

Funcijsko usmerjeni teoretični okvir za načrtovanje mehatronskih sistemov

A Function-Oriented Theoretical Framework for Mechatronic System Design

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Predstavljena je nova funkcijsko usmerjena teoretična mreža za razvoj metod načrtovanja mehatronskih sistemov. Vključili smo tehnološko neodvisni delovni opis vidikov mehatronskega sistema, kot so 1) povezave in razlike ciljne funkcije, spreminjevalne funkcije in prehoda stanja, 2) sestava obdelave podatkov in 3) drugotne funkcije. Vse razprave smo nato povzeli v zbirki aksiomov, ki tako oblikujejo modele načrtovanja in metode za mehatronske sisteme.

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(Ključne besede: mehatronika, delovne usmeritve, ciljne funkcije, obdelava podatkov)

A new function-oriented theoretical framework for the development of mechatronic system design methods is presented. We include a technology-independent functional description of aspects of a mechatronic system, such as 1) the relations and distinctions among the purpose function, the transformation function and the state transition, 2) the structure of the information processing and 3) the secondary functions. All the discussions are then summarized in a set of axioms, which then form the basis for devising design models and methods for mechatronic systems.

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(Keywords: mechatronics, function oriented design, purpose functions, information processing)

0 INTRODUCTION

Mechatronic technologies combine mechanics with electronics and information technology (mostly software technology) to form both a functional interaction and a spatial integration in components, subsystems and systems. Only by treating mechatronics as an independent engineering discipline, instead of just a combination of traditional engineering fields, is it possible to exploit the full potential of the symbiosis of mechanics, electronics and software.

Contributions to a general product theory can be found in cybernetics, system theory, and system engineering ([1] to [3]). In addition, a large amount of published literature ([4] to [9]) has investigated definitions and representations for the function and the functional property of technical systems/products. Unfortunately, few of them show sufficient or substantial focus on mechatronic systems due to an

inadequate discernment of the functional nature and the characteristics of mechatronic systems. As a result, there are few discussions concerning the correlations among the transformation functions, the purpose functions and the state transitions relating to mechatronic systems.

The purpose of any technical system is to support a transformation or process. The effects necessary for the transformation of a process object (material, energy, data, or biological object) are delivered in an interplay between the system and the human operator. The function of a technical system is, therefore, usually described as a continuous flow of material, energy and information. However, a mechatronic system works in different states, and the function of the mechatronic system depends on its states. So the description of the continuous function transformation must be supplemented by a model explicitly describing the states of the system and the transitions between the states.

The design methodology that handles all the aspects of the mechanics/electronics/software combination is still missing because there are significant differences between the designing mechanics, the electronics and the software. Not only are different technical skills required, but the very nature of the design problems differs in terms of the functions to be realized, the types of solutions available, and the realization of the intended functions.

A major difficulty is that the term 'function' is understood and described very differently, ranging from physical effects and the transformations of material/energy/information, to logical relations between the data operations. This means that it is difficult to come to a holistic, abstract understanding of a mechatronic system, i.e., to describe a function structure. The chief obstacle to creating a holistic function structure for a mechatronic system is the absence of traditional methods and languages (such as those describing 'pure mechanics') in the description of the logical relations between functions.

The different design characteristics of mechanics, electronics and software indicate that a new function-oriented theoretical framework for the development of mechatronic system design methods is one of the most important research areas. This paper concentrates on the aspects of a technology-independent functional description of mechatronic systems in the conceptual design phase, where mechatronics is most clearly distinguishable from the traditional technologies of which it is comprised.

All the discussions are summarized in a set of axioms expressing the fundamental characteristics or relations between the characteristics of mechatronic systems, and those most important principles directly applicable to mechatronic systems design, which consequently form the basis for devising design models and methods for mechatronic systems.

