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EVALUATION AND CHOICE OF HETEROGENEOUS SYSTEMS AT FUNCTION TOPOLOGY LEVEL

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ABSTRACT

Precision engineering, which is concerned with repeatability and uncertainty in range of micrometers or sub-micrometers, is a typical application field of heterogeneous systems. A crucial issue of heterogeneous systems design in the context of precision is the optimization of coupling in the technical system. Current approaches to the optimization of couplings are limited to the embodiment stage of the design process. Due to the fact that technological constraints limit the potential of optimizing couplings in this advanced stage of the design process, this frequently results in significant changes of the system-structure.

The first stage of the design process that allows an estimation of the number of couplings in a technical system is the basic function-structure, further on referred to as the function-topology.

This paper describes an approach to evaluating heterogeneous systems exemplified with a planar-positioning-system. Focusing on couplings between sub-functions, it presents an algorithm that allows counting the couplings between any two elements throughout all possible arrangements of heterogeneous subsystems at an early stage of the design process.

Keywords: product and system modeling, system architecture, precision engineering, design for precision

1 INTRODUCTION

Design of heterogeneous systems demands considering contradictory requirements: e.g. high dynamics on one hand and high precision of the movement in positioning systems on the other hand. An aim that has to be achieved at the same time is the minimization of mutual interfering influences between the subsystems [1]. Following the stages of the design process, the first opportunity to minimize these mutual influences is the choice of a suitable function topology.

In the following, function topology is understood as the first disposition of the overall function. This results in a description of a technical system reduced to its basic sub-functions and their couplings [2] and can be comprehended as a form of basic function-structure. A functional coupling is a point of transmission of functional characteristics. During embodiment, every functional coupling is realized by at least one structural coupling.

It is precision engineering in particular that aims for highly dynamic systems with sub-micron accuracy and therefore requires a way of handling complex structures of heterogeneous sub-functions to reduce the effects of disturbances [3].

Often it is not only necessary to optimize the embodiment design of couplings, but also their number and arrangement in order to optimize a system.

Considering function topology offers the opportunity to identify the number of couplings in a heterogeneous system. Thus a pre-estimation of the lowest mutual influence of sub-systems and the selection of a favorable basic structure, depending on previously selected sub-functions, is possible.

2 THE POTENTIAL OF FUNCTION TOPOLOGY FOR OPTIMIZING HETEROGENEOUS SYSTEMS

To manage the huge number of occurring trade-offs during development of heterogeneous systems, the design process often follows a systematic approach utilizing various simulation tools and methods, e.g. MBS and FEM. These methods and tools are used to test the behavior of a system with the aim of optimizing it at an embodiment design level. The potential of optimizing the arrangement and number of couplings on a function-structural level, however, does not attract attention. Since couplings always cause power dissipation, a decrease of stiffness and affecting mutual influence between sub-systems in a technical system, it is essential to take them into account during the design process [4].

Especially in the field of precision engineering, which is concerned with repeatability and uncertainty in the range of micrometers or sub-micrometers, the possibilities of optimization in embodiment design (e.g. design principles) are limited by the basic structure of the system [cp. 5]. The particular problem of handling couplings in the course of simulation is still subject to current research.

The aim of the examination of function-topology is not to improve or change the quality of couplings which could be done by the tools mentioned afore, but to choose an appropriate arrangement and number of functional couplings which determines the necessary linkages within a system. Such a choice of arrangements offers more prospects within the embodiment design stage of design process.

3 APPROACH

Every technical system consists of elements and the relations of these elements. The relations can be divided into arrangements and couplings of elements (Fig. 1). In terms of function-topology, the elements are regarded as function-elements and the couplings as function-couplings. Regarding embodiment design, the elements are parts and sub-assemblies, whereas the couplings are called linkages. [2, 6]

The task of a function-coupling is the transfer of a function variable, thus every coupling in the function-topology appears to have at least one corresponding coupling at the level of embodiment. The number of necessary functional couplings depends on the system, its heterogeneous sub-systems and their couplings, as shown in the example.

The assignment of heterogeneous subfunctions follows the design principle of function separation [3] and is aims to max out the potential of a substructure with respect to a particular sub-function.

