ACTUATION PRINCIPLE SELECTION – AN EXAMPLE OF TRADE-OFF ASSESSMENT BY CPM-APPROACH

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ABSTRACT
The generation of motion is a task of many technical systems. Customized drive systems constitute a challenge to the selection of a suitable actuator during the development of drive systems. Common approaches and tools for actuator selection are limited to the selection of known actuators from a database. However, especially in cutting edge technology conflicts of requirements complicate the selection of a suitable actuator or even actuation principle.
This paper uses the CPM / PDD approach to describe a concept of visualizing the properties and characteristics of actuator-principles in order to identify potential for an influence by the designer. Based on the context of precision engineering, measures to meet conflicting objectives and to identify convenient characteristics for adaption as well as limitations of the proposed approach are discussed.

Keywords: decision-aid, requirement management, CPM/PDD, actuator selection

1 INTRODUCTION
Motion generation is an important function in many technical systems. Various environmental conditions and the variety of the required movements result in a trend towards automation and an increasing number of tailor-made drive systems. By using a suitable control system state-of-the-art gear-less-drives allow almost every motion pattern without using further transmission components, e.g. gears or mechanisms. Therefore, the task of selecting or designing an actuator, which is optimally adapted to the given requirements, is an important task for engineers developing drive systems.
Although all relevant actuation principles are scientifically well characterised and rule sets are available for their design, in practice early ad-hoc decisions for this central component are often made purely based on preferred options and/or experience from previous cases; a systematic search through the entire range of potential solutions is usually not done. This is despite the fact that requirements of the actuator can vary considerably from one case to the next, depending on the application (i.e. motion range, environmental restrictions) and that some requirements may be difficult to formulate in a general manner at all (cost, reliability of supplier, etc.). A careful actuator selection is of particular interest in cutting edge technology, such as low cost automation, high precision engineering or micro systems engineering.
This paper refers to drive systems in the field of precision engineering, which are based on electrical and electromagnetic actuators. In this application area, the achievement of a specific resolution or repeatability is often more important than cost reduction. Trade-off assessment is of particular interest since the additional implementation of other requirements (holding force, performance in high magnetic fields, self-heating, aspect ratios ...) is often decisive. The required parameters are properties of the actuator system and can only be determined by the development engineer via changing the material and/or geometrical characteristics of the potential actuator.
The distinction between properties, which can only be influenced implicitly, and characteristics, which can be affected directly by the designer, is the foundation of the CPM/PDD-approach [1]. The existing (as said: generally well investigated) descriptions allow mapping the characteristics of an actuator to the its properties, i.e. they model the relations between the two, which, according to the CPM/PDD approach, are crucial for the development process..
The intention of this paper is to integrate existing knowledge on actuator principles into the CPM/PDD framework in order to make actuator evaluation and selection (and development???) better structured. This approach does not address actuator developers but design engineers who intend to evaluate and select an actuator principle for tailor-made drive systems –who are expected to have some overview knowledge of (some) actuators and actuation principles. The purpose of the approach is to provide

these engineers with a method for the qualitative comparison and assessment of actuation principles referring to conflicting requirements during conceptual design stages. With regard to the context of precision engineering, the mapping concept will be presented with a view to the selection of actuation principles. The difference between actuator and actuation principle selection will be highlighted and limits as well as conclusions referring to the concept of actuation principle selection will be discussed in this paper.

2 ACTUATION PRINCIPLE SELECTION VS ACTUATOR SELECTION

In the process of designing a drive system, the engineer has to decide between using an *actuator*, which is available on the market, or developing one independently (often with the assistance of a specialised supplier), based on a common *actuation principle*. Actuators are usually selected from a convenient database – i.e. a paper or software-based product catalogue.

There are different approaches and tools to support actuator selection. A practical solution for this problem is the one proposed by HUBER [2]. He adapted the concept of the *material selector* software [3] and applied it to actuator selection. This resulted in a number of particular ratios/indicators of actuator properties, which are called *performance indices*. Working ranges of various actuation principles can be visualised according to the required quantitative performance indices.

Proposals for software-based implementations are delivered by [4] and supplemented by a *Skyline/ Pareto* based approach of visualisation in [5].