1 A FUNCTION-ORIENTED THEORETICAL STARTING POINT FOR MECHATRONIC SYSTEM DESIGN

1.1 The mechatronic system in relation to a general design procedure

It is claimed in this paper that product (technical system) design involves successively establishing four systems, each corresponding to a (mental) working domain for the designer, as shown in

Figure 1. These four systems represent four different aspects of the product:

- 1) The transformation function (or process) system: a structure of processes, where the focus is on the purpose-oriented transformation of process objects like material, energy and information.
- 2) The (purpose) function system: a structure of purpose functions or effects needed in the product to create the specified transformations. An effect is a physical effect. For example, the interaction between the teeth of two gear wheels constitutes a gear as a component, and the physical effect of a gear is the transfer of rotational speed and torque.
- 3) The component (or function carrier) system: a structure of components. A component in the paper can be understood as a category of physical entities that creates the required physical effects and exhibits similar working principles to realize a required (purpose) function. The mode of action of a component is based upon a physical effect. Some components are in direct physical contact with the process object, while others deliver effects in the vertical chain of causality [8].
- 4) The parts system: a structure of single product parts, where the focus is on the allocation or distribution of the components into parts, which can be produced and assembled so that every machine part contributes to the totality.

This then leads to:

- The transformation function (or process) of a mechatronic system/product is the action that changes a process object (material, energy or information) from an input state to a desired output state. An example of the process in a mechatronic system can be identified in an electronic photocopier: 'The line pattern on the original paper is read, and a similar pattern is printed on copy paper'.
- The purpose function is the ability of the mechatronic system to create an expedient effect needed to realize a desired transformation, and the sum of all the necessary effects constitutes the purpose of the system. A mechatronic system is an effect structure with a causality relationship of the 'if ... then ...' type between the purpose functions and the effects of the system.

The process of product/system design cannot be described as a simple sequence of activities belonging to each domain. The human designer has the ability to freely jump back and forth between the

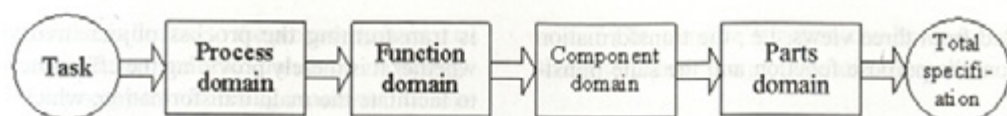


Fig.1. A general procedure for technical system/product design

four different perceptions of the product in his/her mind in an iterative sequence.

The main advantage of the general procedure is that it allows a precise positioning of design models and design methods, either within a particular domain or on a transition from one domain to another. In other words, knowledge of the domains in product design permits designers to develop design methods attached to one domain or to the transition from one domain to another. Using a catalogue of electronic components, for example, is a method for proceeding from an abstract description of a function to a physical realization.

The purpose of a mechatronic system is to facilitate a technical process, i.e., to effect the transformation of a process object from a given state to a desired state. The mechatronic system is not in itself a technical process; instead, it exerts the effects necessary to make the technical process happen. (For most technical processes, the effects created by the system in collaboration with a human operator can be understood as purpose functions). A mechatronic system can accordingly be regarded as a system of transformation functions, of purpose functions, of components, of parts.

Since the function of a mechatronic system depends on the state of the system, it is believed that mechatronic system design can be based directly on the general design procedure above, provided it is extended to deal with the logical concept of state transitions.

1.2 The function characteristics of mechanics, electronics and software

The term 'function' is used in mechanics, electronics and software. In machine-design theories it is common to describe the main purpose of a machine in terms of the transformations of material, energy and information. However, when adopting the term 'functions', designers think not only of transformations, but also of the 'effect needed in a machine' or purpose functions. Indeed, there seems to be a duality between transformation functions and purpose functions.

In a mechanical system information cannot exist independently; it must be attached to the substance of either a material (a punched card carries information) or an energy (hydraulic pressure may carry information). In machine design, the handling of energy and material is emphasized in comparison with information aspects.

In electronics design, function may be completely described as the transformations of electric properties (voltage, current, frequency, etc). In principle, some are transformations of information attached to energy, but the circuit designer usually ignores the energy aspects and only regards the flow of signals. Later, energy aspects always pop up as a recurring nuisance: heat dissipation, non-ignorable resistance in conductors, emitted electrical noises, etc.

In software design, the abstract function of a program can be described as transformations of data and logical relations of the 'if ...then...' type between transformations. At each level of the program it is possible to distinguish between the data to be transformed and the control data. In software, data (information) can be handled independently of energy representation, even though it will be tied to the electrical properties, once the program is implemented in the electronics hardware.

