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DEVELOPMENT OF MODULAR ACTUATOR SYSTEMS

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1. Introduction

The development of actuator systems that are based on shape memory technology is still combined with additional development risks. In order to be able to use the potentials of shape memory alloys [Otsuka Wayman 1998] beneficially, extensive experiences with this functional material are necessary. Existent actuator concepts are designed for specific applications and only rarely allow a transfer to other tasks. Furthermore, intensive testing of the designed devices is often crucial to ensure the required product characteristics. To reduce the development risk for the individual applications, a modular actuator system with standardized and tested modules shall be developed. This allows configuring actuator systems that are adapted to specific application cases. Besides, common benefits of modular systems like reduction of costs and development time as well as an increase of quality are pursued. The development of the modular actuator system is based on experiences that have been made by the realization of a switching and a positioning actuator [Welp Breidert 2002, Breidert Welp 2003a] with shape memory elements as central actuator components.

2. Objective

The objective of this paper is to present the development process of a modular actuator system and to report about the experiences with the methods employed. Thereby, problems occurring during the design process will be discussed and as far as possible, weak points of existing methods will be shown. Moreover, the focus will be on the interface design, particularly on aspects of embodiment design and related subjects. The development process will be verified by a modular system, which will be presented here. The work shown will help to identify topics for further research.

3. Methods

A method for the development of modular systems, the Modular Function Deployment (MFD™) [Ericsson Erixon 1999] is applied in an adapted way to modularize and detail the system. The function-means tree [Andreasen 1980] is used to structure solution principles concisely, related to the respective functions. In order to generate combinations, configurations and variants, combinatory matrices and schemes are used multiple times. According to combination schemes [Pahl Beitz 1996], variants of total solutions for the different configurations are considered in a combination scheme, based on the various solution principles for the sub-functions. Furthermore, the 'classical' design methodology [Pahl Beitz 1996] is used, especially in the embodiment design phase. Finally, CAD-modeling is applied in the embodiment design phase to describe the geometric interfaces and to check the kinematic interactions.

4. Results

In the following sections, the development process for the modular actuator is presented. The sections are structured according to the main development stages, starting with the analysis of the application characteristics and ending with the embodiment design of the modules.

4.1 Analysis of application characteristics

Initially, the application characteristics of the planned actuator system are described and classified using a tree structure (see Fig. 1). In this tree the main functions of the variants (move, switch and position) are defined as well as the motion of the required kinematic output (rotation, translation). The consideration of the requirements is completed by an analysis of possibly occurring load profiles. Furthermore, the dimension of the required mechanical energy output (product of force and displacement) as well as the ratio of load to displacement are important indicators that influence the actuator design.

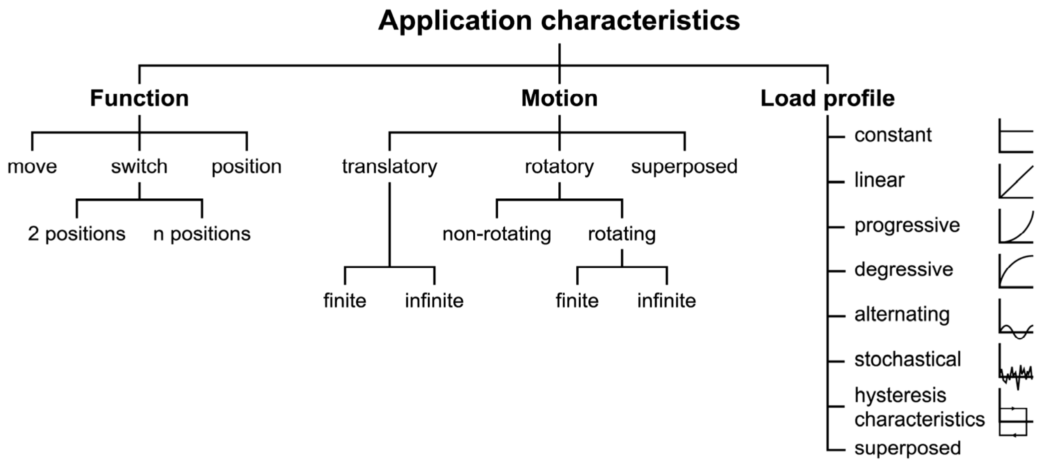

Figure 1. Application characteristics of actuators

Moreover, relevant configurations of application characteristics are examined by considering combinations of them. To reduce the number of possible combinations, the different variants of the application characteristics are reduced through grouping, selection and exclusion. Some examples for simplification are that of the function group ‘switch’: Only the path ‘switch between two positions’ is selected; additionally superposed motions are not considered and only alternating loads with a constant maximum load and repeated cycle load are taken into account. Besides, the available energy, the required packaging volume and, in this case, the selected actuator technology are additional requirements. By using a combinatory matrix, possible configurations based on the selected application characteristics are generated. Thus, a three-dimensional scheme with function, motion and load profile as arranging criteria is created.