The main advantage of the *material selector* based approach is a small amount of required data sets (suitably distributed) to give a representation of the working space of different actuator principles. However, the range of properties in the application area of actuators is larger and depends on the actuator principle, which also makes it more heterogeneous than the one of materials. The dependencies between the individual parameters are only given implicitly. In addition, two-dimensional graphic representations lead to the assumption of a direct one-to-one dependency, which does not exist in that manner. The number and complexity of inter-dependencies between actuator properties vary according to the actuation principle. Furthermore actuators, which are capable of working in the same operating area, are in many cases characterised by distinct and not directly comparable qualitative properties.

Another approach was described by EGBUNA [6], addressing the actuator selection in the context of low-cost automation. He proposed a qualitative actuator selection based on a subtractive rule set. The actuator selection support is focused on cost comparison, for low-cost automation on the basis of lifetime-relative costs. Although low-cost automation and precision engineering are different application fields, the approach is, in principle, also applicable for precision engineering tasks.

Both approaches focus on the selection of existing actuators, leading top a sort of interactive product catalogue. That is why those are of limited use for the estimation of trade-offs in the development of new actuators.

While EGBUNA’s approach enables the selection of actuators with respect to qualitative and quantitative parameters, it is impossible to search beyond the solution space of given data sets. By contrast, HUBER’s approach allows interpreting the distances between the required quantitative parameters and the “working area spots” of known actuators.

In both approaches described, the actuator selection is conducted by providing an overview of many different actuators represented by numerous (ideally arbitrarily selectable, but not yet fully implemented [5]) properties. For actuation principle selection, however, it is necessary to represent the influencing options and their influence on the required properties. This involves an at least qualitative model of the dependencies of the properties for different actuation principles.

3 CHARACTERISTCS AND PROPERTIES SUBJECTED TO ACTIVE PRINCIPLES

The CPM/PDD approach proposed by WEBER (e.g. [1], [7]) addresses two fundamental aspects of the theory of technical systems:

- *Characteristics-Properties Modelling* (CPM) as an approach for the modelling of technical products using its properties and characteristics, and
- *Property-Driven Development* (PDD) as a process model for the development of technical products based on their properties and characteristics.

The CPM/PDD-approach is still subject of ongoing research. Therefore, different distinctions between the terms properties and characteristics as well as between implicit/indirect/dependent and explicit/ direct/independent can be found in articles of various authors (cf. Tab.1).

Table 1. Selection of different definitions for the terms “property” and “characteristic” with respect to the influence of the designer.

Author/Reference	can be		Comments to the term definition
	directly influenced by the designer	not directly influenced by the designer	
WEBER [6], [8]	Characteristics	Properties	Characteristics as like properties are generally defined and not limited to physical products
HUBKA [9], [10]	Elementary Designproperties	External properties	Structure and behaviour are considered as properties, attribute and property are alternative terms and considered as a subset of characteristics
EEKELS/ ROOZENBURG [11], [12]	intensive properties as the sum of physio-chemical form and geometric shape	Extensive Properties	Extensive properties are often associated with a "property pattern". This "pattern" sums up both the properties and their dependencies. (see also [15])
EHRLENSPIEL/PONN/ LINDEMANN e.g. [13]	Direct Properties Consistance Characteristics Relational Characteristics	Indirect Properties Functional Characteristics	„Distinguishing“ properties are called characteristics, they have a meaning (quality) and an expression (quantity)
SUH [14]	*„design parameters“* basically – to a limited extend – as well as the dependencies of the *“design matrix“*	*„functional requirements“*	Proposed by SUH the "axiomatic design" approach is not restricted to the domain of mechanical engineering resulting in application dependent „parameters“ and „requirements“
BIRKHOHER/ WÄLDELE [18]	Independent properties	Dependent properties	The difference between independent and dependent properties is used to discuss product models, development processes an supporting tools

Essential for WEBER is the distinction between properties (only indirectly assignable by the designer) and characteristics (directly assigned by the designer). Furthermore, he describes the behaviour of a technical system as the sum of its properties.

