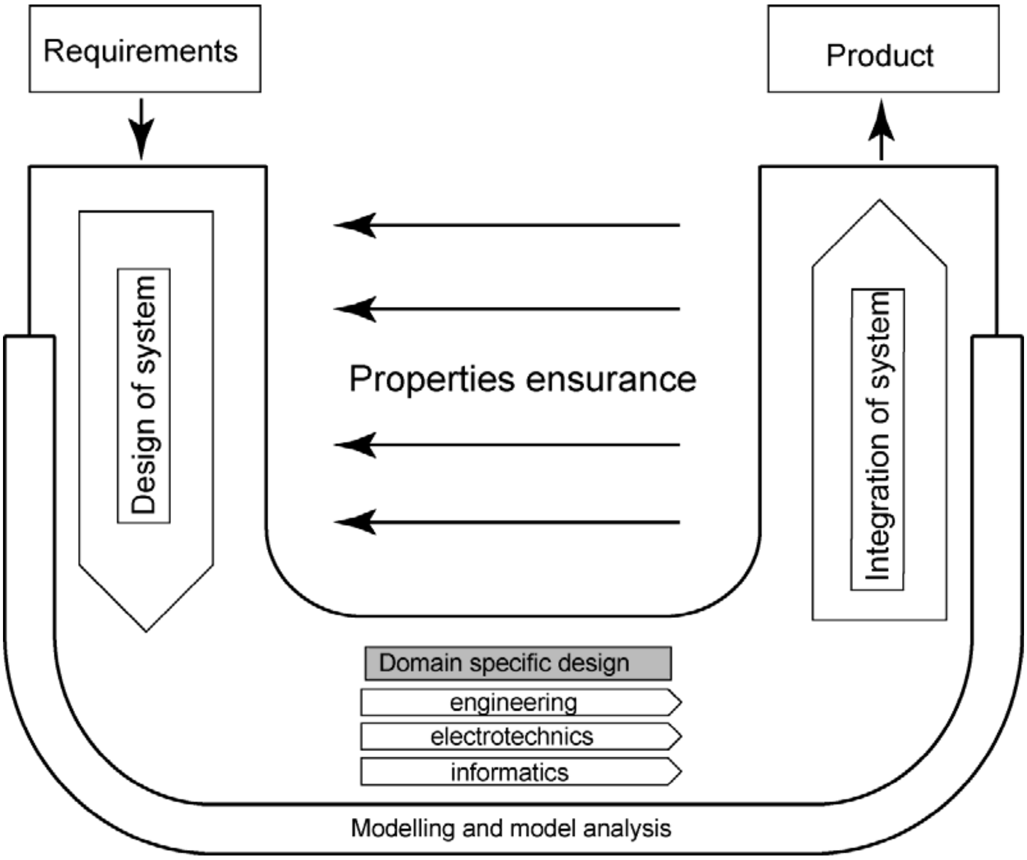


Fig. 5.2: Design cycle at macro level (macro cycle)

This idea contains also the so - called conceptual proposal and is derived from the terminology of mechanical engineering. Therefore, designing is a process that comes from requirements and leads to a particular technical system. This accomplishment is expressed by mechatronic elements and interactions between them.

Requirements: a point of origin is created by the actual development requirements. A defined subject is defined approximately and is described in the form of requirements. The requirements are related to the product and evaluated later.

System design: the goal is to create an interdisciplinary conception of the solution, which describes main physical and logical operation characteristics of the planned product. The whole function of system is brought together to individual main functions for this design. Suitable operation principles or solved elements are assigned to these functions and execution of them is tested on the system.

Domain - specific design: the accomplishment usually proceeds separately in an appropriate domain and is based on jointly developed conceptions of solution. A more detailed interpretation and computation is necessary to ensure the completion of functions, mainly in case of critical functions.

System integration: the creation of the whole system is done by integration of results from different domains so as investigation of mutual interactions is possible.

Assurance of properties: a design procedure has to be monitored continually on the basis of jointly developed solution concepts and requirements. An agreement with real and required properties of system has to be ensured.

Modelling and model analysis: these phases create, describe and investigate the properties of system with use of models and tools of computer support for simulation.

Product: the product is a result of a continuous macro cycle. In this case, the product is understood in a means of a never - ending process. A real, existing product can be improved by increasing diversification of planned product – ***maturity*** of product is increased. Degrees of maturity of the product are e.g. laboratory sample, functional sample, prototype, etc.

The whole mechatronic product is not, in general, designed during one macro-cycle. While designing the product it is necessary to carry out several macro-cycles, fig. 5.3.

During the first cycle, for example, the function of the product is defined and first operating principles and/or first solution elements are chosen. The operating principle describes the relation between the physical effect and dimension and material attributes (real dimensions, real movement and material). This allows us to express, using sub - functions, the defined principle of solution. Operating principles and solution elements are roughly sized, checked with regard to the operation of the whole system, and a prototype is manufactured. In general, this is a laboratory exemplar. Solution elements are put into practice and results of the function operations are tested. In general, these are modules/subsystems based on the operating principle. A computer representation of the element being solved compares different criteria of behavior as well as a shape. During the development process and its individual phases, each of these criteria is specified. The shape criterion includes general conditions of the defined solution principle and more specific conditions for defining the process of the development. The behavior criterion can in case of software include work with abstract data in the initial stage of development, and in later stages, work with codes.

In the second cycle, when final dimensions of the elements being solved are set and the simulation of behavior and design is carried out, the first pilot-run product is manufactured. Depending on the operating process of the design and the type and complexity of the development task, additional macro-cycles can be required so as to manufacture the product in series. The number of external cycles and steps carried out by the V-model depends on the type of the development task.

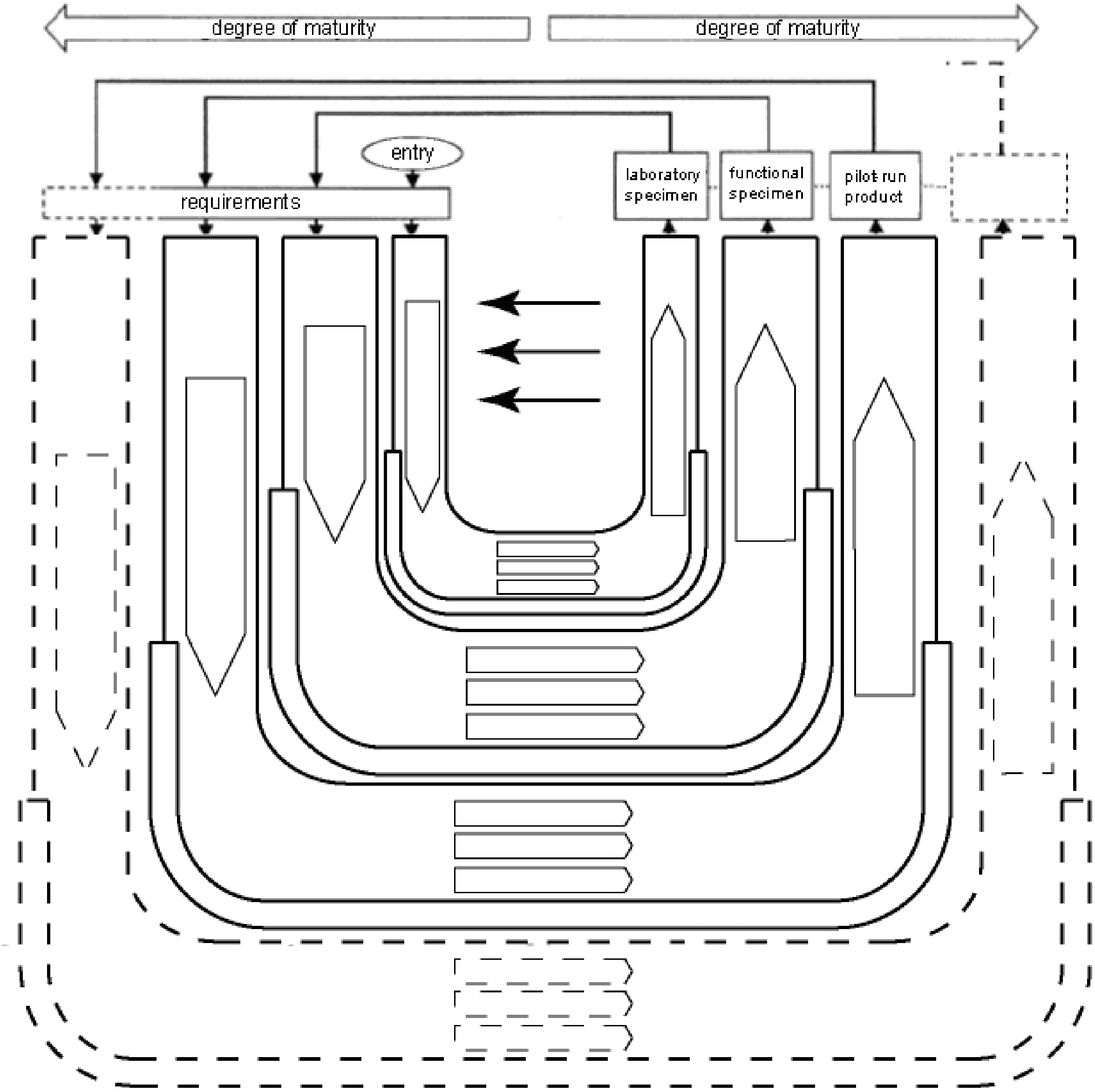


Fig. 5.3: The process of more macro-cycles as the maturity of the product increases

5.4. Modules of the operating process for reversible development steps

Some partial steps back carried out while designing the mechatronic system can be described more specifically as partially pre-defined modules of the operating process. Modules of the operating process of the ***system design***, ***the modelling and analysis of a domain-specific design***, ***the system integration*** and ***the assurance of properties*** are explained hereafter:

System design: this design starts with an abstraction of requirements from the list. The abstraction enables us not to use immediately strictly defined elements that would limit the number of possible solutions. The aim is to find out what is fundamental and generally usable with respect to the problem definition. This is achieved, for example, if the list of requirements is reduced to the most important requirements and if the problem is defined in a neutral way with regard to the solution.

Definition of the operating structure: main function is derived from the task description (fig. 5.3). It represents the ***goal operation*** of the system in working conditions. Working conditions represent ***input variables***, while output variables describe ***requested behavior***. After the input of general variables – material flow, energetic flow and information flow (chapter 2.1) – and the draft of block diagram, the relations between input and output variables can be specified. However, this task is too general and complicated and cannot be put into practice from the technical point of view. That is why the whole operation has to be divided into sub - functions. The sub - functions of mechatronic systems are: actuator, closed-loop control, measuring, driving gear, etc. They are connected through material flow, energetic flow and information flow so that they form the ***function structure***, describe the behavior and detect discrepancies as early as possible. The aim is to define as closely as possible the function structure so as to find operating principles and solution elements that will be carried out by these functions. If, for a certain sub - function, this is not possible, this sub - function has to be divided further by means of repeating steps of analysis and synthesis (chapter 5.2).

Search for operating principles and solution elements to perform sub - functions: appropriate operating principles and solution elements for individual sub - functions are sought. The sub - function performance need not always materialize as a relation of one operating principle/one solution element; it can also appear in the form of polyhierarchical relationships. This is the case of supporting solution elements such as the housing that fulfils different sub - functions (fastening, support, sealing). Search and assignment are carried out during an iterative process where beneficial functions as well as disturbing functions and compatibility conditions are taken into account. The process goes on until all sub - functions have appropriate operating principles and/or solution elements. The search is facilitated by catalogues for physical effects and operating principles and product catalogues. For the performance of the whole function, solution elements are linked (through material flow, energy flow and information flow) so as to create the ***operating structure***. The structure is a connection of operating principles/elements and facilitates the search of the principle of the solution of the whole task. The goal is to find out about the physical compatibility of operating principles and solutions elements and ensure a trouble-free material, energy and information flows. Often though, the operating structure itself is not sufficiently specific to allow the assessment of the solution principle. The operating structure must be quantified using an approximate calculation or rough dimensioning of the geometry, for example. Further specification of the operating structure leads to the ***building structure***. This structure takes into account space relations, production and completion requirements etc. It includes assembly spaces and elements as well as assembly groups and their associated bonds that define the concrete product. In this way the compatibility of operating principles/solution elements is controlled with regard to their shape (especially in case of space integration). The solution elements are also to be embedded in a ***supporting and enveloping system***, which ensures the functionally appropriate arrangement of the elements and their interaction.

