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DOMAIN ALLOCATION IN MECHATRONIC PRODUCTS

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1. Introduction

Mechatronic products are based on the synergetic integration of different engineering domains. Mechanics, electronics and software technology are combined in order to improve product properties and to obtain new product functionalities. In the mechatronic development process, the domain structure of the product has to be generated in a partitioning process by allocating the different domains to the functions that have to be fulfilled within the product. In many cases it is possible to fulfil the same function by different domains or combinations of domains. Therefore, a variety of domain structures exists for each product. Since the domain structure has a fundamental influence on product properties, the process of domain allocation is an important step in the development process of a mechatronic product and should be supported by design methods [Gausemeier 2003].

This paper presents an approach for a method which can support the process of domain allocation. The method may be used for the development of new products as well as for the improvement of existing products. The goal of this systematic approach for domain allocation is to avoid wrong decisions in the conceptual design phase and to support the creation of advantageous domain structures for mechatronic products. The domain structures are represented by three-dimensional models that take into account the geometrical arrangement of the functions and the selected function-fulfilling domains as well as feasible solution principles.

2. Existing approaches and demands on a method for domain allocation

The integration of mechanics, electronics and software technology leads to mechatronic products. In contrast to conventional products, whose functions are mainly realized by a single domain, mechatronic products are characterized by the consideration of domain integration from the beginning of their development process. Therefore, mechatronic development processes as well as the resulting products tend to be more complex than conventional ones and the existing design methods from mechanics, electronics and software technology often cannot be used without appropriate adaptations. Because of that, several research activities concerning the improvement of the development process for mechatronic products have evolved in the last years. The mechatronic-specific problem of domain allocation is addressed by several authors, who have developed design methods for mechatronic products.

2.1 Analysis of design methods for mechatronic products with regard to domain allocation

In [Buur 1991] domain allocation is characterized as the essential problem in mechatronics. Two important aspects of domain allocation are identified, namely the general choice of an appropriate technology (mechanics, electronics or software) for each function and the choice of suitable working

principles for each function. It is mentioned that domain allocation is a complex activity which depends on the particular application area as well as on the technological state-of-the-art.
For the interaction of solution principles from different domains, interfaces are required. These interfaces are used to transform the domain-specific parameters from one domain to the corresponding parameters of the connected domain. For example, the interface between electronics and mechanics is realized by actuators and sensors which transform electric variables into mechanical variables and vice versa. The arrangement of domain interfaces within the system is directly influenced by the process of domain allocation. For this reason, Buur briefly describes the different interfaces within the mechatronic system and between the system and its environment. For the specification of the interfaces he proposes the use of design catalogues. In addition, design principles for mechatronic products are presented. Some of these principles are closely related to domain allocation, but they are formulated in a very general way and therefore cannot directly be applied to a specific product development.
Another approach for a design method for mechatronic systems is presented in the new VDI-guideline [VDI 2206]. The guideline describes a flexible procedure model which is based on the V-shaped model on the macro-level and the cycle of problem solving on the micro-level. In addition, several predefined process modules for typical design tasks are provided. The partitioning of the system, i.e. the process of domain allocation, is mentioned in context of the transition from functions to solution elements. However, the guideline does not give any detailed information or methodical support concerning this design step.
Isermann describes different design steps which are relevant for the development of mechatronic systems [Isermann 1999]. The procedure starts with a basic idea for the process that has to be carried out by the system. After that, it has to be decided which of the basic functions are preferable realized by information technology and which ones should or must be fulfilled by energy-dominated principles. At this point the interfaces like sensors or actuators should be considered. In later steps of the development process the chosen initial allocation is checked for possible optimizations and improved if necessary. Thus, domain allocation can be considered as an iterative approach that starts in early phases of the development process and the domain structure can vary during the development process due to optimizations which are carried out in later steps.
A more detailed concept for the process of domain allocation is proposed by [Lippold 2000]. The domain structure is generated in different steps. Before the functions are allocated to the mechanical, electrical or software domain, the system is divided into energy- and information-dominated areas. After that, the domain structure is detailed and varied in order to obtain an appropriate solution.
The analysis of the different methodical approaches for the development of mechatronic systems shows, that domain allocation is one of the major problems in the development of these systems. Nevertheless, to date there exists no systematic approach to support this step of the development process. Since product properties are crucially influenced by the domain structure of the product and wrong decisions in early phases can lead to inferior products, a methodical support of domain allocation seems to be useful.