For further discussion, the term distinction by WEBER [1] is used. According to the CPM/PDD-approach and this distinction the analysis of a product can be understood as the determination of its properties (P_i) by the characteristics (C_j), and its synthesis as the determination of its characteristics by the properties (Fig. 1) [1].

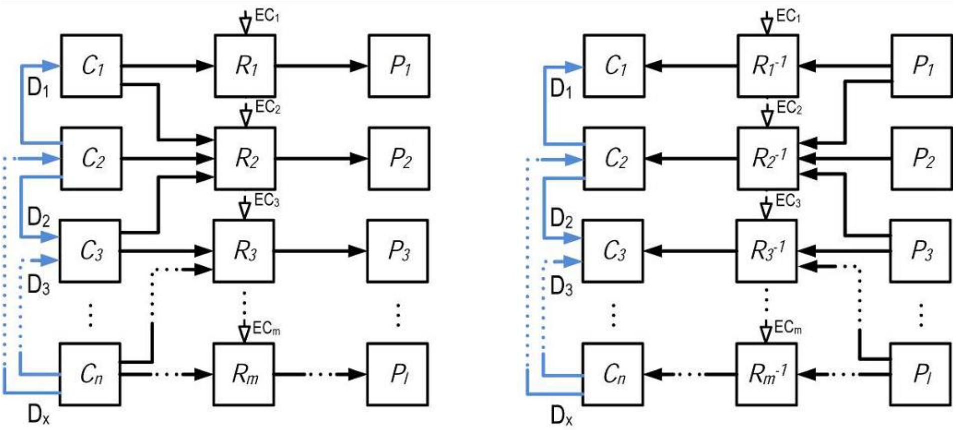

Figure 1. Types of relations in the CPM/PDD-approach. The arrows represent the determination of properties by characteristics in the case of the analysis (on the left) and vice versa (on the right) in the case of the synthesis of technical systems (cf. e.g. [1])

The determination can be displayed by relations (R_k, R_k^{-1}) and is, besides the characteristics and the properties, dependent on external conditions (EC_k). In addition, there are dependencies (D_x) between the characteristics themselves.

The essential challenge of the theoretically powerful CPM/PDD-approach is the identification of the relations (R_k^{-1}) in the process of the synthesis. The main reason is that the properties, which the designer attempts to achieve, are the effects of the characteristics. Since it is impossible to conclude from the effect to the cause unequivocally, the synthesis process is undetermined. Moreover, usually only a few properties of the ones required of a product are given from the beginning. Specifying only a few properties – requirements and definition of other "means" of the product in general – results in a reduced model of the intended behaviour (this again can be understood as the purpose function, cf. e.g. [12], [15], [16]).

Another difficulty is to create a manageable CP-model. The attempt to create as unambiguous relations (R_k, R_k^{-1}) as possible would result in an impractical and complex map of physical interactions. Thus, the set of relationships needs to be limited to the required ones instead of expanding it.

The consideration of actuator principles, however, allows building different models of properties/ characteristics-relations of each actuator principle on the basis of existing descriptions.

4 CONFLICT OF OBJECTIVES DURING ACTUATOR DESIGN

Transforming non-mechanical (usually electrical) energy into mechanical energy of motion is the purpose of a drive system and its basic function is precisely defined prior to the selection or design of an actuator. The parameters listed below represent the basic requirements (properties) for a general actuator system and are predefined in the beginning of its design process:

- mode of motion (limited or unlimited),
- direction of motion (reversible or non-reversible),
- degree of freedom (DOF) of the actuator (between 1 and 5),
- type of motion (rotational or translatory),
- ability to maintain position without actuator energy supply and
- (effective) power output

In particular cases all these requirements have to be fulfilled, so that they cannot be a differentiating criterion for the actuator or actuation principle selection.

The first step during drive system design is to search for existing actuators (e.g. via the actuator selection tools). If no existing actuator meets the requirements, the cause could be that (cf. change request types in CPM/PDD, [17]):

- a different set of required properties,
- different external conditions or
- different (direct) restrictions of characteristics

are given in this particular case.