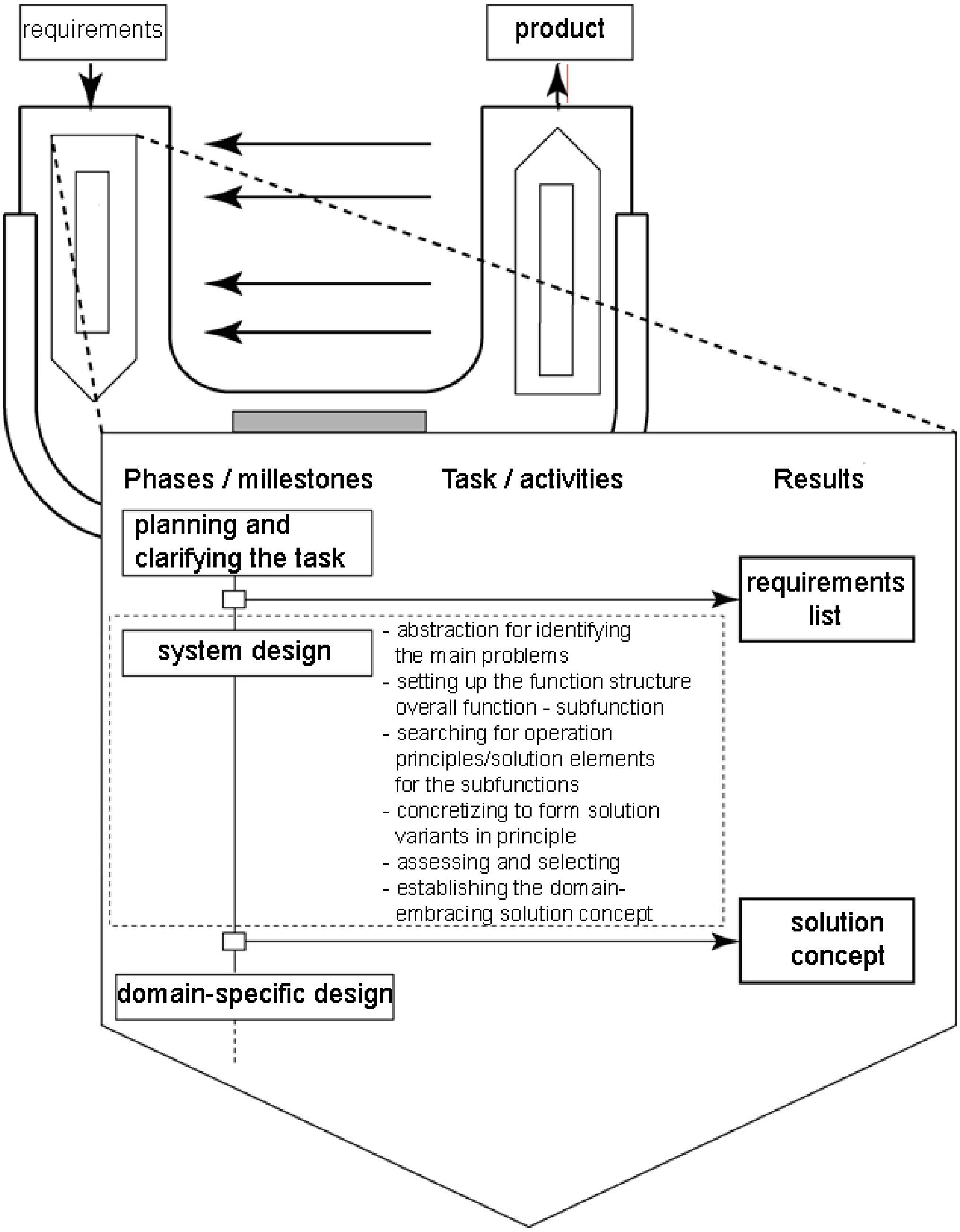


Fig. 5.3: Activities in system design

Accomplishment of solution variants: The ideas worked out for a solution are generally not concrete enough to stipulate the final cross-domain concept and allow the design to be continued in the technical disciplines. Further aspects such as fault susceptibility, weight, service life, etc. must be taken into consideration. Among the means of obtaining information are Finite Element Method (MKP/FEM), analysis of multibody systems (MBS) – chapter 7.7, outlined creation studies, viewing models. The operating principles and solution elements are specified on the basis of the newly obtained information until solution variants in principle of the defined object can be identified. These are subjected to a final assessment on the basis of technical and commercial criteria. The result of the system design is a cross-domain ***solution concept***, which describes the main physical and functional characteristics of the future product and the type and arrangement of its components.

***Modelling* and *model* analysis:** Considering their complex structure and cross-domain character, mechatronic systems should be depicted in a computer. Without modelling the entire behavior, it is not possible to deal with the complexity of mechatronic products. The modelling and analysis of the system consider dynamics, heating, stray fields, vibrations, etc. It is also necessary to take into account some special aspects, which are described in greater detail in chapter 7.6.

Domain-specific design: When assigning operating principles and solution elements to sub - functions, partitioning is performed, i.e. dividing the performance of the function among the domains involved. The development in the relevant domains takes place on the basis of established, domain-specific development methodologies, which are characterized by their own ways of thinking, conceptual ranges and experience.

System integration: is understood as bringing together the individual parts to form a super - ordinate whole (a future product represented according to degree of maturity as, for example, laboratory specimen, functional specimen, pilot-run product). A suitable type of integration is to be chosen in accordance with a defined object. The types of integration are as follows:

- ***Integration of distributed components:*** Components such as actors, sensors and power actuators are integrated into one new whole via signal and energy flows. Signal processing is carried out via communication systems (for example sensor-actor bus, field-bus, etc.), energy flows via cabling and plug-in connectors. It is advantageous that series components can be used. However cables and plug-in connections entail the risk of contact problems, cable breakages and short-circuits, in particular under rough ambient conditions.
- ***Modular integration:*** The system is made up of modules of defined functionality and standardized dimensions that are coupled via unified interfaces. These modules that are included in a modular system can be flexibly combined and make it possible to obtain a great functional variety. Modularly integrated systems have generally a larger component volume and a higher material expenditure and component complexity in comparison with spatially integrated systems.
- ***Spatial integration:*** All components are spatially integrated and form a complex functional unit. As an example of integration of all elements of a drive system (controller, power actuator, motor, transfer element, operating element) into a housing, see the integrated multicoordinate drive in chapter 8. Advantages include a smaller installation space; greater reliability brought about by reduction of the interfaces, faster data transmission/higher power and lower assembly effort. However, the spatial proximity of the components also allows undesired interactions to arise, such as heating, stray magnetic fields, vibrations, noises and voltage peaks, which are to be taken into consideration as early as possible. Electronic components are to be adapted to the operating environment (temperature, humidity, vibrations, etc.) and so under some circumstances, additional measures such as encapsulation or cooling may be required to ensure the component reliability. Spatial integration therefore requires a systematic procedure in designing and a support by modelling and IT tools.

To achieve a high degree of integration, the operating principles and solution elements are to be checked for compatibility taking the beneficial and disturbing functions into consideration, and also the interfaces for later integration (rough dimensioning) are to be formulated as early as in the system design.

However during the fine dimensioning in the technical disciplines involved (domain-specific design), there may occur changes in the operating structure and the building structure (due to function integration, function separation, etc.). Possible incompatibilities must therefore be detected and eliminated during the system integration (Fig. 5.4).

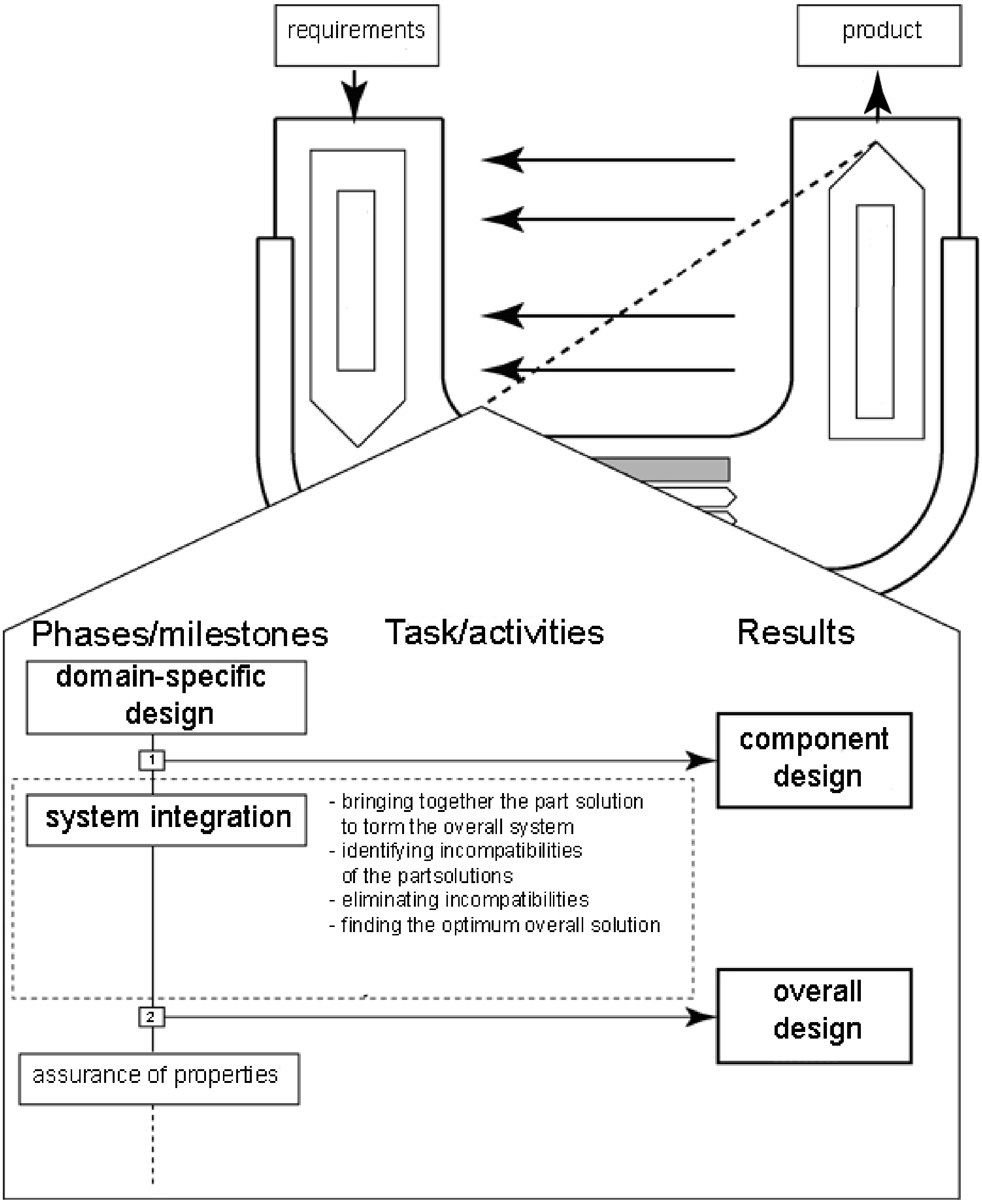


Fig: 5.4. Activities in system integration

In traditional mechanical engineering, the problem of system integration lies in the form-determining properties. When designing mechatronic systems, various interactions (for example behavior, electromagnetic compatibility, etc.) have to be taken into consideration for checking the compatibilities. Apart from the use of IT tools for simulating interactions, a close cooperation between the technical disciplines is required, since the assessment of these interactions requires detailed technical knowledge.