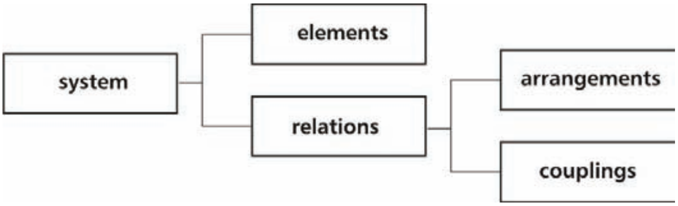

Figure 1. Setup of a technical structure

The minimum number of couplings that are necessary in a heterogeneous system is given by the couplings between the single heterogeneous sub-systems. This number can be specified by setting up the function topology. By changing the function-topology, the number of couplings between the respective sub-functions can be changed and thereby improved with respect to particular requirements – e.g. a large number of couplings to attenuate the detrimental influence between sub-systems or a small number of couplings to increase the rigidity of the whole system.

4 EXAMPLE – PLANAR POSITIONING SYSTEM

A typical example of a heterogeneous system is a multi-axis-actuator like a three DOF (x-y-φ_z) planar positioning system. Such systems are typically applied in semiconductor industry and laser machining.

In the case of positioning systems, the heterogeneous systems fulfilling disparate functions are the machine frame, the actuator- and measurement systems.

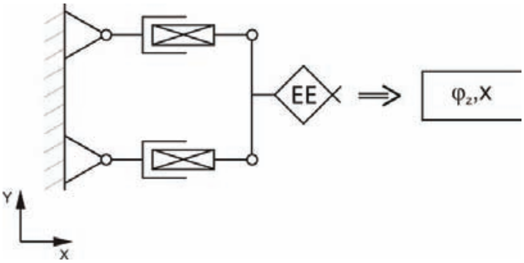

Figure 2. Differentiation between actuator and drive-system; a two-linear actuator mechanism results in a (x, φ_z)-drive-system

Due to the requirements specified by particular applications and restrictions like operating volume, acceptable footprint, positioning or measuring resolution, there is no categorically optimal solution for the function-topology of a system. The common evaluation of these criteria enables the choice of suitable structures, but does not allow a comparison of solutions. A planar positioning system can be realized by various designs (cp. Fig. 3) with different numbers of actuators and kinematics-structures while their function topologies are comparable (cp. Fig. 3 I, II; parallel (x, y, φ_z)-drive system; Fig. 3 III, IV serial (x, y, φ_z)-drive system).

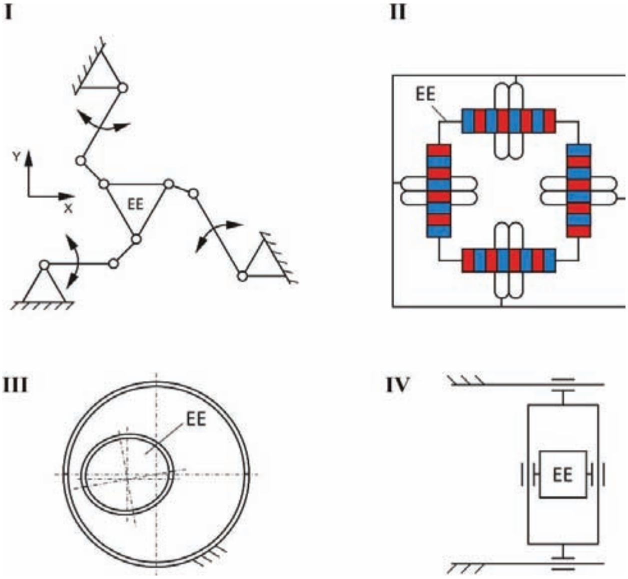

Figure 3. Potential planar positioning systems
- *I) parallel-mechanism with 3 rotary drives,*
- *II) electro-magnetic direct-drive-system,,*
- *III) serial-mechanism with rotary drives,*
- *IV) serial-mechanism with linear drives*

Crucial requirements for precision systems like thermal and dynamic rigidity are mainly dependent on embodiment design and are currently not taken into account at early stages of the design process. This

results in time-consuming back-steps during the design process including fundamental changes of technical principles aiming to change arrangements, number and embodiment of couplings.
To realize a three DOF planar positioning there are many different supposable structures. According to the predefinition of function-topology, the quality of actuators is not taken into account. Coarse-acute-drives, kinematics, etc. are generalized to an actuator of one (or multiple) DOF.
In order to adapt a function-topology, existing restrictions of valid arrangements have to be formulated.
The general method and formulation of restrictions, developed on the basis of a planar positioning system, will be carried out below.