The option of the designer is developing an existing actuator into the region (cf. "working area spots") of the new required properties/external conditions. As stated before, this can only be accomplished by modifying the *Gestalt*-characteristics – the sum of the geometry, material and their state (e.g. magnetisation, hardness, tolerances …).

However, if properties/external conditions cannot be met in this process, conflicts will occur. According to PDD a "conflict" exists, if in order to achieve a required property (or properties) one or more characteristic(s) are modified and this change leads to a deterioration of one or more other required property/properties, which in turn can not be compensated by changing other characteristics (cf. [17]).

If there are several actuation principles that can be developed to meet the given requirements, this may lead to different conflicts in each case; the task is then to identify the most promising actuator principle without having to detail all options. What *promising* means can be rated on the basis of:

- the type of characteristics eligible for an adaption (size, material or condition of the latter)
- the relative magnitude of adaption of eligible characteristics (also dependent on the type of relation, e.g. linear, logarithmic, cubic, ...)
- the absolute magnitude of the eligible characteristic itself (e.g. hardness, modulus of elasticity but also the grain size with respect to magnetisation are physically limited).

for each potential actuation principle. The assessment itself depends on the set and types of requirements; besides that, physical boundaries, technological capabilities, lot sizes, technical periphery etc. have to be taken into consideration.

5 USE CASE – EXAMPLES AND OPPORTUNITIES TO SOLVE TRADE-OFFS

For the purpose of a simple representation, the CPM model was rearranged. The aim was the separation into input and output parameters, as it is common for actuator representations. The parameters are separated with respect to the forms of energy, as shown in Fig. 2 and Fig. 3 for electro-magneto-mechanical and piezoelectric actuators.