Assurance of properties: when running through the phases of system design, domain-specific design and system integration, it is necessary to keep selecting solution variants and assess their properties on the basis of requirements list. The property variables are numerical characteristic values, verbally formulated statements, etc. This so-called assurance of properties subsumes the two terms ***verification*** and ***validation***, which describe different stages of ensuring the required system properties.

Verification: Transferred to technical systems, it is to be understood as meaning checking whether the way in which something is realized (for example a software program) coincides with the specification (in this case the description of algorithms). The verification is generally realized in a formal manner. In everyday language, verification is the answer to the question: ***Is a correct product being developed***?

Validation: Transferred to technical systems, it is to be understood as testing whether the product is suitable for its intended purpose or achieves the desired value. The expectations of the technical expert and the user come into the equation here. Validation in general does not have to be carried out in a formal manner. In everyday language, validation is the answer to the question: ***is a right product being developed***?

6. Model-based system design

For the efficient and computer based development of a mechatronic system, models of the systems in a computer are required. These models are created for all components of the system under consideration, in dependence on the objective of investigation, and they take into consideration the elements of the domains involved. A fully inclusive consideration at the model level provides the developers with support in the design of mechatronic system.

In the course of system design, a wide variety of models respectively describing a specific aspect of the system are created. Model types are, for example, requirement models to represent system requirements or behavior models to depict the function. CAD descriptions are likewise models, which contain the form of a system. The behavior descriptions are particularly important in the case of modelling mechatronic systems, since with them the functional interrelationship can be captured and formulated in a cross-domain way.

The technical areas of mechatronics that are involved have developed various forms of representation for behavior models, for example the block diagram in control engineering. With increasing use of computers, computer-aided tools for modelling became available to mirror the known written representations; these tools are differently characterized in accordance with the domains involved (chapter 7.)

Since the overall function of a mechatronic system is only satisfied by the interaction of the technical disciplines involved, there is the necessity to bring together the models of the sub - disciplines. The integration of models on the basis of mathematical descriptions is a procedure that is flexible and easy to handle, since mathematics forms a standardizing representation for a wide variety of domains on account of its general applicability. To do so, it is necessary in each case to clarify the question as to which information can be formulated with which type of mathematical equation within a domain and which correlations with this information exist in a cross-domain way.

Ideally, models of later development phases are built up on models of earlier phases. Implementable specifications, which in early development phases roughly describe the function of the system, can be used for example for building up more detailed behavior models. Behavior models may be precepts for the geometrical configuration or else for software algorithms. It is appropriate for this so-called "universality" to be retained over all development phases up to the final system.

The model based procedure for the design of mechatronic system offers important advantages in terms of time and costs by the use of modelling and computer-aided analysis. Modelling initially needs more time and gives rise to costs, but it makes time and cost-saving secondary effects possible in relation to the entire development processes. The behavior of a system or a component can be checked and analyzed long before completion of the first prototype by means of realistic simulation models. Consequently, iterations can already take place in early stages of development to verify the product properties; then the accomplished prototype, which is still needed, represents a much more mature product.

An important precondition for this procedure is that the simulated properties coincide adequately with reality. However, particularly in early stages of development, validity of this cannot always be verified. The use of modelling and simulation therefore requires a certain critical attitude and ongoing checking of the plausibility of the results obtained.

The basic procedure for model-based system design is divided into five steps (fig.6.1).

1) Objective: Firstly, investigation goals and tasks are to be stipulated, to allow the suitable methods of modelling to be selected. The following may be among the investigation goals and tasks and reasons for modelling:

- basic investigation carried out on mechatronic systems that are to be newly developed (support of the function-oriented design, analysis of first solution concepts, generation of setpoint selections for the domain-specific design)
- targeted controller design (linear/nonlinear analysis and synthesis for the handling of control-engineering tasks)

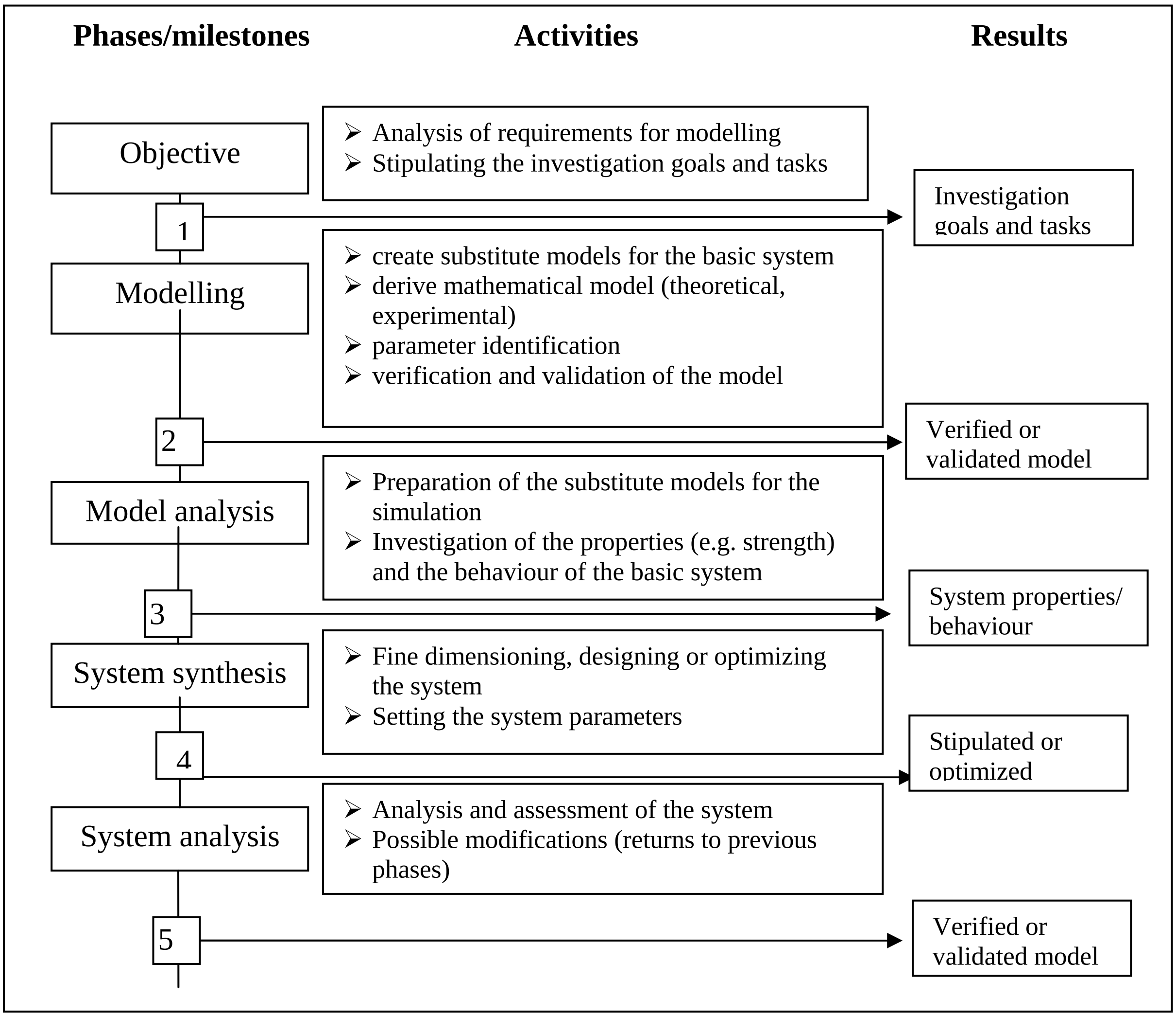


Fig. 6.1: Procedure for model-based system design

- analysis and optimization of existing mechatronic systems (fine modelling to solve existing problems or for targeted improvement, for example costs or functionality)
- measuring devices affecting the system and distorting the measured signals (weight and heat conduction from measuring devices, etc.)
- experimental investigations carried out on the system are too expensive, too dangerous or irresponsible (e.g. limit state tests) can only be performed with maximum caution (e.g. cold/heat tests)
- experimental investigations take too long on account of the system time constants (materials tests, investigations into wear, etc.).
- reduction of costs in prototypes by means of preceding simulations (model-based integration of the developed subsystems, testing of the interaction of system components)
- hardware in the loop simulations for function checking

2) Modelling: The quality of model is decisive for the quality of analysis results. Only if the model truly describes the system, the subsequent model analysis can produce results transferable to reality. The procedure for modelling and the various model abstraction levels are explained in greater detail in chapter 6.1.

3) Model analysis: On the basis of the model, the properties of the basic system are investigated as well as its behavior. The analyses reveal the system behavior necessary for the subsequent synthesis phase.

4) System synthesis: In the synthesis, the simulation and calculation results of the model analysis are transferred to the system to be developed. Operating principles and solution elements are finely dimensioned or optimized. Synthesis and optimization are to be considered in their entirety. The requirements for the synthesis arise from the model analysis. If a completely or partially new design of the system is designed, a developer will stipulate the final parameters of the system in the synthesis phase. The results of the analysis phase are implemented in a concrete form.

5) System analysis: So stipulated or optimized system is then analyzed and re - assessed. Sometimes it is necessary to return to previous steps. This interactive procedure is all the more efficient the quicker the parameters of the overall system converge towards an optimum solution. A selection of the model is of great significance here.

6.1. Modelling

A required quality of the model is fundamentally dependent on the problem to be considered. Therefore, before modelling is commenced, there should be clarity concerning the development task. For new development tasks, different modelling approaches are to be chosen compared to those required for further development or optimization of existing products. Depending on the question to be answered, the depth of modelling varies with regard to the consideration for specific physical effects. For instance, in certain cases the modelling of a mechanical system comprising a number of components (for example a motor vehicle) as a point mass is adequate, while in other cases complex multibody models or else finite-element models have to be constructed. For a fully inclusive procedure in terms of mechatronics, a combination of various, domain-specific models with adapted modelling depths is required to allow systems to be developed and validated in a cross-domain and model-based manner.

The procedure for modelling may vary for different domains of mechatronics. In the domain of software technology, for example the interrelationships between requirements for the system and the subsystems may be structured and represented in a functional description - on the basis of requirements analysis that has been carried out. In this case, a description of the structure and of the behavior over time is required.

In order to describe the behavior with the required accuracy, substitute models of the system are formed on various abstraction levels.

Topological model: Firstly, the topology of the system to be simulated is to be modeled. It describes the arrangement and interlinking of function-performing elements (for example solution elements, subsystems or modules). An element generally represents the three basic functions: kinematic function (for example number of joints, length of arm and positions of joints of a robot), dynamic function (for example movement of masses under the effect of forces) and mechatronic function (for example control, monitoring, path planning, etc.). The topology of mechanical elements for example essentially determines the kinematics of the mechatronic system; therefore, these elements must be fully taken into consideration in the simulation model. The situation is different for example in the case of hydraulic elements. Here, it is already possible at the topological level to make meaningful simplifications - hydraulic components are replaced by greatly simplified assumptions. However, the procedure strongly depends on the underlying problem being addressed and on the objective of the simulation.