5 METHOD

The basic assumption of function topology is the existence of heterogeneous subfunctions that can not be unified. Other couplings to different subsystems than the considered ones (e.g. control systems, see the example) are not taken into account. Albeit the existence of feedback loops between the heterogeneous subsystems have never been discovered they should also be feasible by the algorithms. Subject to these limitations, the arborescent structure can be transformed into linear structures with different levels (cp. Fig. 4) enabling an algorithmic treatment.
In order to adapt the topology of function-elements intended to fulfill a given function, the following algorithms were set up to determine all structures (without redundancies) that can be compiled from a given multiset (a set allowing arbitrary multiplicities of its elements) of sub-functions (e.g. actuating and measurement), and to count the emerging couplings on the level of function-topology in each solution.
Since there are six DOF to be incorporated by a positioning system, the actuator- and measurement-sub-functions consist of 6 different elements each: the translatory x- y- and z-elements and the rotatory elements φ_x, φ_y, φ_z

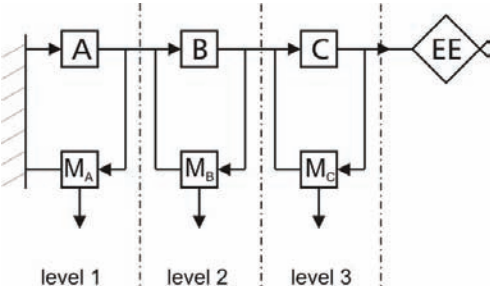

Figure 4. Transforming into linear structures

The first algorithm reproduces the entirety of possible structures of any given multiset L of single drive systems. It requires the input of the mentioned multiset L and the minimum number of single DOF-specific drive systems coupled to the base frame. There are technical (formulated in chapter 6) and mathematical restrictions that can be checked to assure that the given multiset can be used to build an expedient structure. To generate the complete solution space, the algorithm implements a recursion, utilizing combinatorial laws.
Any two subsystems occurring in a structure of a positioning system can be put into base-follower-relations, answering the question whether one of them is moved along by the other one. If a subsystem is not moved along by any other one, it is directly coupled to the base frame. If one subsystem is moved along by the same subsystems as a second one, and none of the two moves the other, they will be said to be placed on one level with respect to the base frame.
Since putting two similar actuators on the same level would cause a redundancy, every level contains at most six elementary drive systems. That is why a whole structure will be built up from substructures of six elements each.

First, the solution spaces for $|L|=1, 2, 3$ are listed manually according to the restrictions (the entire list is provided in the detailed description) to start the recursion. For $|L|=4,5,6$, the entirety of arrangements of $k=|L|$ drive systems is built upon the underlying solution spaces for $k-1$ elements, considering any combination of $k-1$ elements of the given k-set and coupling the remaining element to each of the $k-1$-solutions, according to the mathematically formulated restrictions that are set up to avoid redundancies.

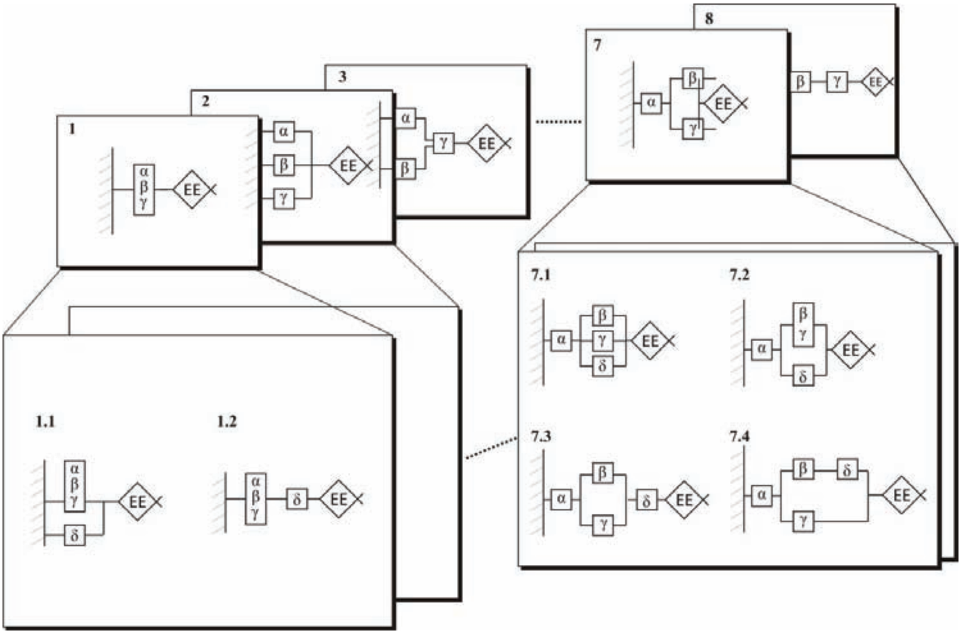

Figure 5. Visualization: Building up four-element substructures from three-elemented ones

As mentioned above, the cardinality of L is represented as $k=6r+s$ $(s<6)$. A complete solution is composed of r sub-structures containing six elements each and one sub-structure of s elements after the complete classes of 6-elemented and s-elemented structures have been set up.