In the next step, the system is described on an abstract level. A generalized structure of function is created (see Fig. 2), which contains identified basic and optional functions. Essential functions are the transformation of electrical into thermal energy and the transformation of thermal into mechanical energy. These functions describe the simplest case of a moving actuator, which is also the basis for switching and positioning actuators. For a switching actuator, the supplementary functions of switching energy and processing signals are necessary. The positioning actuator requires a conditioning of the supplied energy and a detection of the actual position. Additional functions are to reset motion, which depends on the load (alternating load with either zero mean value or zero minimum value), and the transformation of the motions, which adapt the output of the actuator elements to the demanded motions. In order to save energy, the function ‘keep position’ (without energy consumption) is integrated. Aiming to give an overview of the different sub-functions, a function tree is generated.

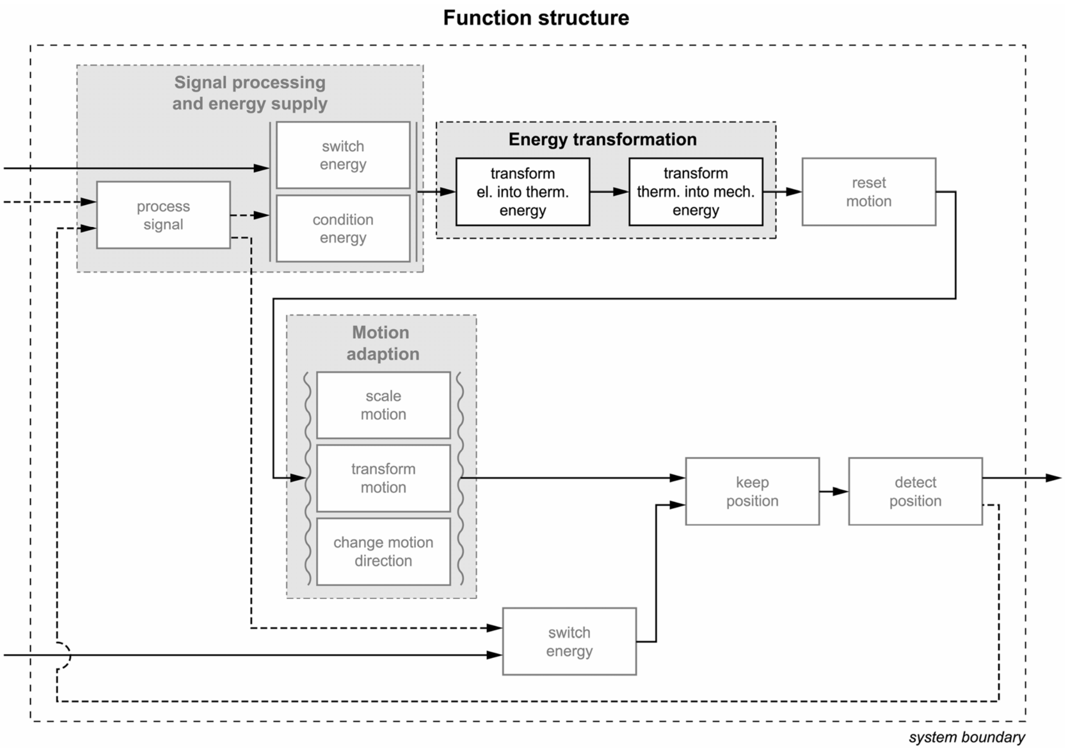

Figure 2. Generalized function structure of the modular actuator system

4.2 Search of possible principle solutions

Simultaneously, solution principles for each single sub-function are considered. The generated function tree is completed to a function-means tree and utilized to describe alternative solutions for the different functions. A section of the function-means tree for the actuator system is illustrated in Fig. 3.