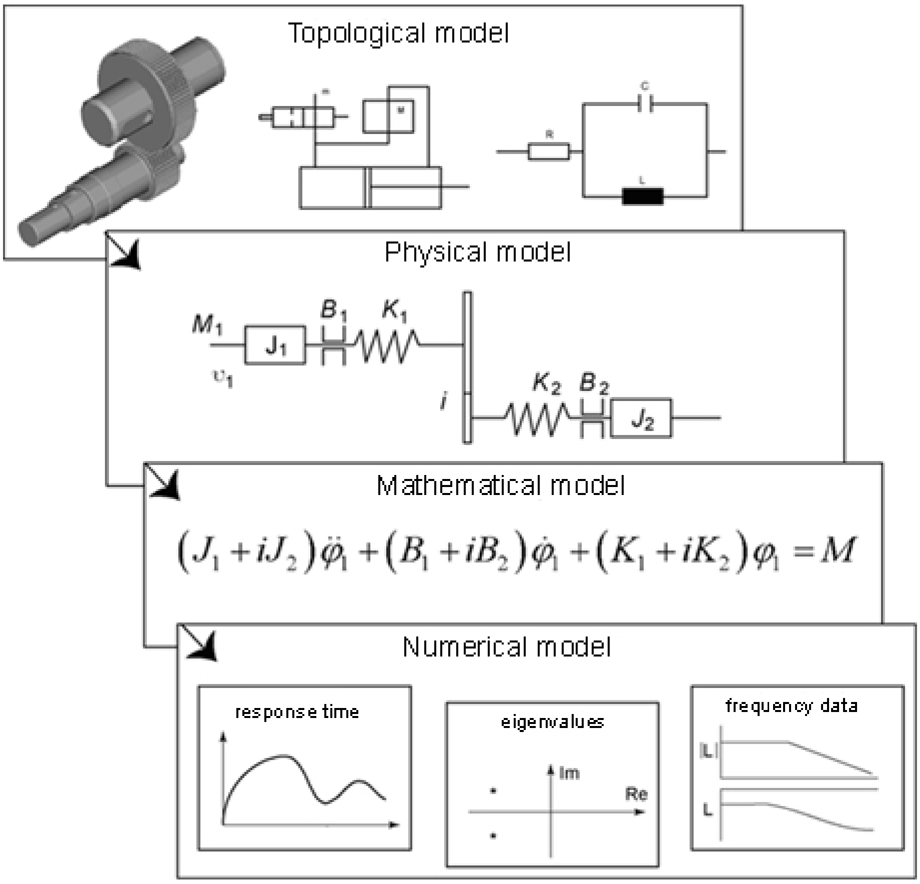


Fig. 6.2: Model abstraction levels in the modelling process
φ - rotation angle, i - transmission, B - degree of damping, C - el. capacitance, J - mass moment of inertia, K- rotational rigidity, L- inductance, M- driving torque, R- el. resistance

Physical model: Starting from the topological description, a physical model is created. This is defined by system-adapted variables, such as for example masses and lengths in the case of mechanical systems or resistances and inductances in the case of electrical systems. In the case of mechanical elements, e.g. the number and connections of rigid bodies, definition of flexible bodies, bearing friction and clearance or mass distributions are stipulated. With hydraulic systems, the physical model comprises e.g. such components as hydraulic chambers and valves, but also the replication of physical effects, such as leakages, frictions or hysteresis. The physical model describes the system properties in a domain-specific form.

Mathematical model: The mathematical model forms the basis of behavioral description of the system. For this purpose, the physical model is transferred in an abstract, system-independent representation and the physical properties of the model described above are formulated with the aid of mathematical descriptions. Differences in the depth of modelling may arise here for example due to more faithfully detailed hydraulic line models, more detailed friction models, due to more sophisticated bending evaluations in the calculation of elastic structures or due to consideration of nonlinearities instead of linearizations. The mathematical model integrates different domain-specific model representations.

Numerical model: The mathematical model is then prepared in such a way that it can be algorithmically handled and subjected to a computer-aided process, for example simulation. The numerical model depends very strongly on the depth of modelling realized, on the solving method used and on the mathematical model (in particular with regard to nonlinearities). The numerical model is provided with concrete numerical values (parameterized). These numerical values are possibly determined by an identification of the real system (if present) (cf. procedure for modelling). Figure 7.11 shows procedural steps for modelling that are typically to be taken and under some circumstances must be iteratively repeated.

Planning and clarifying the task: On the basis of the respective task, a suitable model is devised. For this purpose, the specific requirements for the model of the desired abstraction level must be stipulated. The most general requirement is the adequate replication of properties of the real system as the model.

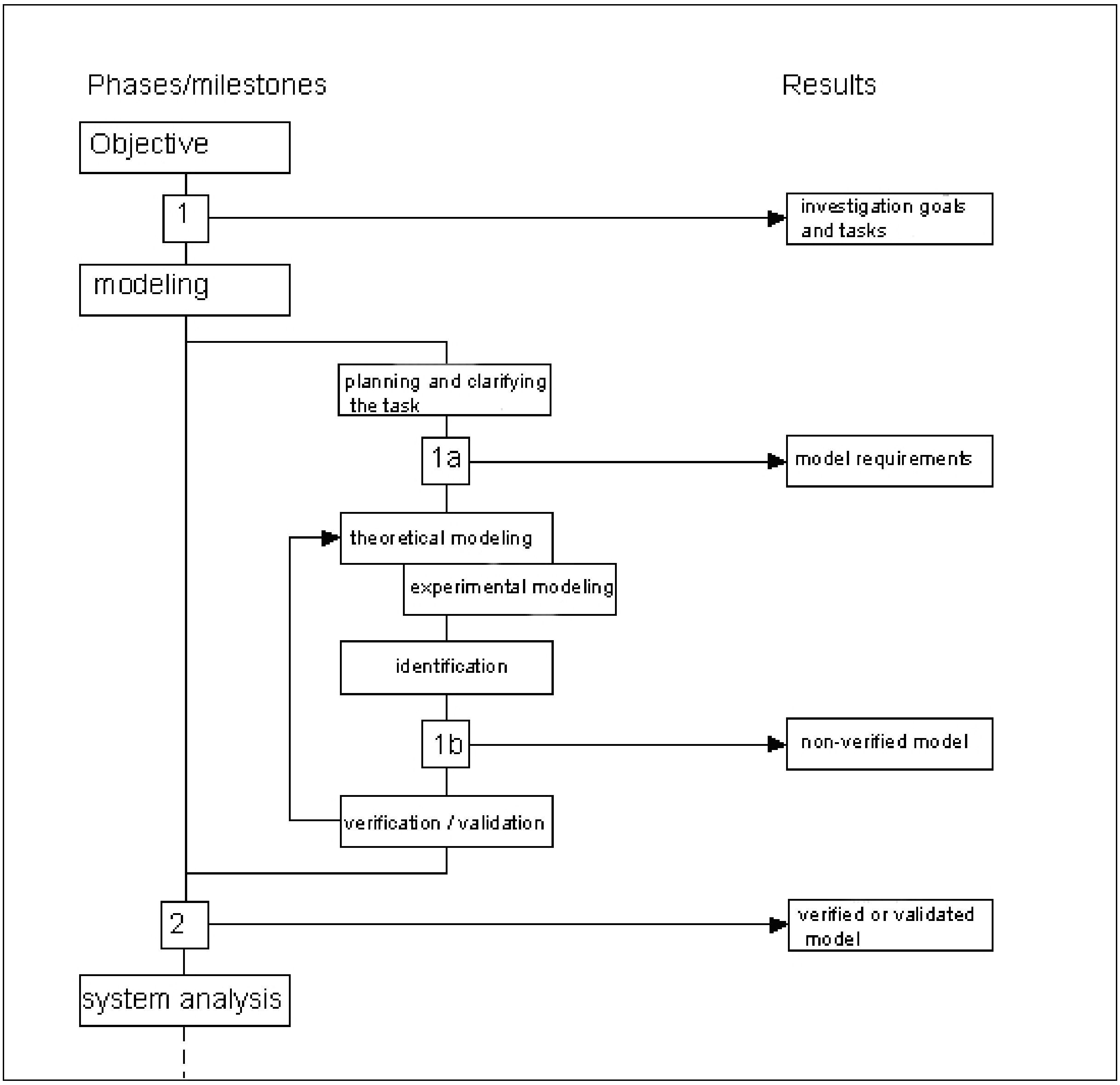


Fig. 6.3: Procedure for modelling

Theoretical or experimental modelling: The aim of this phase is to obtain mathematical substitute models of the system describing the behavior with adequate accuracy. Starting from the topology, the physical model is transferred into an abstract, system-independent representation (cf. previous description of the abstraction levels; Fig. 6.3). There are essentially two ways of how to do it:

1) Theoretical modelling: The system equations are derived by applying the physical principles, the quantitative information being obtained from the geometry of the formation concerned, from material constants and empirical interrelationships.

2) Experimental modelling: From measurements on the system to be described, ex post facto conclusions are drawn with respect to the system structure (equations). It is also common to combine the two ways, for example to compare the behavior of the initially theoretically set up model with measurements on the real system or to determine still unknown parameters by adjustment to the real system. This takes place where possible by experimental analysis. Most methods are based on the stimulation of the technical system with adapted time function and the analysis of time response. The model parameters are then adapted in such a way that the response of the model corresponds to the response of the real system. The most frequently used stimulation function is the jump function.

Identification: In the case of further development of an existing product, measured technical values of the real system are transferred to the model. In the case of a new development, the parameters are fixed in a way corresponding to the requirements. The result of the phase forms a model provided with particular numerical values, which however is not yet verified.

Verification/validation: Verification determines whether in principle a model is plausible and correct and whether it satisfies the requirements imposed at the beginning. A statement as to whether the model created adequately describes a real system, and consequently also satisfies possibly not specified requirements, is provided by validation. For the new development, it is appropriate at this point to perform a plausibility check, which determines whether the model can correspond to a real system. This procedure generally requires considerable empirical knowledge of realistic technical variables or physical behavior. If the model satisfies the prescribed requirements (accuracy, adequate replication of reality, depth of modelling, etc.), the modelling process is completed. The now verified or validated model can subsequently be investigated in the model analysis. If the requirements are not satisfied, a return is made to the theoretical or experimental modelling and the model is improved.

6.2. Model Analysis

The model analysis generally serves for determination of properties for a prescribed system. The system may exist in reality or as a model. In many cases there is a real system from which a model can be derived. A distinction can be made between two purposes for model analysis: analysis for establishing the actual state and analysis of possible behavior. In both cases, knowledge of the system is determined (dynamics, strength, etc.). The questions directed at the analysis determine the procedure and the tools with which the system is analyzed. An analysis on real models is also customary if the computer-aided model is too complex or, for example, the environment cannot be mathematically or physically reproduced, or only with difficulty. This applies in particular in the case of strongly nonlinear or chaotic behavior. An example of such analyses that may be cited is the dynamic behavior of ships on rough seas, which is investigated with a scale model in an artificial wave tank. However, it is evident from the development of computing technology and analysis tools that investigations on real models will increasingly be replaced by investigations on computer-aided models.

Apart from these special cases, establishing the actual state almost always serves for setting up or parameterizing abstract computer-aided models. In this case, the model analysis is part of the modelling process.

The analysis of the model of a system is intended to provide statements about the system behavior. With a model it is possible to analyze system states into which the real system cannot or must not be brought.

The **actual sequence of a model-based system design** may be as follows: A control system is to be designed for an existing technical system (for example a machine tool). Firstly, a multibody system model is set up on the basis of the existing geometry model data (generally CAD) (modelling). This abstract model is subsequently compared with the real system. The free parameters of the model must be determined or set (identification); this is accomplished through measurements on the real system. Further methods of determining the system behavior follow, e.g. a modal analysis. The analyses are also intended to determine which model describes the respective task in an adequate way (model analysis). To improve the dynamics of a vehicle construction, under some circumstances only the modes, which are in the relevant frequency range, have to be modeled.

For the parameterized model, a control system can then be developed (system synthesis). The structure of this control system essentially arises from the structure of the model (or from the structure of the system from which the model was derived) and its transmission behavior. The overall controlled system is in turn analyzed, for example frequency analysis, eigen value calculation, simulation, etc. (system analysis). The results of this analysis phase serve for optimizing the newly designed overall controlled system.