The algorithm processes the complete list of 6-elemented structures, checking whether their first levels contain the minimum number of drive systems to be coupled to the base frame and whether the respective multiplicities of the contained drive systems still allow building up the complete structure from L, reduced by these elements. Having found a first building block, the second is searched for, starting over with the complete list of 6-element structures. (The requirements the next building block has to satisfy are put up at every single stage of the recursion.) This step is iterated until the last block is searched among the s-elemented structures if $s>0$. If no next building block can be found in the whole list of 6- or s-elemented substructures, the last block is removed from the currently built-up structure, and a substitute is searched for among the structures not tried out at this stage yet.

The multitude of arrangements arises from the possibility of joining single drive systems together, given they are placed at the same level. Again, this possibility is constrained by the requirement of generating non-redundant composed drive systems.

While the solution space for any multiset of single drive systems is completely determined by the first algorithm, each of the found solutions permits a variety of arrangements of its respective measurement systems. A measurement system can be placed at the same or any lower level as the associated actuating element (since it should not be moved along by its associated drive system). In addition, some arrangements of drive systems allow certain rearrangements of their measurement systems, still expanding their variety.

Since more than six measurement systems can be gathered at one level and joined together arbitrarily, the second algorithm starts out with a structure joining all measurement systems at the lowest level. Then, measurement systems belonging to drive systems at higher levels are placed at the respective levels successively, starting out at level two. After such a “raising” step, all possible variations of the new arrangement of measurement systems are generated, leaving each system at its current or a lower level.

In order to determine favorable structures with respect to the amount of couplings between two elements (which may be single drive systems or measurement systems, respectively), the numbers of couplings between every two elements is determined and logged in a matrix for each structure constituting a solution or partial solution. These matrices evolve from each other throughout the successive development.

Due to the fact that the algorithm provides only the number of couplings between subfunctions it is up to the designer to decide whether he is aiming for a large or small number of couplings, depending e.g. on his wishes to increase rigidity which makes a reduction of the number of couplings recommendable, or to attenuate retroactive effects between subsystems which makes it preferable to raise certain distances.

6 PARTICULAR RESTRICTIONS FOR POSITIONING SYSTEMS

The following rules restrict the arrangements of actuators. Some of them are technical formulations of the constraints already mentioned. Others are induced by the quest of avoiding redundancies:

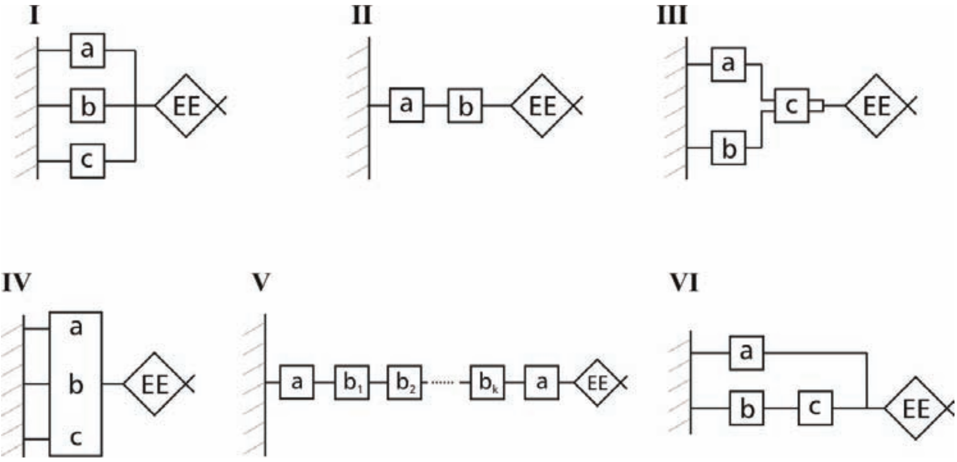

Figure 6: I) Parallel arrangement of drive systems
II) Serial arrangement
III) Parallel arrangement at the first level with a single drive system at the second
IV) Joint actuators in a composition
V) Serial arrangement with two homonymous translatory drive systems
VI) Bypass

1. Only parallel or serial arrangement of actuators are allowed, so the elements form “levels” (Fig. 6 I) to III))

2. Only actuators of disparate kinds appear at each level, so that there are at most 6 single actuators per level. (Cf. Fig.6: *a, b, c* stand for the translatory and φ_a, φ_b, φ_c for the rotatory actuators. Equal letters stand for equal axes.)