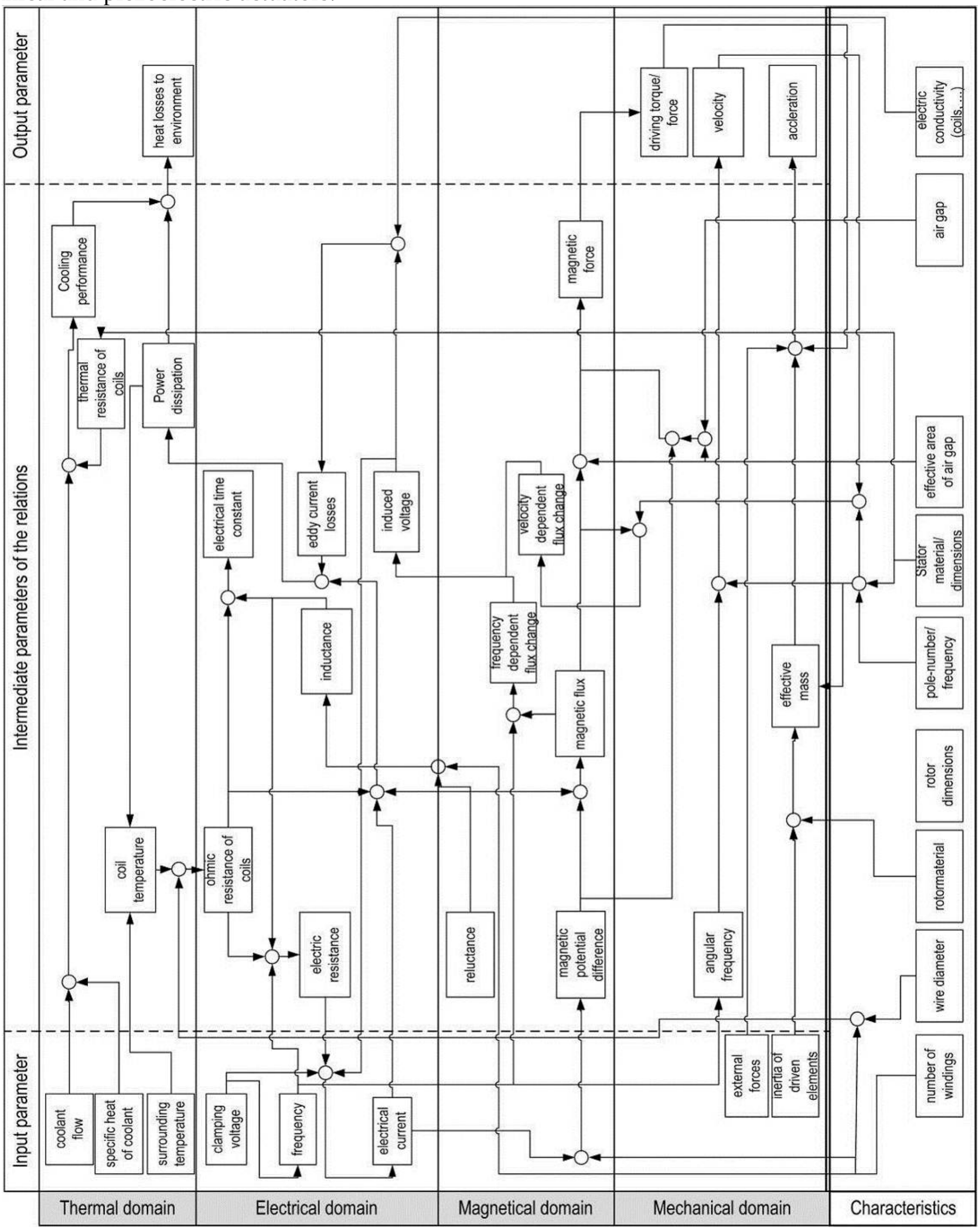

Figure 2. Electro-magnetic actuator-model arranged in order to distinguish input and output parameters as well as characteristics

Because of the different energy domains the models of electromagnetic actuators (Fig. 2???) appear to be more complex than the ones of other actors which internally do not have further energy conversions (apart from the basic one between input and output energy and omnipresent heat losses).
The task is to identify for which potential actuation principle(s) it is, in order to satisfy particular requirements (required properties), easier to make changes to the characteristics without compromising other properties.. The proposed model helps to illustrate the dependencies qualitatively and visualises the required changes of characteristics to achieve the desired properties and - vice versa - the qualitative impacts of changes of characteristics on other properties.