7. Tools

The development of mechatronic systems requires the use of a large number of methods. The use of these methods is supported by IT tools. The aim of integrated development is to allow the design process to proceed as far as possible in a computer-aided manner. In this case, a distinction is to be made between four different levels of integration:

- ***Method-technical level***: On this level, the methods and tools, which are to be used for a specific product development, are selected.
- ***Process level***: The actual development stage of the product is analyzed, tasks are defined and their implementation is focused on. The methods to be used are determined on the basis of informativeness and time costs; for this case the ABC classification is recommended. The corresponding CAE tools are selected on this basis.
- ***Process-technical level***: on this level, the current state of the development project is analyzed, the definition of the task packages is supported and their implementation is monitored. One element of this level is process management. The process management component plans/controls the use of the integrated tools.
- ***Model-technical level***: In order that CAE tools can exchange information and cooperate with one another, they must have the same conceptual understanding. The aim of model-technical integration is to create an environment with various product model representations that is transparent for the user.
- ***System-technical level***: It is the IT system, not the mechatronic system that is specified in this section. On this level, a reliable and consistent information exchange of the integrated CAE tools is realized. For this purpose, a common communication medium ensuring the communication of the overall system must exist.

  The customary tools for the design of mechatronic systems can be divided into classes. The individual tool classes are described below.
- ***Tools to describe requirements***

  At the beginning of the product development there are usually only vague ideas as to what a product is intended to do and may cost. These ideas are specified in the form of requirements and wishes and documented, usually in textual form, in the requirements list or in the specification. Special tools for the description of requirements support the systematic recording and classifying of requirements, provide check lists and ensure consistent documentation. If the requirements can instantly be specified in greater detail (for example by precepts specified by the customer), tools that are also used in the system design are additionally used. Examples of these are geometrical properties such as installation spaces or connection dimensions (description with CAD tools), functional properties (description with tools for behavior modelling) and desired sequences in the form of application cases (description with application case diagrams). The description of requirements may, under some circumstances, lead to the so-called executable specification of requirements, with which desired properties can be simulated.
- ***Tools to manage requirements***

  The necessity of rapid adaptations to changing customer requirements, increasing requirements on product properties and the general pressure on costs make it necessary to develop products that can be reused in the highest possible way. In order to assure this re - use, a structured, comprehensive and complete documentation of the requirements imposed on the product is of great significance. However, it is also important to know throughout the ongoing development stage which requirements have which effects throughout the manufacture of product and who has introduced which requirements and when. Tools for requirement management (synonymous with requirement engineering) are used to achieve this. These tools also support allocation of funds and determination of persons responsible for check – ups of completeness and non – existence of contradicting requirements.

- ***Tools to model functions***
  The aim of function modelling is to formulate design tasks at a solution-neutral level. The overall function of the system can be derived from the overall task of a problem being addressed. This overall function is further broken down into subfunctions that are linked together to form the function structure. For representation of a function we often use a block representation (black box) and for description of interlinkages we use flow variables (material, energy, information). With the aid of so-called system engineering tools, desired behavior and misbehavior of functions and their inputs and outputs are specified. Consequently, early investigations with respect to the compatibility of functions, error diagnostics and failure mode and effects analysis (FMEA) are carried out. The transition from pure function modelling (solution-neutral, description of the desired behavior) to solution-in-principle modelling (assignment of operating principles, physical variables and solution elements) is smooth. The solutions found can be evaluated with the same tools as previously mentioned.
- ***CAD tools***
  CAD systems make it possible to model the shape of the future product. Geometrical requirements and initial form-determining stipulations form the basis for example for achieving a specific behavior. Through a choice of suitable operating principles and solution elements and also through determination of the parameters related to geometry, technology and materials, the form is further specified (rough dimensioning). In interaction with computation and analysis methods (see FEM, MBS), the parameters are optimized. The CAD system provides dimensions and derivable variables for this. The result of the domain-specific design is a complete CAD model of the product and its components, which along with geometrical information (dimensions, tolerances, etc.) also comprises structure information (assembling procedures, list of components) and production information.
- ***FEM tools***
  For a detailed analysis of structure mechanics, dynamics, electromagnetism, fluid dynamics, acoustics or temperature fields, the Finite Element Method (FEM) is used. It is the method that solves general field problems by approximation. For this purpose, the continuum considered is approximated by a finite number of small elements (discretized). It investigates, for example, how a component is deformed under a static load and where maximum stresses occur (e.g. to demonstrate strength); however, the analyses of dynamic and nonlinear processes can also be carried out (for example vibration analysis, limit state analysis). The required geometry can generally be adopted directly from 3D-CAD systems.
- ***BEM tools***
  Along with the Finite Element Method, the Boundary Element Method (BEM) is another important discretizing method for computation of initial-boundary-value problems, for example for the investigation of fluid behavior. The advantage of BEM over FEM is that only the surface of the structure being considered has to be discretized, not its volume. For this purpose, the boundary is subdivided into elements and boundary nodes are introduced. The boundary elements are provided with basis

functions. Main areas of use are electrostatics, acoustics, hydromechanics and thermodynamics.

- ***Tools to simulate multibody systems***
  The simulation of multibody systems (MBS) is used to investigate the movement behavior of complex systems, which comprise a large number of coupled movable parts. A spectrum of applications ranges from the check ups of the movement behavior of individual sub-assemblies, which comprise only a few components, through the identification of collision problems caused by component movements to the movement behavior of the overall system. Furthermore, forces and moments that act on the system due to movements can be determined by means of MBS simulation. The form data can likewise be generally adopted from a 3D-CAD system or be generated as simplified 3D models with the aid of a volume modeler integrated in the MBS system. Some 3D-CAD systems also contain integrated modules for MBS investigations.
- ***Tools for fluid-technical design:*** With the aid of Computational Fluid Dynamics (CFD) tools, thermodynamic and fluid-dynamic processes in a bounded area through or around which the flow passes (control space) can be analyzed to allow them to be influenced in a targeted manner. A CFD analysis produces qualitative data (for example type, extent and effect of flow-mechanical effects) and quantitative data (numerical values for thermo – fluid - dynamic state variables). Application areas include [6]:
  - automotive engineering: exterior aerodynamics, climatic control of the passenger compartment, flow and combustion in the engine, etc.
  - aeronautical and aerospace engineering: exterior aerodynamics, aircraft engines, rocket engines, etc.
  - energy technology: components of power generating plants such as steam generators, furnaces, condensers, steam turbines, pumps, etc.

  In addition, tools support the modelling of fluid-technical systems on the topological level. Models are created interactively by using model libraries.
- ***Tools for control-engineering design:*** Most tools for control-engineering design are based on block diagram representation. Each block has a precisely defined input/output behavior. Reaction-free directional signal lines provide the links between the blocks. The hierarchical arrangement of the function blocks allows even relatively complex structures to be modeled in a clearly presented way. As part of system design, the models originating from the modelling of requirements are to be concretized and partitioned. As this happens, the system structure of the future product becomes ever more detailed. The assignment of individual functions to the later modules of the mechatronic product becomes more precise. The expected reactions on the considered production options are incorporated in the models. The result is a largely complete functional model of the product to be developed that is partitioned with a view to the later realization.
- ***Tools for electronic design:*** Electronics pick up command and sensor signals; process them and output messages and actor activation signals. Electronics can directly replicate the required user function in the form of hard-wired analog or digital signal processing. They can additionally form platforms with which the user functions are realized entirely or partly in programmable analog and digital modules. Electronics can also form platforms on which user functions are programmed more or less completely by user software.
  The development of analog or digital circuits is supported by so-called EDA programs, which are specialized for the design and simulation of electronic circuits

and layout creation. The required functions are usually described in the form of circuit diagrams or by means of VHDL lists, from which the production data for the printed circuit boards and the programmable modules used on them can be generated by means of automated processes. For an efficient development of the electronics of mechatronic systems, it is important that there is a means that is as automated as possible for deriving the circuit diagrams or VHDL lists from the system model. For this purpose, the partitioning of the various functions must be taken so far in the system design that each module of the system model can be replicated on an electronic component of its own, e.g. as an analog module, as FPGA, or as a microprocessor with user software.

- ***Tools for electric design:*** Electrics interconnect all the electrical components of a mechatronic product. They ensure the supply of all the electrical components with electrical energy. It is expedient for these functions, which are indispensable for reliable operation, also to be already modeled in the system model. The generation of the circuit diagrams necessary for wiring could then be performed in an automated manner from the system model.

  Positioning of the electrical lines between the distributed electrical or electronic modules affects geometrical properties of the product and must be incorporated into the CAD model.
- ***Tools for software design****:* here “software” stands for embedded software. This is divided into operating system software, such as run-time control and hardware drivers, and user software. The operating system software can be regarded as a special hardware module. It ensures that the user software is loaded into the target electronics and is processed in the required time intervals so that the user software has access to the data of the connected sensors and that the user software can execute all the necessary outputs. The user software then determines the functions of the microprocessor-controlled electronic modules, with which open - loop and closed - loop control functions are realized.

  Within the present guideline, the development of user software is particularly relevant. The functions to be realized there are defined, modeled and tested in the system design. So-called CASE (Computer Aided Software Engineering) tools offer graphic editors, with the aid of which the software can be modeled and the consistency between parts of a program can be ensured. In the following formal conversion of the function defined in this way into the code that can be executed in the target electronics there is no further change in the content of the function. Therefore, today there is a widely observed desire to generate the executable code by an automated or automatic code generation directly from the user software modeled in the system simulation. This includes all necessary conversion and compiler processes. This is supported by special design environments.
- ***Tools for HIL (hardware-in-the-loop) simulation:*** As soon as individual components are realized, they must be tested in an environment resembling their later environment. For this verification or validation, an HIL environment is set up, which uses real-time simulation to simulate the real environment for the component or the product to be tested.

  In the course of the development, different HIL environments are to be set up for components, groups of components and the end product.
- ***Tools to validate the product in the real environment*** In the final stage, it is checked whether the complete real product, made up from its components, behaves in its real environment under real operating conditions in the way intended. There are tools that can record and process measurement data of a real system in real time to provide

support. If the product is validated in this way, there is nothing to prevent it from being launched on the market.

- ***Product data management systems:*** In the course of product development, a considerable amount of information is processed at various workplaces in the company. The volume of information no longer allows an overview and access is not transparent, i.e. the developer must know exactly where the information is to be found. The task of the product data management system (PDMS) is to manage all relevant data on a product and the processes of product development. The functionality of modern PDM systems comprises product structure management (model of the relationships between subassemblies and individual parts, for example in terms of production or assembly), documentation management (ensuring consistency, access rights, etc.), configuration management (version management of product structure states) and the classification of product data. Apart from the management of product data, PDM systems also support the planning, control and monitoring of sequences (process management).

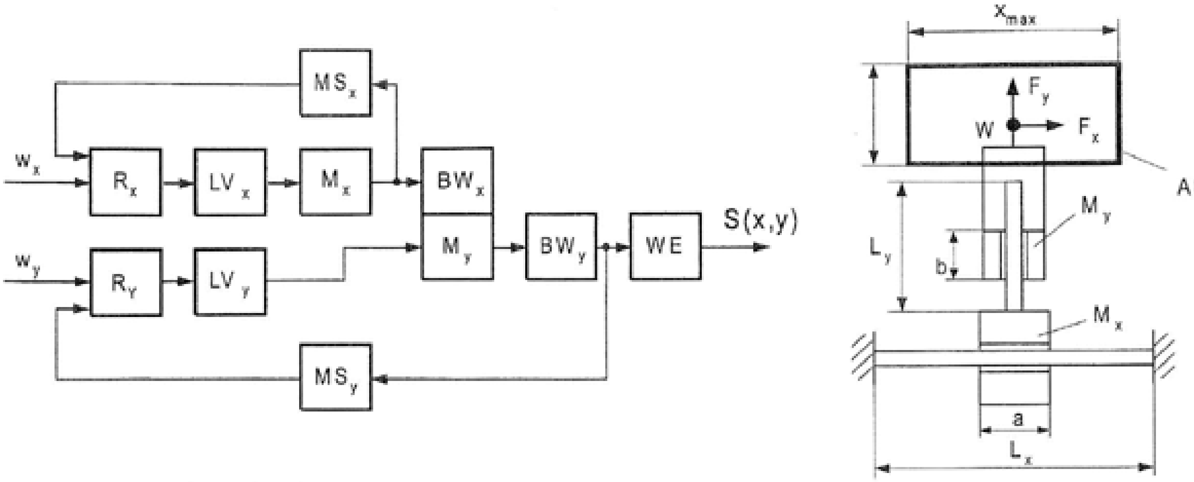
8. Design of mechatronic system

It is not possible to present a complete design of mechatronic system design because of scope and purpose of this publication. Therefore, the following sub - chapter will show only one particular example of a typical mechatronic system – a multi-coordinate drive.