3. Separation of translatory actuators (Fig.6 V)): Between two homonymous translatory actuators, there must be at least one level containing a rotatory actuator different from φ_a (φ_b or $\varphi_c \in \{b_1, b_2, \ldots, b_k\}$

4. Possible arrangements besides levels: Bypasses (Fig.6 VI))
   Actuator *a* must be translatory. The actuators *b* and *c* are either:
   - Translatory, different from each other and from a
   - Rotatory and equal to φa
   - One is translatory and different from a, the other one is equal to φa

5. Chains: Let *a, b, c* be the translatory and $\varphi_a, \varphi_b, \varphi_c$ the rotatory actuators. (Fig. 7 I)-VI))
   - In chains of the 1st and 2nd kind, *b* and *c* can also be placed at lower levels arbitrarily and independently of each other.
   - In chains of the 3rd, 4th or 5th kind, *c* can be placed at any lower level.
   - In chains of the 6th kind, φ_c can be placed at the lower level.
   - Chains of the sixth kind can be adhered to any chain of the 3rd, 4th or 5th kind with the two *'c'*s merging together. Hereafter, *c* can be placed at any lower level, or φ_c can be placed at the level of *c*.

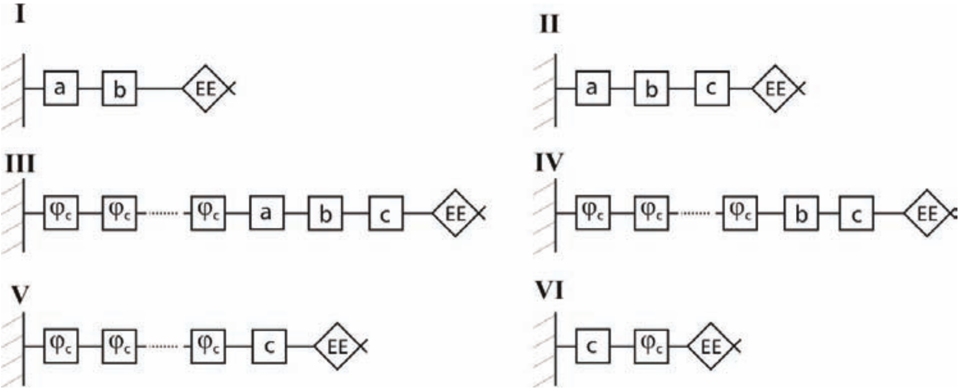

Figure 7: Chains
I) Two different translatory drive systems
II) Three pairwise different translatory drive systems
III) Three different translatory d. s., adhered to a chain of homonymous rotatory ones
IV) Three pairwise different translatory d. s., adhered to a chain of homonymous rotatory ones
V) One translatory drive system, adhered to a chain of homonymous rotatory ones
VI) Coupling of a translatory and the homonymous rotatory d. s.

Restrictions for structures of measurement systems:

1. Each measurement system can be placed at the same or a lower level as the respective actuator.

2. Measurement systems can be combined in composed measurement systems without any restrictions.

Assuming that any of these replacements has been done, arbitrary combinations of actuators can be carried out.

7 CONCLUSIONS

By topological analysis the solution space for arbitrary systems of actuators can be covered holistically on the basic level. Consideration of function-topology enables a systematic search for structures of subfunctions with minimal mutual interference. The innovation gained by the presented method is the possibility of estimating the potential interferences of heterogeneous subfunctions and evaluating a huge set of alternatives which can be done by an evaluation of the arrangements and the number of couplings.

This enables a choice structures with a minimal number of couplings that can minimize disturbances on a function-structural level or invariant structures if the complete independence of subsystems is possible.

A further evaluation of heterogeneous systems requires the knowledge of characteristics that depend on the properties of particular embodiments.

The utilized algorithm is extendible to systems containing different heterogeneous subsystems, whereupon the complexity of the structure can be estimated from below by evaluating the number of couplings within a system.

For one exemplary positioning problem (X, Y, Z-translatory movement) the method yields 610 different possible arrangements of three translatory drive- and measurement-systems respectively and provides the numbers of all couplings between any two elements throughout all possible arrangements.

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