2 THE FUNCTION-ORIENTED THEORETICAL FRAMEWORK FOR MECHATRONIC SYSTEM DESIGN

The interior structure of a mechatronic system, independent of any technology realization, is explained in this section. The most important issues about the functions of a mechatronic system are the applicability of the purpose function concept in a mechatronic system, the role of state transitions in a functional framework and the structure of information processing in the mechatronic system.

2.1 The function structure of mechatronic system

The completeness conditions of the function structure of a mechatronic system must be ex-

pounded from three views, i.e., the transformation function, the purpose function and the state transition.

2.1.1 The transformation function and the purpose function

(1) The transformation function and the purpose function

Accordingly, the mechatronic system can be regarded as the structure of the transformation functions or the structure of the purpose functions with causal or logical relations. The link between the transformation function and the purpose function is the choice of technology. (Here, 'technology' must be understood as the kind and sequence of the sub-processes of a process and the interaction in space and time between the process objects and the effects, which create the transformations) [9]. This means that the designer has to decide on a general technology before he/she can transform a process structure into a structure of purpose functions.

The concept of the purpose function is important, because it explains the step between the description of the transformations and the actual realization of functions through the physical principles in the system, i.e., the components. Also, the term comes close to the designer's practical understanding of system functions. For instance, the function of a ball bearing or of a static structure is much more easily explained in terms of effects than in terms of transformations.

A discussion of a transformational versus a purpose functional description of a mechatronic system really comes down to whether the machine itself

is transforming the process object involved, or whether it is merely providing the effects necessary to facilitate the main transformation, which is then realized somehow externally to the machine. The purpose relates to the effect that the component provides to a system at a higher level. The transformation relates to the object (material, energy) that is processed by the component itself.

The concept of purpose functions was derived from observing a material-transforming machine, because there the distinction between transformation function and purpose function is evident. The effects created by the machine can be described almost independently of the transformation taking place.

One example is the fully automatic ECG (electrocardiogram) electrode manufacturing machine illustrated in Figure 2. A basic layer of foam is cut, a label is attached, and then a rivet, a ring and a foam block are added and so on, all in a sequential pattern. The effects of the machine corresponding to those processes are to provide a cutting effect and to generate a circular pattern, to establish the position and provide an attachment force for the label, etc.

The relations shown in the figure between purpose functions are of the causal type: all the purpose functions are necessary to accomplish the required transformation.

Is a purpose functional description of computer programs possible? In fact the definition of the purpose function rules out this option. Software cannot in itself exert any effect on a technical process – only the combination of computer software and hardware can do that. The functional descrip-

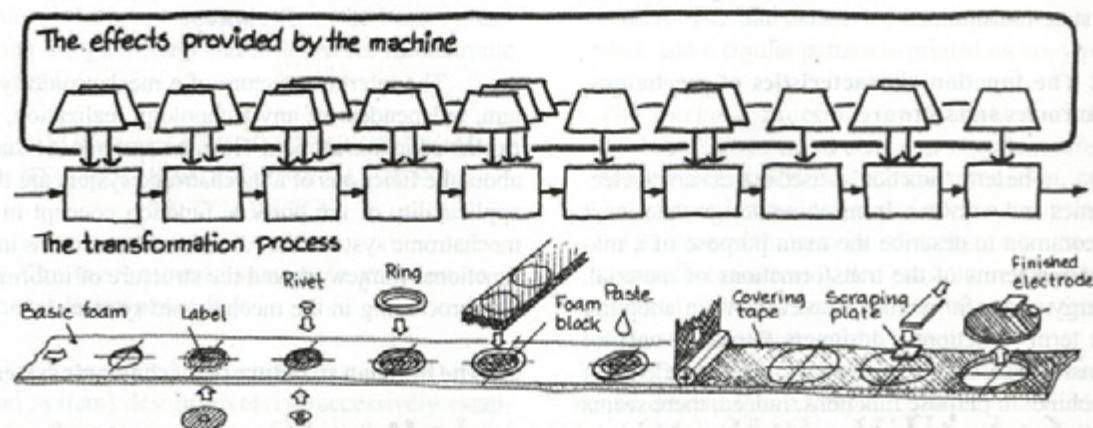


Fig. 2. The manufacturing process of an ECG electrode

tion of software is limited to the process domain, i.e., data transformation and state-transition modeling.