Drive systems, which can produce freely programmable movements in the plane (degree of freedom 1, 2, 3) with high dynamics and accuracy, are increasingly required.

8.1. Structures

Traditional solutions were realized by the individual movement axes coupled in series. In this case, linear axes with a rotation motor including a movement converter (spindle) were arranged one above the other (see fig. 8.1).



R	controller
LV	power booster
M	motor
LV	movement converter
WE	operating element
MS	measuring system

a , *b*	length of motor
A , *B*	working range
F	force
L	length of rotor
M	motor
W	tool

Fig. 8.1: Two-coordinate drive with serial coupling [7]

These drive systems are very common; they have a number of advantages and disadvantages, which are summarized in table 2.

Table 2: Advantages and disadvantages of drive structures with serial coupling [8]

Advantages	Disadvantages
High mobility	Low rigidity
Large working space	Difficult calibration/adjustment
Modular/standardized elements	Low positioning accuracy
Easy-to-service structures	Movable masses
	Unfavorable cumulative effect of errors/defects
	Small bandwidth
	Backlash

In comparison with the above, drive structures with parallel coupling of the drive axes are more convenient as to the achievable dynamics and positioning accuracy.

These advantages may be even more distinctive if the force-generating structures, the measuring structures and the guiding structures are mutually space - integrated throughout a mechatronic design process. This produces drive structures that can be seen in fig. 8.2. (multicoordinate hybrid stepping motors).

The application of the principle of spatial integration to electrodynamic multicoordinate drives is to be presented in greater detail below.

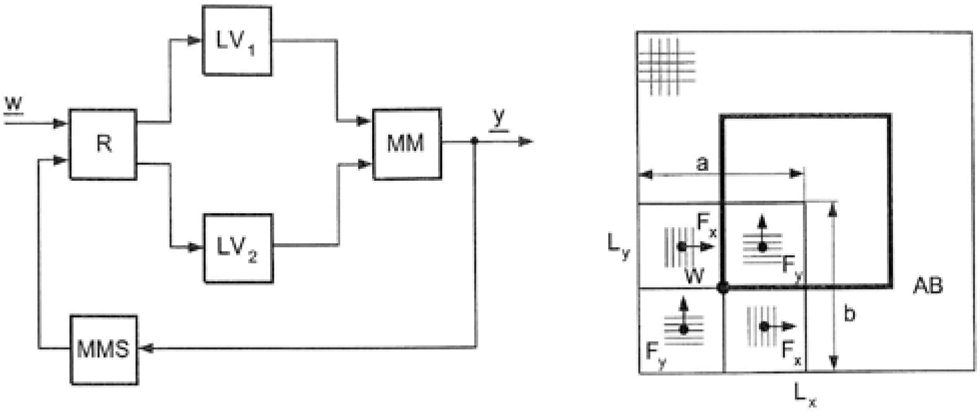


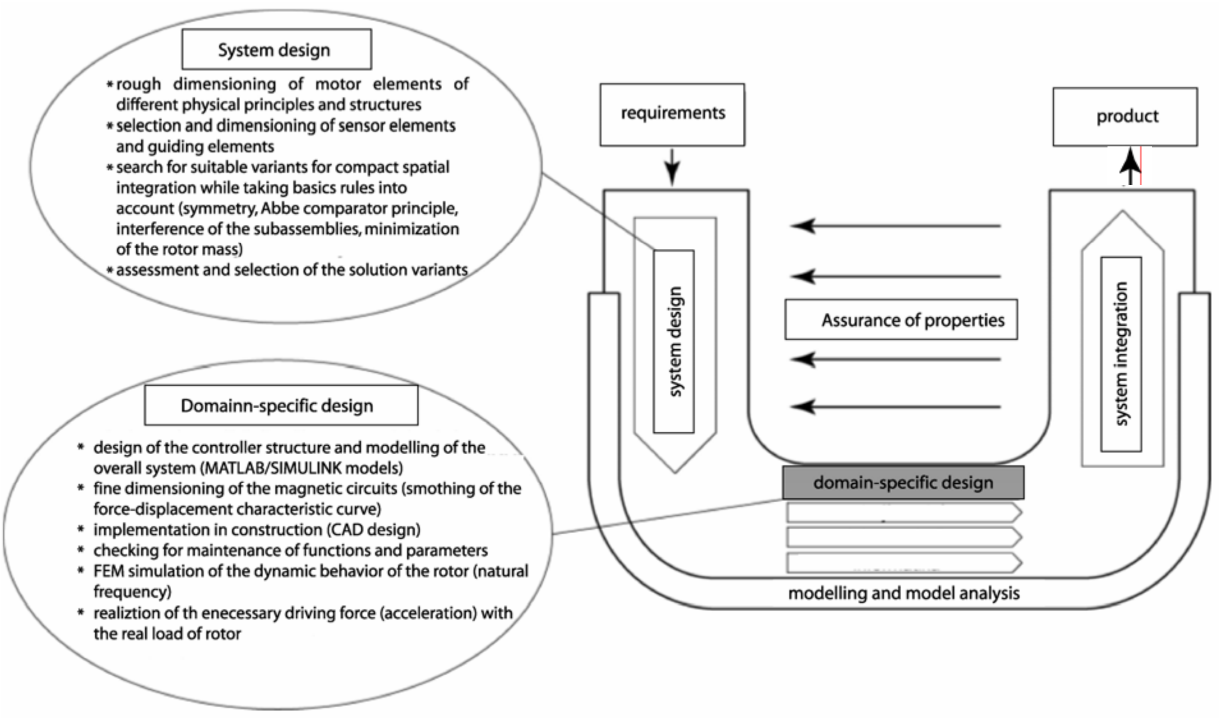
Fig. 8.2: Integrated multiocoordinate drive with degree of freedom 2.
MM – multicoordinate motor, MMS – multicoordinate measuring system

8.2. Design process for systems with volume integration

Procedure: The aim of designed mechatronic system optimization in its entirety requires more efforts throughout the design process, since not only mechanical elements but also electrical elements and information-processing elements have to be taken into consideration.

Various procedures based on the construction methods of mechanical engineering are described in the literature. The example illustrated in figure 7.14 is based on the procedure referred to in chapter 5.1.

Early phases of the design of integrated multicoordinate drives: In the case of a top-down design, the starting point is a pre - defined task. To achieve further specification, the task can be used to derive the overall function, from which the function structure (sub - functions and how they are linked together) is obtained in a further design step. In this case, it must be ensured that the defined task is complete and free from contradictions. In the case of a planar multico-ordinate motor, a movement is required in three movement coordinates $\left(x, y, \varphi_z\right)$. For this purpose, it is necessary to generate forces or moments in the directions of movement.



System design

- rough dimensioning of motor elements of different physical principles and structures
- selection and dimensioning of sensor elements and guiding elements
- search for suitable variants for compact spatial integration while taking basics rules into account (symmetry, Abbe comparator principle, interference of the subassemblies, minimization of the rotor mass)
- assessment and selection of the solution variants

Domainn-specific design

- design of the controller structure and modelling of the overall system (MATLAB/SIMULINK models)
- fine dimensioning of the magnetic circuits (smothing of the force-displacement characteristic curve)
- implementation in construction (CAD design)
- checking for maintenance of functions and parameters
- FEM simulation of the dynamic behavior of the rotor (natural frequency)
- realiztion of th enecessary driving force (acceleration) with the real load of rotor

Fig. 8.3: System design and domain-specific design of a multicoordinate drive

One of the technical solutions inheres in the fact that the linear force-generating elements integrated in the armature (see fig. 8.4) generate the movements in movement coordinates. The forces are generated by magnetic fields, during which time the bond between the coupled effective areas of driving forces is rigid.

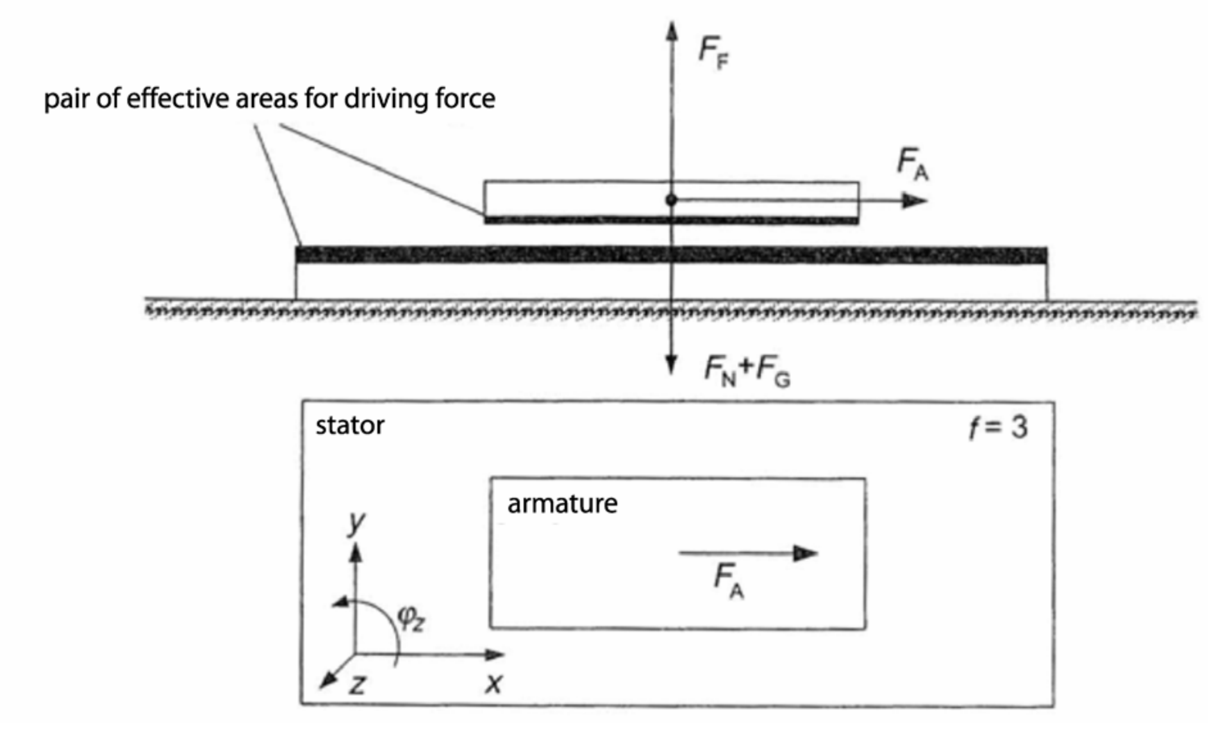


Fig. 8.4: Structure of a force-generating element for planar integrated multicoordinate motors
F_N - normal force, F_A - driving force, F_F - armature guiding force, F_G - force of weight

In principle, the transition from the functional element to the basic element is multivalued. For example, the force-generating elements may be based on the following principles:

- ***dc linear motor,***
- ***dc linear motor with Halbach array,***
- ***reluctance linear motor,***
- ***synchronous linear motor,***
- ***linear reluctance stepping motor,***
- ***linear hybrid stepping motor.***

All these motors have specific advantages and disadvantages. In order that the armature of the multicoordinate motor can realize the desired degree of movement (3), the actor elements must remain movable in each of the three movement coordinates after their integration. If the force vectors do not run through the center of gravity of the armature, torques are also generated and either have to serve for generating force or possibly have to be compensated.