2.2 Demands on a methodical support for domain allocation

From the analysis described above several conclusions can be drawn, that should be taken into consideration when creating a method for domain allocation. First of all the interfaces between the different domains are of fundamental importance for the process of domain allocation and the creation of domain structures. Therefore, the domain interfaces have to be analysed with respect to their influence on domain allocation. The process of domain allocation also depends on various factors of influence which should be identified. The interdependencies of these factors and possible impacts on the appropriate domain structure need to be investigated. For the applicability of a method for domain allocation in practice it is important to notice that the creativity of the product designers should not be hindered but stimulated. For this reason, the allocation method and the models created by the use of the method should be flexible with regard to the level of detail and abstraction as well as to the selection of solution principles. Additionally, typical restrictions of domain allocation which for example can be a consequence of company strategy or preferred technologies should be considered by the method.

3. Factors of influence on domain allocation

For the creation of advantageous domain structures, product requirements have to be considered as well as allocation-related restrictions. The analysis of product requirements with respect to their influence on domain allocation leads to three different problems. Firstly, a high number of possible requirements exists and general product requirements have to be specified for the concrete product development. This makes it difficult to establish a complete list of requirements. Secondly, there is often no clear correlation between a specific product requirement and the appropriate domain structure. For example, there is no general relationship between the weight of a product and the number of functions realized by software instead of mechanics. A product with direct drives which are connected through electronics and signal processing units may often have a lower weight than a product with the same output characteristics using a central drive connected to the outputs by mechanical gears. But a general rule, according to that the requirement of a low weight always leads a domain structure which is dominated by electronics and software instead of mechanics, is not valid. And thirdly, the influences of different product requirements on domain allocation can be contradictory. For example a high level of reliability may require mechanical connections while functional flexibility can rather be realized by software and electronics. Thus, domain allocation on the basis of product requirements can be considered as a trade-off problem.

Allocation-related restrictions derive from the general framework which comprises the situation and strategy of the company that develops the product. They may occur, for example, when the company strategy demands the use of a certain domain in conjunction with a certain product function or when the number of different types of interfaces (actuators, sensors etc.) is limited by standardization requirements. Allocation-related restrictions directly reduce the variety of appropriate domain structures.

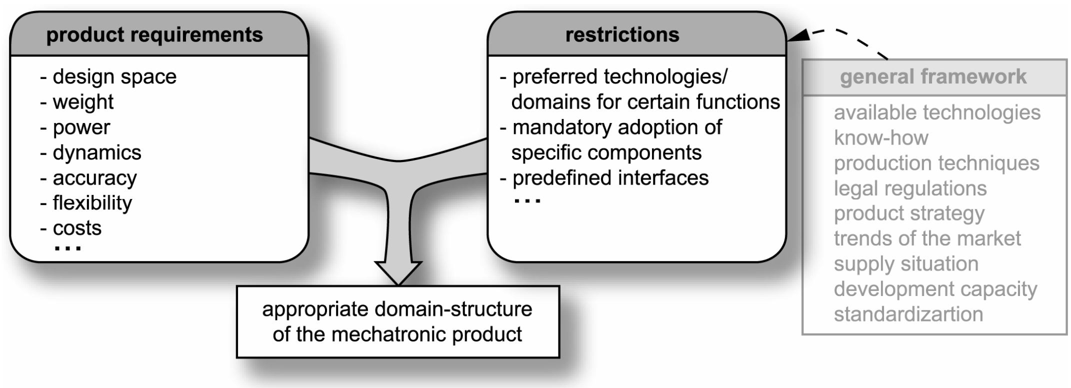

Figure 1. Factors of influence on domain allocation

Both, product requirements and restrictions have an influence on the appropriate domain structure (Figure 1). As discussed above, it is often not possible to derive general allocation rules from these factors of influence. Nevertheless, they can deliver important information that can be used in the process of domain allocation. The geometry and size of the available design space and the input and output flows of the system that has to be designed are determined by the requirements and can be used as a basis to build up a model of the domain structure.

For other product requirements a more or less clear correlation with the domain structure can be identified. The flexibility of a system's behaviour can be increased if the inputs and outputs are not connected to each other by mechanical elements but by electrical components and software functions. The more functions are realized by software, the more flexible the output characteristics can be adapted to the specific requirements. Using direct drives rather than a central drive combined with coupled mechanical movements can increase flexibility, too. On the one hand, independent

movements can be realized with direct drives and on the other hand it is easier to change the geometrical arrangement of the independent actuators within the system, because electrical connections in most cases are easier to handle than mechanical transmissions.
Shifting mechanical and electrical functions to software can also reduce the costs per unit because the fixed development costs for a software program are distributed to the whole number of equal products. Thus, the costs per software function decrease with an increasing number of produced units.