For energy-transforming machines the distinction between the transformation function and the purpose function is not so evident. A mechanical gear, for instance, transforms the rotary energy from one speed of revolution to another. Here, it becomes difficult to point out effects that the machine exerts to facilitate the transformation.

Energy transforming processes are central to any mechatronic system, because information is mostly tied to energy. Electronic circuits, for instance, realize only energy transformations, i.e., those of electronic signals. The interpretation of purpose functions in energy-transforming systems must therefore be examined more closely.

(2) The representations of the transformation function and the purpose function

A reasoning based on the analysis of well-known systems is necessary, i.e., one must ask which functions that existing systems and components fulfill are expressed in terms of transformations and exerted effects. From such reasoning it may be possible to generalize findings that are also applicable to the synthesis of non-existing systems.

It is presented as an axiom in the paper that transformation functions (or processes) and purpose functions can be distinguished by the strictly verbal formulation of verb/noun combinations.

The transformation function can be expressed in passive constructions of the form:

{object (noun)} is {transformed (verb)}

For instance, for a turntable: 'record is rotated', the state of the object 'record' is changed from non-rotating (input) to rotating (output) in the process.

The purpose function can be expressed actively to denote the purpose of the machine:

to {activate (verb)} {effect (noun)}

For instance, for rotating the record in the above example, the purpose function of the turntable is 'to create rotation', since 'rotation' is the effect exerted by the machine. The following table lists some examples:

It is evident from the list that the same component may serve several different purpose functions, depending on the system it is part of. The purpose of the gear, for instance, could also be 'to ensure sufficient torque' or 'to ensure correct orientation of movement'.

When observing the purpose function and the transformation function of individual components, functions seem to be formulated on different levels. The purpose relates to the effect that the component provides to a system at a higher level, but the transformation relates to the object (material, energy), which is processed by the component itself. The purpose of the motor, for instance, is 'to create rotation' in order to facilitate a transformation of some objects in a system, where the motor is a component. If we ask, 'How does the motor create rotation?', then the answer is, 'By performing the transformation of electrical energy into rotational energy'. This transformation process is only one of a number of alternative ways to 'create rotation', another is, 'By performing the transformation of potential energy into rotational energy' (e.g., a spring).

So it can be concluded as an axiom that there is a causal hierarchical relationship between the purpose functions and the transformation functions. A transformation requires different effects (the purpose functions) from the system, and an effect can be realized by alternative transformation functions on a secondary level.

Table 1. Components with associated transformation functions and purpose functions

Component	Transformation function	Purpose function
Motor	Electric energy is transformed into rotation	To create rotation
Gear	Rotation energy is transformed into revolution/torque	To ensure suitable revolution or torque
Electronic amplifier	Signal is amplified	To ensure sufficient amplitude
Battery	Energy is stored	To provide power
Diode	AC signal is rectified	To reject signals of negative polarization

Typical electronic (energy transforming) components can also be described in terms of purpose functions. Such a description is not common for electrical engineers and will even appear alien to them, but the purpose-function concept can help to clarify the hierarchical pattern of functions and alternative sub-solutions in electronics design.

2.1.2 The state transition and the transformation function

Two types of transformation functions can be distinguished: continuous and multi-state types. The multi-state type is characterized by its external control input.

In the continuous type of function-transformation process a function is described as a continuous flow of material, energy and information, and the output has a 'continuous' quality, i.e., it depends only on the state of the input (e.g., conducting, amplifying, transducing). However, when describing a complete structure of 'continuous' transformation functions, the different states of the system cannot be expressed explicitly. So a full functional description of a mechatronic system cannot be accomplished by using transformation functions only.

The mechatronic system works in different states (as a minimum there are the on and off states), and the function of a mechatronic system depends on the states of the system. Transitions between states are controlled by logical conditions (e.g., if a switch is turned on by the operator, then the machine changes to its on state). Nevertheless, when modeling the state-transition behavior, the flow of information is not clear – information is required for a change of state. This implies that the functions of mechatronic systems likewise cannot be described properly by state-transition presentations only.