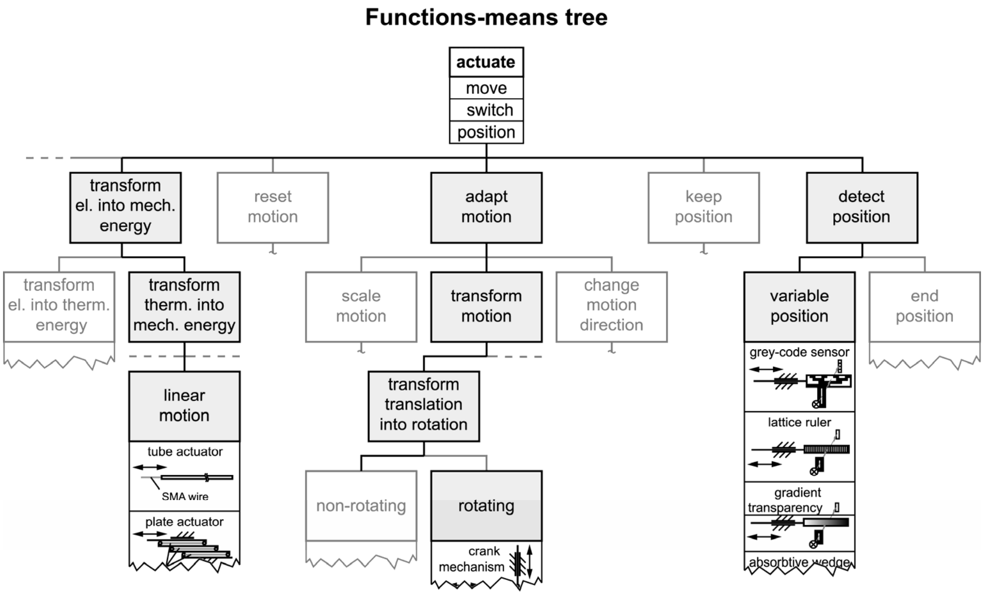

Figure 3. Section of the function-means tree with solution principles for the sub-functions

In order to select proper solution principles, the solutions are not only assessed separately, but also analyzed related to their potential for beneficial combinations with solution principles of other functions utilizing a combinatory matrix. Benefits can be achieved, i.e. from combining a tube actuator

with a crank mechanism. Thus, the comparative short displacement and the large force of shape memory wires can be transferred into relatively fast rotation.
Based on this analysis, the solution principles that are able to fulfill the respective functions are selected. Using a combination scheme that contains sub-functions and configurations, clusterable solution principles are identified, which can be summarized into one module. According to classical morphological schemes, the solution variants on basis of solution principles are illustrated. In contrary to the conventional use of morphological schemes, variants for a total solution of a configuration are created by combining different but suitable solution principles. This means that the matrix shows already total solutions. This procedure is carried out for each of the selected configurations. Based on the variants of the total solutions for the different configurations such variants are selected. These include solution principles that are used in many configurations. Furthermore, solution principles, which are always used together in the different variants of the total solutions, are candidates that can be integrated into one physical module. Besides, solution principles that are used only in few configurations or in different formations have to be transferred into modules consisting of single solution principles.

4.3 Modularization

In order to identify the characteristics of the structure and the interrelation between the modules of the modular system, the interface matrix, which is part of the MFD™-method is used. In Fig. 4 the interface matrix of the actuator system is shown. The interrelations have been described by their characteristic relation types (energy, geometry). The signal relation has been additionally introduced to complete the description of the interface flow. Hence, it could be clarified, that the recommended structure for the modular system is a sectional structure type referring to the defined architecture types in [Ulrich 1995].