With regard to later integration, it is expedient in the phase of selecting a principle to consider not only the geometry variables but also all other variables that are of interest in the volume integration.

The transition from the function structure to the building structure (see fig. 7.16) is a synthesis process, i.e. it is not single-valued. The function structure comprises function elements that are linked to one another and realize the desired overall function. The fact that a technical principle is assigned to each function element has the effect of producing the operating structure, which comprises the coupling of the operating elements.

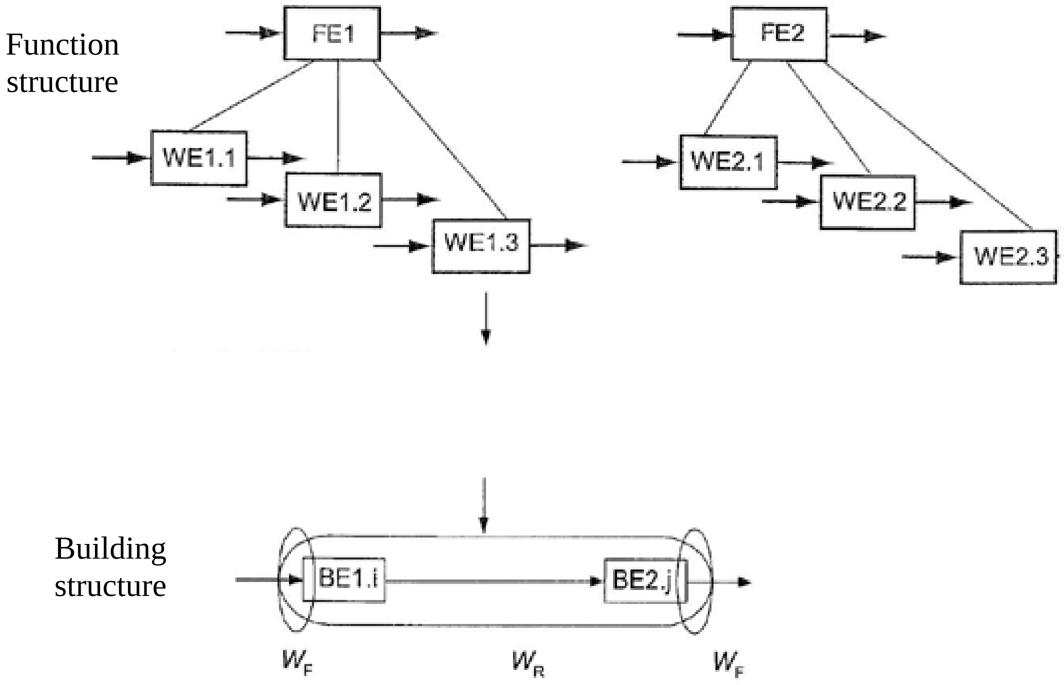


Fig. 8.5: Transition from the function structure to the building structure
F_E - function element, W_E - operating element, B_E - building element, W_F . .effective area, W_R - effective space

After the operating structure, the determination of the building structure is required, and this can be carried out for example on the basis of a parametric design. In this way, construction variants in the sense of a rough form can be found by using parameters. With the rough form, the geometry of the individual elements, the effective areas, the effective area pairings and the effective space is fixed.

8.3. Structural setup

For generation of a linear movement in a multicoordinate motor on the electrodynamic principle, only those force-generating elements, which allow a movement transversely to the direction of force generation, can be used. The force-generating element represented in fig. 8.6. satisfies these requirements if, for example, the coil lines are much longer than the magnets. Figure 8.7. shows the integration of four force-generating elements in a multicoordinate motor.

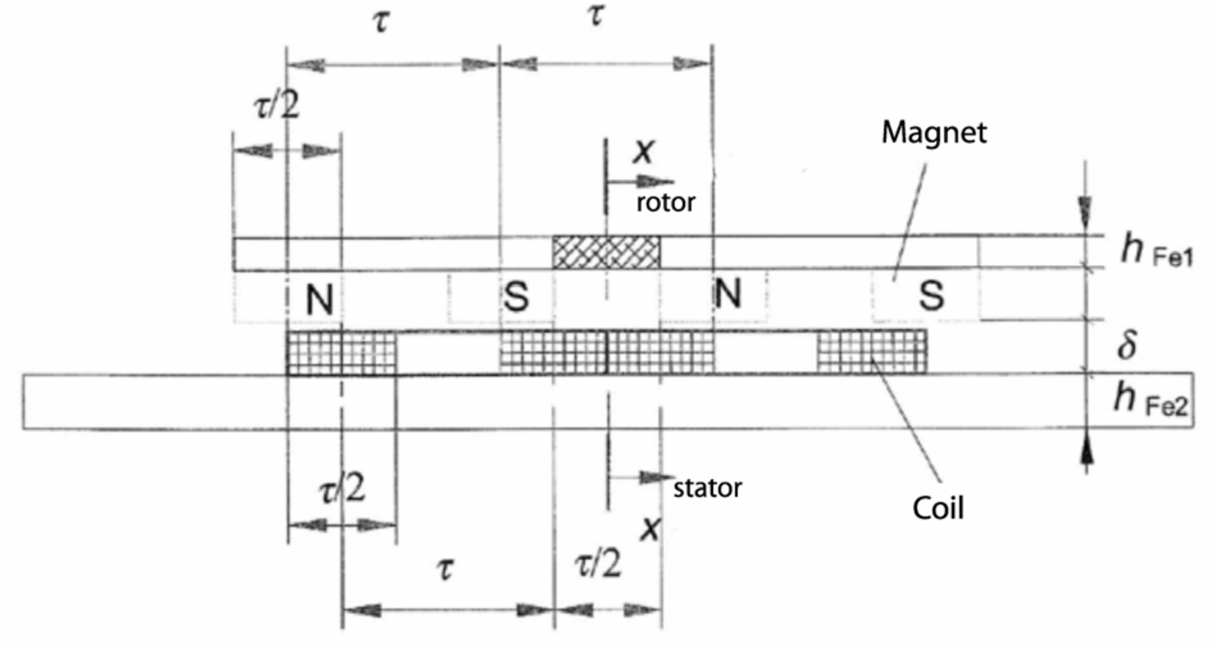


Fig. 8.6: Basic diagram of force-generating element

The movement of the rotor causes the degree of coverage of the pairs of coil magnets to change, but it remains virtually constant for the arrangement as a whole, whereby a force fluctuation of less than 1 % can be achieved.

Of the two possibilities, moved coils/stationary permanent magnets or stationary coils/moved permanent magnets (see fig. 7.18), the latter is more favorable, because it makes it possible to dispense with feeding the exciter current to the movable armature and also allows the heat loss to be dissipated well by mounting the exciter winding on the stator.

For the purposes of spatial integration, the exciter coils or the permanent magnets are respectively fixed in the stator or in the armature, whereby further advantages are obtained in comparison with the series arrangement of the individual drive axes which are connected to one another via movable coupling elements.

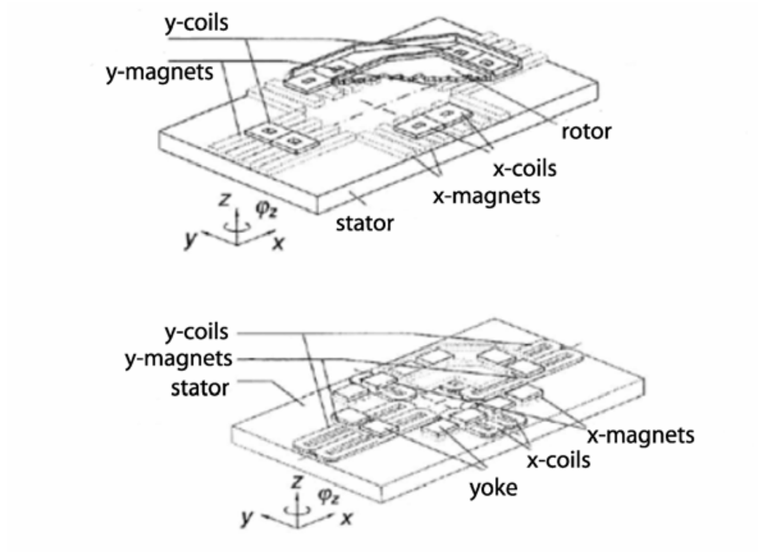


Fig. 8.7: Drive with moved coils (on the left in the figure) and with moved magnets (on the right in the figure)

Electrodynamic motors may only be used for positioning tasks if a position control loop is set up. The multicoordinate measuring system, which in the present case is likewise volume integrated and which comprises three sampling units arranged on the stator and a cross-grid scale arranged on the rotor, is necessary. The guidance of the armature is achieved by means of four magnetically biased air - guiding elements, which allow a movement with the degree of freedom 3 in the x, y and φ_z directions in the area predetermined by the construction. This dispenses from friction, play and stickslip characteristic for conventional sliding and rolling guides.

8.4. Control

On account of the stronger internal couplings because of the volume integration, the integrated multicoordi-nate motor is a very complex system, the potential of which can only be exploited with powerful hardware and software.

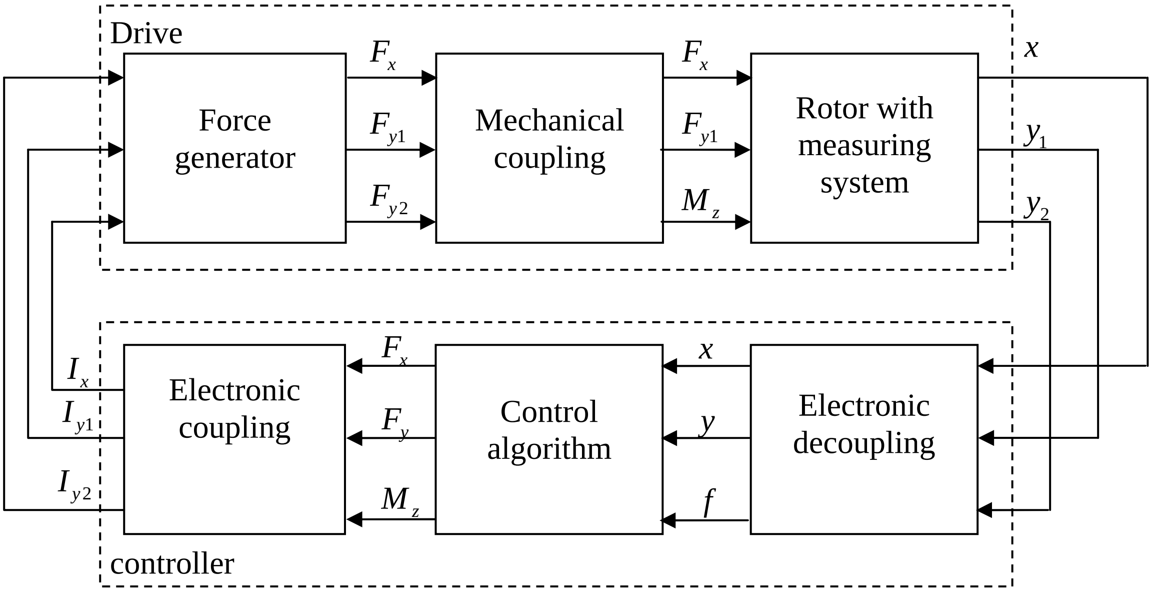


Fig. 8.8: Coupling structure of the control loop

From control engineering viewpoint, the multicoordinate drive is a three-variable system (x, y, φ_z), with two states in each case (displacement, speed) per controlled variable. The coupling structure of the control loop is illustrated in fig. 8.8.

Open-loop control: A powerful DSP control (see fig. 8.9 for hardware structure) makes a fully synchronous, micrometre-exact movement possible in the coordinate axes with high path speeds. Prediction permits more uniform traversing speeds. A movement without contouring errors is achieved by speed and acceleration pre - control.