4. Interfaces between different domains

Since domain allocation is directly related to the number, arrangement and complexity of interfaces between different domains, the analysis of these interfaces is of major importance. In most cases the type and the quality of the mechanical output variables (e.g. movements) are of major interest, while software and electronics are primarily used to control the mechanical variables. Therefore, the development process of a mechatronic system as well as the domain allocation procedure usually starts with a consideration of the mechanical part of the system. As illustrated in figure 2, the interface between the mechanical and the electrical domain is realized by sensors and actuators, while the interface between electronics and software is rather a virtual one, because in mechatronic systems software is always represented by electrical variables.

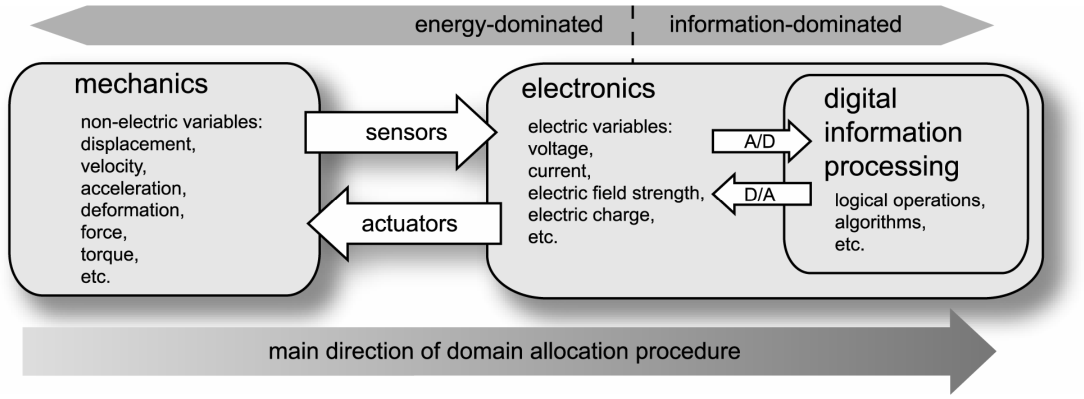

Figure 2. Interrelations between different domains

Actuators are used to transform electrical energy into mechanical energy. This transformation can be done by different physical effects. As an example, the Lorentz force can be used to transform an electrical current into a mechanical force. This principle is used in DC-motors. Other examples for physical effects that can be used as interface between electronics and mechanics are piezoelectricity, magnetostriction, electromagnetism or the shape-memory-effect. Since these effects have different properties, their applicability as an interface depends on the specific set of requirements. Especially the required mechanical output variables of the mechatronic system have to be taken into account in this context, because an actuator-principle can only be used for a particular application if it is capable of providing the required output of mechanical power. Another important issue for the selection of actuator principles is the complexity of the mechanical transformation which is necessary to convert the actuator output to the output of the mechatronic system. The output characteristics of a considered actuator principle can be compared to the required output characteristics. Based on this comparison, the complexity of the mechanism for the conversion can be estimated.
The transformation of non-electrical variables into electrical variables is performed by sensors. Domain allocation and sensor selection are closely linked to each other, because the variables that have to be measured and controlled are partially determined by the domain structure. Therefore, the complexity of sensor interfaces and the required accuracy of measurements have to be considered as well as the arrangement of sensors within the system.
While the arrangement of actuators and sensors strongly influences the design of the energy-dominated portion of the mechatronic system, the interface between electronics and software is primarily related to the optimization of control and signal processing. Since the output variables of a

mechatronic system are mainly mechanical, the interfaces between the mechanical and the software domain should be varied in early phases of the domain allocation procedure. On the other hand, the more detailed interface between electronics and software can only be specified when the functions that have to be fulfilled within these domains are known. Thus, the energy-dominated parts of the domain structure must be considered first. Nevertheless, the capabilities of software and electronics have to be taken into account even in early steps of domain allocation

5. Concept for a domain allocation method

Although the problem of domain allocation is mentioned by several authors, there exists no systematic approach to support this step of the development process. Because of that, a new concept for a domain allocation method has been developed. The method uses a three-dimensional model which represents the domain structure of the product. The domain structure can be considered as an intermediate step between the functional structure and the structure of working principles. It specifies the domain in which a certain function is fulfilled, but not the detailed working principle. Three-dimensional models of function structures and design spaces are known for example from [Koch 2003] and [Lossak 1997]. Although these research activities do not treat the problem of domain allocation, the proposed representation schemes can be used as a basis for the representation of domain structures.
The creation of the domain-structure is exemplarily illustrated in figure 3 for the development of a mechatronic gripper. The process starts with the definition of the available design space and the identification of the desired mechanical output variables of the system, which are two forces that operate in opposite directions. Similar as in the example, the geometric arrangement within the three-dimensional system often can be estimated in early phases of the development process. From the estimated behaviour of the forces and their displacements over time, the mechanical power and dynamics that have to be performed by the outputs can be calculated.