This conflict between the continuous function transformation and the state-transition process is a

primary obstacle to mechatronic design, since mechanical and electronics engineers have an ingrained mode of functionally oriented thinking, whereas software designers are preoccupied with sequences of operations and causal relations. So the description of the continuous function transformation must be supplemented by a model explicitly describing the states of the system and the transitions between states (e.g., a Petri-net). In fact, a transformation function belonging to the function structure of a mechatronic system must be considered to be of the multi-state type if it causes the system output to change state momentarily due to an external logical input. Moreover, a structure of transformation functions has multiple states, if at least one of its elements is of the multi-state type.

It should be noted that the type, i.e., continuous or multi-state, of the function-transformation structure is related to different scopes of observation. A subsystem with multiple states may be regarded as a one-state, i.e., continuous, system on the next higher level if the external input causing the change of state becomes internal. For example, the function of a switch has two states (on/off), but if the switch forms part of a pulsing relay, the function becomes continuous, as shown in Figure 3. It is rather a question of the scope of the observation in the hierarchical structure of systems and subsystems.

Then, how to single out the logical functions (logical functions are closely related to the understanding of the state transitions of mechatronic systems) of a multi-state transformation function system? The multi-state function substituting principle is presented as a theorem for the problem: if a multi-state function is present in a transformation-function structure, then it is possible to substitute this function by a state-transition structure and a continuous-transformation structure for each state of the system. It is the case, therefore, that each state of a mechatronic system defines one particular structure of continuous transformation functions.

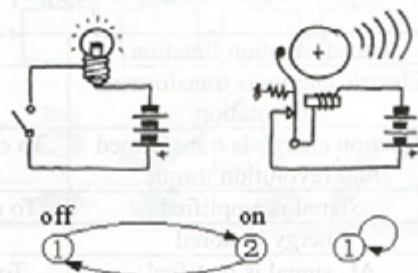


Fig.3. The function of an electric switch: a one- and a two-state system

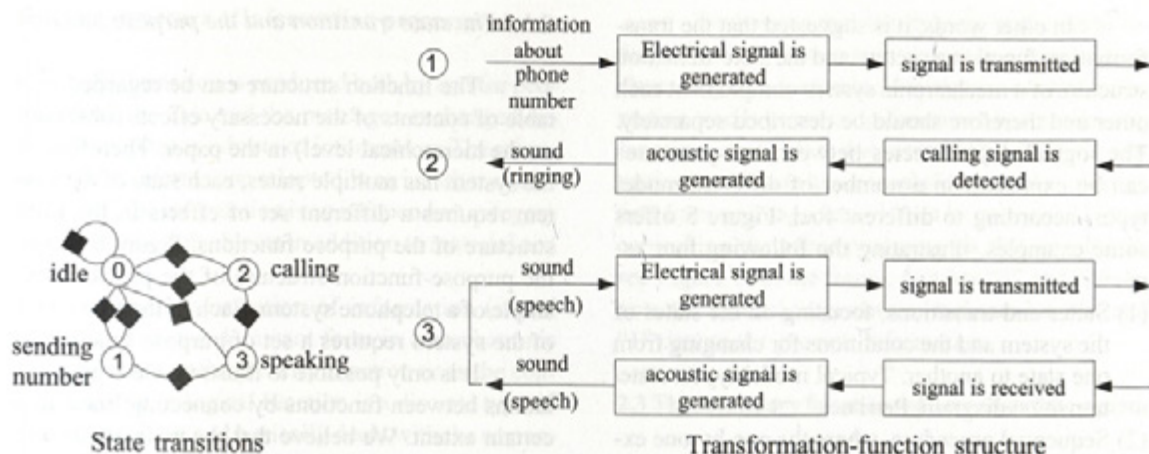


Fig.4. The transformation functions and state transition of a telephone

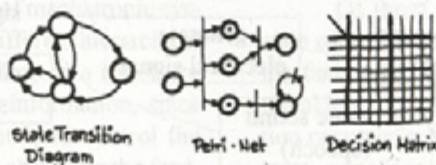
The example of a telephone system can be used to illustrate the above discussion. In order to transmit spoken messages rapidly over a distance, the acoustic signal cannot be transmitted directly, but must be transformed into an electrical signal before it is returned to an acoustic signal again after being received by the other side. The principal functions of a telephone system are just the sound-electricity and electricity-sound signal transformations.