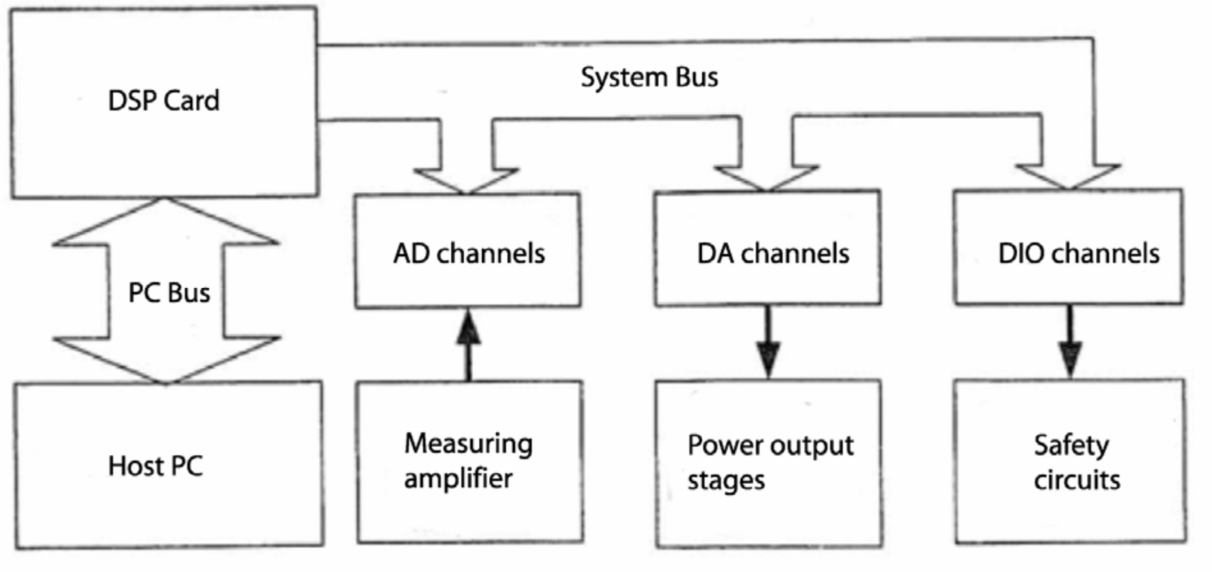


Fig. 8.9: Hardware structure of the control

Closed-loop control: Used for each of the three axes are incremental single-parameter state controllers, the structure of which (fig. 8.10) is determined by the minimizing of the quality functional

$$\psi = \frac{1}{N}\sum_{i=0}^{N-1} qe_{k+i}^2 + r\left(u_{k+i} - u_{k+i-1}\right)^2 ,$$

where

N	length of the optimization horizon
q	weighting of the control error
r	weighting of the change in the manipulated variable
e	control error
u	manipulated variable
k	current sampling point of the control
i	running variable of the optimization horizon

under the secondary condition of the system equation to give

$$u_k = u_{k-1} + l\left(x_k - x_{k-1}\right) + me_k ,$$

where

x	state vector
l	vector of the control coefficients of the state feedback
m	controller coefficient of the control error.

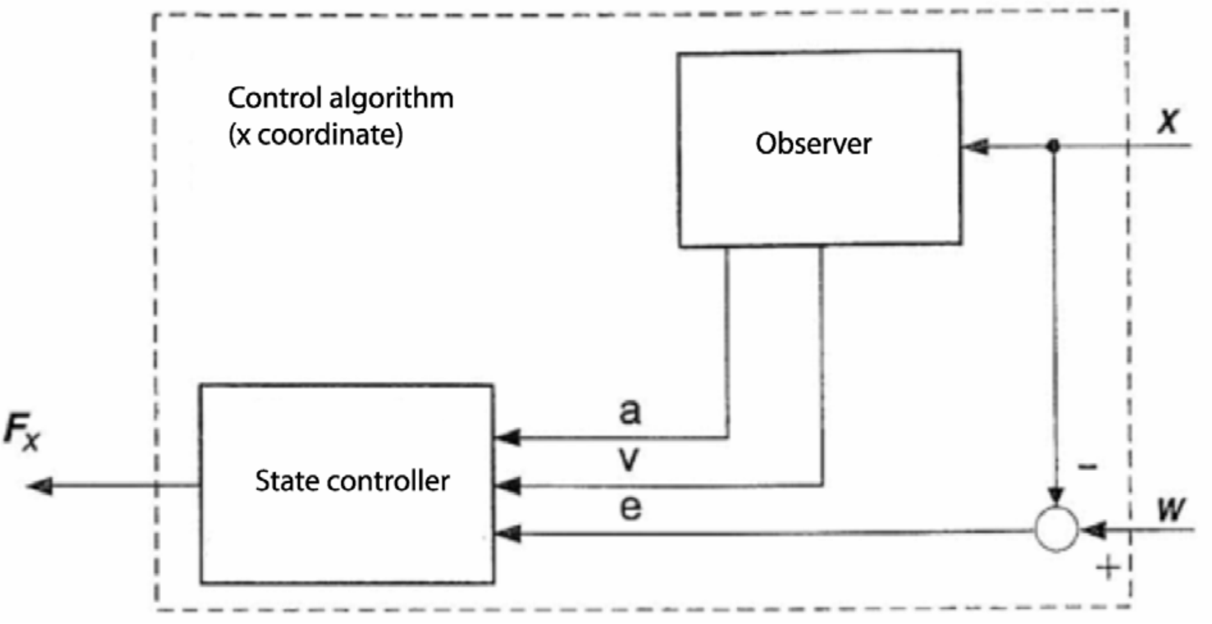


Fig. 8.10: Controller structure

On the basis of the results of the optimization on the motor to the control parameters *l* and *m* were set to the maximum speed without transient overshooting, since the model of the process on which the optimization was based was only approximated.

The first feedback difference of the state vector is obtained after differentiating the control variable by means of a state observer.

8.5. Fields of application

- ***High-speed laser cutting and engraving systems of extreme accuracy,***
- ***Measuring systems with optical and mechanical scanning,***
- ***Microassembly systems,***
- ***Wafer inspection and machining.***

In one application, 100 micro-bores with a diameter of $200\,\mu\text{m}$ and accuracy of $\pm 0.5\,\mu\text{m}$ were cut in a 0.2 mm thick steel sheet with a laser in 19 seconds.

Appendix - Glossary

Actuator: Actors serve for the targeted influencing of state variables in mechatronic systems. The term "actor" consequently goes beyond the English term "actuator" and covers all kinds of output elements for movements and forces.

System analysis: Investigation of the existing properties of a system. The system may be real or in the form of a model.

Partitioning: Dividing a system between a number of units/modules, for example functions being performed by components of different manufacturers or technical disciplines; dividing a system into a part which is implemented in hardware and a part which is implemented in software (hardware-software partitioning).

Problem-solving cycle: General description of the sequence of steps taken to solve a problem.

Macro-cycle: A guide for the macroscopic planning of the procedure on the basis of the V model, which describes the logical sequence of important sub - steps in the development of mechatronic systems. The V model was adopted from software development and adapted to the requirements of mechatronics.

Micro-cycle: Structuring of the procedure in the development process on the basis of a general problem-solving cycle, for example. By arranging procedural cycles in series and one within the other, process planning can be flexibly adapted to the peculiarities of any development task. The micro-cycle is intended in particular to support the product developer working on the subtasks that could be predicted and consequently planned, but also to solve sudden, unforeseeable problems. When designing a mechatronic system, the micro-cycle represents a standard procedure that differs case to case.

Model: Physical-mathematical description of a technical component, subassembly or a complex system.

Modelling: Creation of a physical-mathematical model of an existing system or of a system to be developed.

Process module: A self-contained unit of activities that serve the purpose of achieving a specific interim objective. A process module additionally comprises a description of the input and output information, classification criteria and additional information (such as supporting methods or required competences), which support working with the process module.

Design: "The conceiving of a whole, a solution concept, the identifying or finding of the solution elements required for this and the intellectual, model-based joining together and connecting of these elements to form a workable whole". Designing is accordingly a process which, starting from the requirements, leads to a concretization of a technical system. This concretization is expressed in components of mechatronics and the interaction of these components.

System design: The aim is to establish a cross-domain solution concept that describes the main physical and logical operating characteristics of the future product. For this purpose, the overall function of a system is broken down into main sub - functions. These sub - functions are assigned suitable structures and the performance of the function is tested in the context of the system.

Verification: Transferred to technical systems, it is to be understood as meaning checking whether the way in which something is realized (for example a software program) coincides with the specification (in this case with the description of algorithms). In everyday language, verification is the answer to the question: Is a *correct* product being developed?

Operating principle: "The operating principle refers to the interrelationship between physical effect and geometrical and material-related features (effective geometry, effective movement and material). It allows the principle of the solution for performing a sub - function to be identified".

Solution element: A solution element is a realized and tried-and-tested solution for performing a function. It is generally a module/sub – assembly that is based on an operating principle. The computer-internal representation of a solution element comprises different aspects such as ***behavior*** and ***form***. The aspect of *form* determining the building structure. The aspect of *behavior* has for the case of software, for example, abstract data types for the early development phases and code for the later development phase.

Sensor: A sensor converts a state variable of technical process, the quality which is not suitable as a signal, into a signal which can be transmitted, further processed and registered.

Simulation: Calculation of the behavior of a system model in dependence on time, and the state of a system and environment. The simulation provides projections about the behavior of the real system with the aid of a model, which can be executed in a computer.

Validation: Transferred to technical systems, it is to be understood as meaning testing whether the product is suitable for its intended purpose or achieves the desired value. The expectations of the technical expert and the user come into the equation here. In everyday language, validation is the answer to the question: is the *right* product being developed?

Basic system: Sub – system, which provides the basic for the mechatronic system. Generally the part of the system that represents the system to be influenced (controlled system) in the controller design.

Assurance of properties: Constitutes part of quality assurance and comprises the two aspects of: ***verification*** and ***validation***. Quality assurance generally serves for demonstrating that prescribed requirements are satisfied, that deficiencies are preventively avoided and that a certain quality of a process is ensured.

Information processing: Storing, structuring, amending and assessing of existing information. Information processing uses this information for the targeted production of output information.

Literature:

[1] Gmiterko, A.:Mechatronika. Košice, Emilena tiskáren 2004

[2] VDI 2206: Entwicklungmethodik für mechatronische Systéme. Beuth Verlag GmBH, Berlin, Juni 2004

[3] Lückel, J.,Koch, T., Schmitz, J.: Mechatronik als integrative Basic für innovative Produkte. VDI-Tagung: Mechatronik – Mechanisch/Elektrische Antriebstechnik. 29./30.März 2000, Wiesloch, Düsseldorf: VDI Verlag, 2000

[4] Eversheim, W., Nyemeier, R., Schernikau, J.,Zohm, F.:Unternehmerische Chabcem und Herausforderungen durch die Mechatronik in der Automobilzulieferindustrie, Materialen zur Automobilindustrie Band 23. Frankfurt a M.: VDA-Verlag, 2000

[5] Kallenbach, E., Zöppig, V., Birli, O., Feindt,K., Strhla, T., Saffert, E., Schmidt, J.: Integration Mechatronischer Systéme. Inovative Produktentwickklungen, 4.VDI-Mechatronik Tagung, 12./13. Sept. 2001, Frankenthal, VDI-Berichte 1631, Düsseldorf: VDI Verlag, 2001

[6] Gausemeier, J., Ebbesmeier, P., Kallmeier, F.: Produktinnovation – Strategische Plannung und Entwicklung der Produkte von morgen. München, Sien: Carl Hansen Verlag, 2001

[7] Zirn, O., Treib, T.: Similarity Laws of Seriál and Paralel Manipulators for Machina Tools, MOVIC 98 Zürich, Switzerland, 25. – 28. August 1998, Vol. 3, pp. 865-870

[8] Kallenbach, E., Saffert, E., Schäffel, Chr.: MUlti-coordinate Drive Systems – Opportunitics and Limits, 3rd International Heinz Nixdorf Symposium, May 1999, Paderborn, Proceedings, pp. 11-24