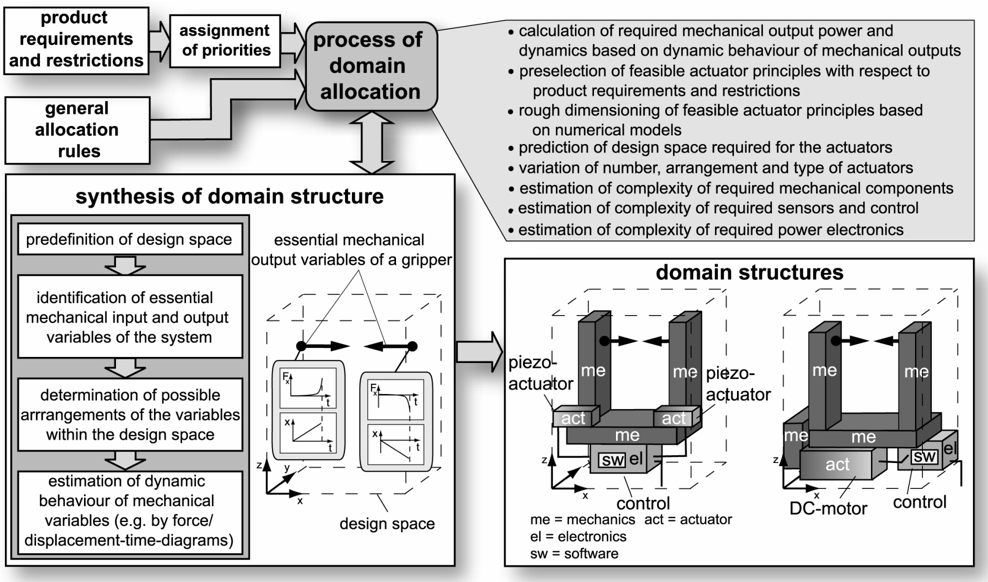

Figure 3. Creation of domain structures

The information gained by analyzing the desired output characteristics can be used as a starting point to build up feasible domain structures for the system. Since the selection of actuator principles and the variation of their arrangement within the system is considered as an important basis for domain-allocation, different feasible actuator principles are determined by variation of parameters. As an example, the length and the cross-section of a piezo-actuator can be estimated based on the required output of mechanical power. Thus, the design space needed by a feasible piezo-actuator which is able to drive the gripper can be predicted. In the next step, the complexity of the mechanical transformation can be evaluated, based on a comparison of the mechanical output characteristics of the mechatronic

system and the actuator output. Other actuator principles can be analyzed in the same way and possible arrangements within the system can be observed. For example, the number of actuators which are used to move the gripper can be varied and the interfaces between mechanics and electronics can be shifted within the model. Sensor interfaces may be varied in a similar manner.
In addition, the influencing factors as discussed above have to be considered in order to build up appropriate domain structures. For this reason the designer has to be provided with information about possible influencing factors and their interdependencies. Although it is not possible to create a complete system of rules for domain allocation, some general rules can be extracted. Furthermore, the complexity of interdependencies can be handled by assigning different priorities to the product requirements and restrictions. If for example the miniaturization of the design space has the highest priority value, the domain structure has to be optimized for this parameter first. The other requirements are taken into account in further iteration steps.

6. Conclusions

Although domain allocation is an important step in the development process of mechatronic products, it is not sufficiently supported by design methods yet. The domain structure depends on different factors of influence derived from product requirements and certain restrictions which result from the strategy of the company and other parameters. An analysis of the factors of influence on domain allocation shows, that the impact of the factors is not always clear. Furthermore, there are many interdependencies between conflicting factors. For this reason, domain allocation can be referred to as a trade-off problem which has to be solved in an early stage of the development process.
A method which supports domain allocation can help to structure the problem and to identify and analyse the interrelations within the mechatronic system. The creation of appropriate domain structures can be efficiently supported by providing quantitative and qualitative information on the abilities of sensor and actuator principles, since these principles constitute the interfaces between the mechanical and the electrical domain.

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