As shown in Figure 4, a telephone can be modeled in the process domain (transformation-function-

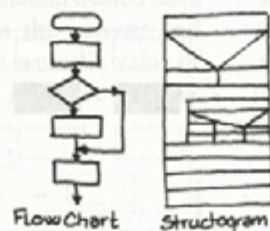
tion structure and the state/transition diagram) and in the function domain (purpose-function structure). The telephone has four states, of which one is idle.

If the function of the system is described in terms of the transformation only, then the output object of one or more blackboxes will exhibit three working states (sending number, calling and speaking). Instead, a 'continuous' transformation structure can be established for each working state of the system, and the structure of the states and transitions can be described separately.

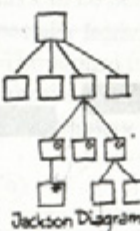
1. STATES & TRANSITIONS



2. SEQUENCE



3. HIERARCHY



4. TIMING

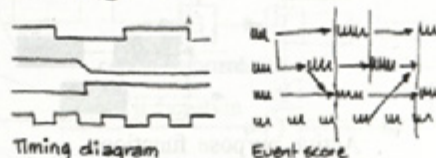


Fig.5. The logical dependencies between the transformation functions of a system

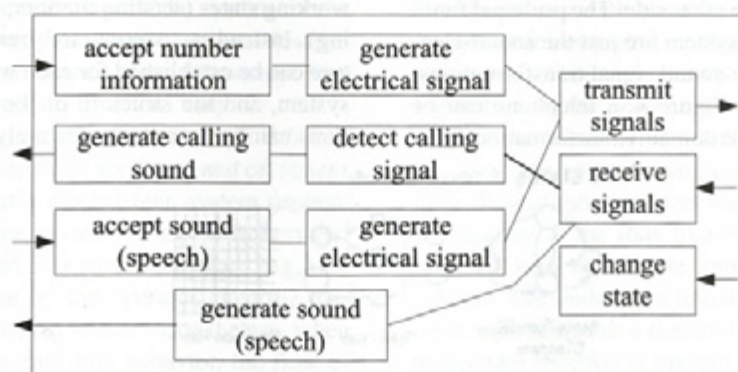
In other words, it is suggested that the transformation-function structure and the state-transition structure of a mechatronic system complement each other and therefore should be described separately. The logical dependencies between sub-processes can be expressed in a number of different model types, according to different foci. Figure 5 offers some examples, illustrating the following four aspects:

- (1) States and transitions, focusing on the states of the system and the conditions for changing from one state to another. Typical model types: state/transition diagram, Petri net.
- (2) Sequential procedure, where the one-by-one execution of sub-processes is emphasized: Flow chart, structogram.
- (3) Hierarchical pattern, where the structure of subordinate levels of the processes is important: Jackson diagram.
- (4) Timing conditions, where the timing of parallel transformations is critical: Timing diagram, event score.

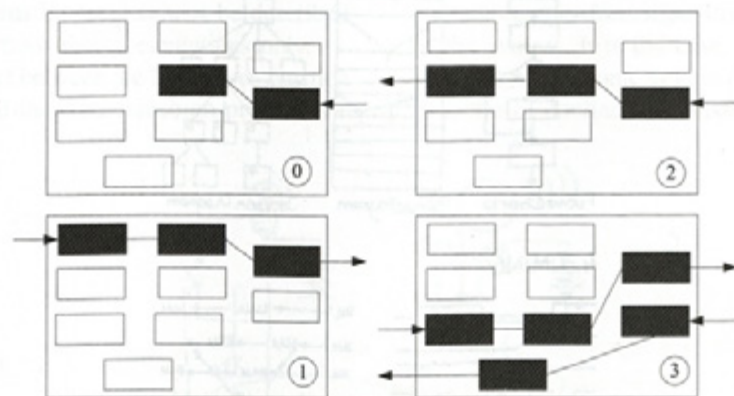
2.1.3 The state transition and the purpose function

The function structure can be regarded as a table of contents of the necessary effects (observed on the hierarchical level) in the paper. Therefore, if the system has multiple states, each state of the system requires a different set of effects in the total structure of the purpose functions. Figure 6 shows the purpose-function structure of the previous example of a telephone system. Each of the four states of the system requires a set of purpose functions.