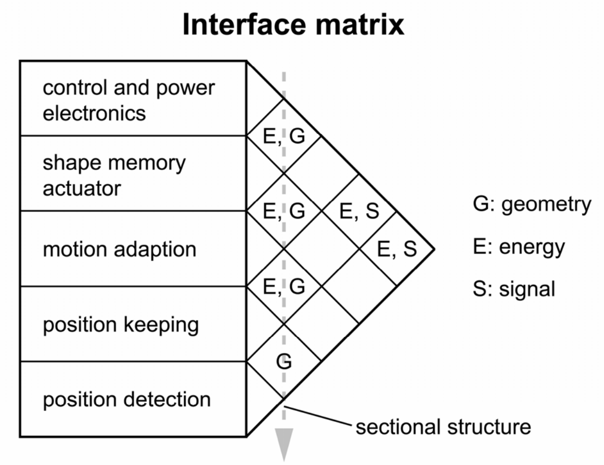

Figure 4. Interface matrix of the modules

4.4 Embodiment design of the modules

For each identified module, the detailed internal concept is designed on the level of working principles. These principles are transferred into concepts on the level of embodiment design to estimate the needed package volume. On this basis, the embodiment design of the module interfaces is carried out. Within this step, the consideration of the connection between the modules and the interface flows are of particular importance for a good modular design. Due to that, aspects of connection technologies as well as assembly kinematics are discussed. Related to the interface structure, the signal and energy flow between adjoining modules and modules that carry out transmitting functions is particularly considered. It is not always possible to fulfill all design aspects with the same excellence. For example, manufacturing reasons demand parts preferably with no undercut. However, the sectional modularity and the possibility that the modules, which are based on the same box design, have to be connectable to a module of the same design and, therefore, does not allow an undercut free design. To some extent, the embodiment design has an influence on the modularization. This reverse influence occurs especially, when the design shall be done in an optimized way, as in the case of the different actuator modules that are connected with the motion adaption module. For detailing the internal design of the modules design, approaches as described in [Pahl Beitz 1996] are applied. A digital mock-up of the modular system is used to verify the geometric compatibility of the modules. In Fig. 5 the digital mock-up of a configured positioning actuator is exemplarily illustrated.

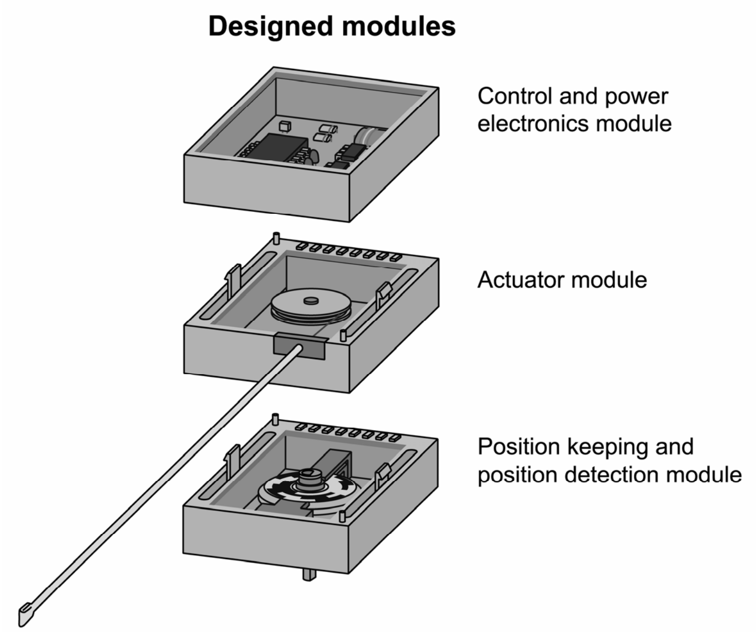

Figure 5. Exemplary configuration of a positioning actuator

5. Conclusions

The description of the application requirements on functional level helps to identify the needed variants. The immediately increasing number of combinations related to some added application requirements leads to complex as well as time-consuming assessment and selection processes. If beneficial combinations must be utilized, it is difficult to select and reduce the number of solution principles, because of the large number of possible combinations. The generation of a general function structure that includes all possible configurations is difficult. In particular with sub-functions, which are optionally usable and may also be combined among each other in a variable order, the function structure could not be illustrated clearly.

The utilization of the interface matrix to identify the characteristic structure and interrelations between the modules is associated with some difficulties. Following the MFD™-method, the modules have to be listed in their assembly order. However, in the present case, the assembly order is not known at this stage of the development process. Therefore, the order can be chosen either intuitively or by a systematic approach through a variation of the assembly order and assessment of the considered variants with regard to their suitability.

Problems with contrary requirements increase the number of needed modules. For example, to ensure high accuracy, a positioning sensor next to the output is essential. However, in order to satisfy translational as well as rotational positioning detecting, two different modules become necessary. Furthermore, solutions that integrate different functions, like the inchworm principle, are mostly not directly derivable from a combination of solution principles for the single sub-functions.

Even if the modularization is supported by some methodologies, the development of modular systems is not well supported. In particular the later design phases including the embodiment design of the

module interfaces lead to problems and complexity. The interdependencies between parameters of different modules are often not quite obvious. Problematic topics of the synthesis of modular systems and especially the interface design that have been described in [Breidert Welp 2003b] are pointed out through the development of the actuator system presented.
The development of a modular actuator system shown here, leads to some questions that will be considered in further research.

- What are the characteristics and properties of module interfaces? How are the properties interrelated?
- What influences the interface design, from product as well as from process perspective, and what are the impacts?
- In which way does the joint technology influences the interface design?
- What are sufficient strategies to carry out the interface design? What activities have to be carried out and which order is advantageous? What are the advantages and disadvantages of the different strategies?

Besides, it is necessary to verify the benefit of the modularization for the shape memory based actuator system through exemplarily testing in different applications. It has to be examined, if the development risk is lower than for an actuator that is purpose-designed for an application case and if the features of the modular version obtain comparable performance characteristics.

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