It is only possible to illustrate the logical relations between functions by connecting lines, to a certain extent. We believe that the main advantage of the purpose-function structure is the total view of the necessary effects in the system. Therefore, it provides a good starting point for allocating technology, i.e., for suggesting solutions in the physical entity domain.



Purpose-function structure



Active purpose functions

Fig.6. The functions of a telephone

2.2 The structure of information processes

Information is produced both by and for people. Both the data and the messages exchanged between people are subsets of information. The meaning of the information adopted here is rather cybernetic, i.e., the information is an independent category of transformation objects in addition to material and energy.

The transformation of information (signal processing) is the dominant form in a mechatronic system, either as the primary function or as the control function (a logical function is a discrete type of control function and basically deals with the semantic value of the information in order to derive decisions) of material or energy transformations. Control functions constitute the logical relations between the purpose functions of the mechatronic systems.

A mechatronic system basically handles two types of information:

- Process information, which is transformed, i.e., processed, by the system regardless of its semantic value.
- Control information, which is applied by the system for control purposes (the control of energy or material transforming processes), i.e., it is 'understood' by the system.

It is justified that both the process information and the control information of mechatronic systems have relative meanings at different hierarchical levels. An electronic feedback loop in a robot, for instance, clearly carries control information, since the purpose of the arrangement is to control the movements of the system. When observing the feedback sensor and the signal-conditioning circuits locally, however, the type of information treated has a process character. As far as the sensor and preamplifiers are concerned, the semantic value of the process information has no influence on their functions.

We believe that the process and control information in a mechatronic system in general appear alternately in a hierarchical structure: control information needs processing functions and processing functions are likely to be governed by control information on the next lower level (for example, information from an image sensor must be processed before controlling the robot programs on the next level), see Figure 7. In the figure, number "4" and "2" denote the control information, and number "3" and "1" denote the process information.

2.3 The secondary functions of a mechatronic system

Although the topic of this paper is just technology-independent functional descriptions, in order to ensure theoretical completeness and consistency, secondary functions (including the control function) of mechatronic systems will still be briefly discussed in the following.

In general, any primary function of a mechatronic system will need the simultaneous realization of some, but not necessarily all, secondary functions. An appropriate set of secondary functions includes: the power function, the control function, the interface function, the protection function, the communication function and the structure function.

Of these, the control function governs the state of the means realizing a primary function and the functional performance in accordance with external inputs, e.g., a feedback loop. The control function occupies a special position in mechatronic systems, since it is often realized by a multifunctional microprocessor with software. Two important statements can be derived from existing design theories (especially from those of machine design):

- The control function is a secondary function and always depends on the choice of means to realize a primary function.

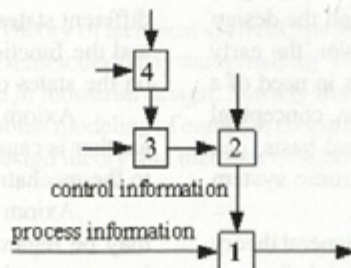


Fig. 7. The process/control information hierarchy in mechatronic systems

- The control function belongs to different levels of the function/means hierarchy.

In other words, it does not make sense to discuss the control function until the means to realize the function to be controlled has been decided on. And the interrelations between different control tasks in the system quickly become complex, because they connect controls on different hierarchical levels.

Both working functions and control functions in a mechatronic system can, at least theoretically, be realized in any or alternative combinations of mechanical, electronic and information technologies and furthermore performed by the operator of the mechatronic system. The state transition behavior of a mechatronic system is determined by the structure of the control components and their programmable instructions. Control components realize the logical relations between purpose functions on the same and different levels of the causal chain of functions and means.

The aspect of recursiveness is important: the secondary functions can themselves be regarded as primary functions on the next lower level of the hierarchy, each requiring some new secondary functions. This means realizing the function, which determines which types of secondary functions are needed on the next level. So the power function of a higher level may mean, for instance, the need for a control function, which again may require power.

3 CONCLUSIONS

There is a growing understanding that high-quality products can best be achieved through the use of methodical procedures. A comparison of the design characteristics of mechanics, electronics and software, indicates that the most important areas for mechatronics research are a theoretical framework for the functional understanding of mechatronic systems, and design models (a 'common language') to describe the functional structures and the design concepts for such systems. In particular, the early stage of mechatronic-system design is in need of a methodology for functional description, conceptual design, etc. Accordingly, the functional basis, i.e., the functional principles for mechatronic system design, is the main topic of this paper.

It is advantageous to acquire a general theory from machine-design literature and models for handling the sequence and state transitions from soft-

ware literature, in order to form a mechatronic system theory. It is also true that a synthesis theory for mechatronic systems can be based directly on the general design procedure, provided it is extended to deal with the logical concept of state transitions.

A new function-oriented theoretical framework for mechatronic system design is formulated in a set of axioms expressing the fundamental characteristics or relations between the characteristics of mechatronic systems, and essential conditions for the structured understanding of mechatronic systems, which consequently form the basis for devising design models and methods for mechatronic systems.

This research marks a new attempt to describe a function-oriented theoretical framework for mechatronic design. It is based on, if possible, a complete knowledge of product development practice in industry. The proposed theory permits the explanation of a great many observed phenomena in the literature and in industry, and it covers the common functional basis of system models and design principles.

4 APPENDIX:

AXIOMS OF MECHATRONIC SYSTEM THEORY

Axiom 1: A mechatronic system can be regarded as a system of transformation functions, of purpose functions, of components, and of parts.

Axiom 2: Transformation functions (or processes) and purpose functions can be distinguished by a strictly verbal formulation of verb/noun combinations.

Axiom 3: There is a causal hierarchical relationship between purpose functions and transformation functions. A transformation requires different effects (purpose functions) from the system, and an effect can be realized by alternative transformation functions on a secondary level.

Axiom 4: The mechatronic system works in different states (at least in an on- and an off- state), and the function of a mechatronic system depends on the states of the system.

Axiom 5: The transition from one state to another is caused by logical inputs that are external to the mechatronic system.

Axiom 6: A subsystem with multiple states may be regarded as a one-state (continuous) system on a next higher level, if the external input causing the change of state has become internal.

Axiom 7: Two types of transformation functions can be distinguished: continuous and multi-state types. The multi-state type is characterized by its external control input.

Axiom 8: A structure of transformation functions has multiple states, if at least one of its elements is of multi-state type.

Axiom 9: Each state of a mechatronic system defines one particular structure of (continuous) transformation functions.

Axiom 10: Each state of a system requires a different set of effects in the total structure of purpose functions.

Axiom 11: A mechatronic system handles two kinds of information:

- 1 process information, which is treated regardless of its semantic value;
- 2 control information, which is directly applied ("understood") by the system.

Axiom 12: Control functions constitute the logical relations between the purpose functions of the mechatronic system.

Axiom 13: Control functions are secondary functions, which always depend on the choice of the means to realize a primary function.

Axiom 14: Both working functions and control functions in a mechatronic system can be real-

ized in alternative combinations of mechanical, electronic and information technologies.

Axiom 15: There is a causal relationship between purpose functions and components: A function can be realized by alternative components, and each component will in turn require purpose functions on a secondary level.

Axiom 16: For the realization of any function, some or all of the following set of secondary functions are simultaneously required: the power function, the control function, the interface function, the protection function, the communication function and the structure function.

Axiom 17: In a mechatronic system, process and control information is transformed alternately in a hierarchical pattern of systems and subsystems.

Axiom 18: If a transformation-function structure representing a mechatronic system includes one or more multi-state elements, then it is possible to substitute these functions by a state-transition structure and a continuous-transformation structure for each state of the system.

Axiom 19: The state transition behavior of a mechatronic system is determined by the structure of control components and their programmable instructions. Control components realize the logical relations between purpose functions on the same and different levels of the causal chain of functions and means.

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