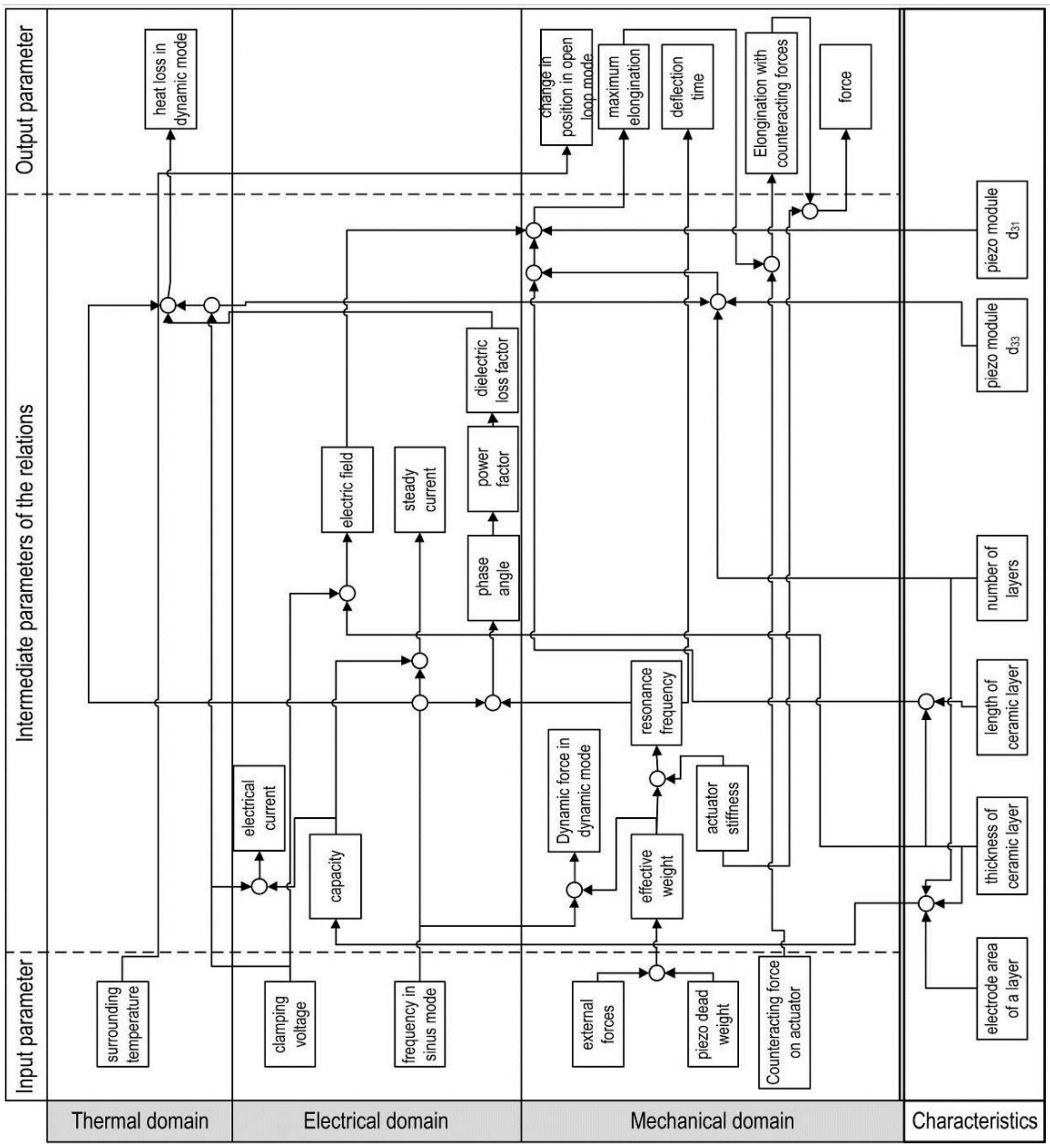

Figure 3. Piezo-actuator-model arranged in order to distinguish input and output parameters as well as characteristics

Based on the property or characteristic that has to be changed, the effects can be mapped comparably to a cascade or chain of opportunities. By using fuzzy (+ +, +, 0, -, --) correlations, a rough estimate of the impact can be made (Fig.4).

The necessary changes to achieve the particular (set of) requirements are dependent on the actuation principle.

Because relations between characteristics and properties are fixed by the actuation principles the conflicting objectives can only be resolved by:

- changing dependencies (resulting in a new actuator configuration; e.g. piezo, piezo-stack, inch-worm drive, …),
- redistributing requirements of the drive system (e.g. using a coarse-fine drive concept instead of a direct drive or to use yet a gear),
- changing characteristics (by extending the scale of the parameter set – e.g. change materials; ferrit to neodymium) or
- weakening the requirements of the particular actuator (appears at first sight preposterous, but is sometimes the last resort).

An alternative strategy could be considering the above listed measures starting from the bottom: In most practical cases, the development of a new actuator configuration is, due to the complexity of the required special knowledge, the least preferred option and usually not viable for an unexperienced designer.

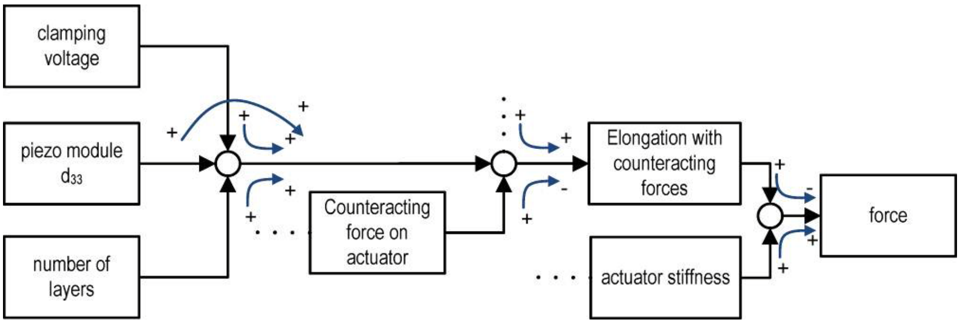

Figure 4. Qualitative correlations for the estimation of the impact of changes of characteristics; exemplified on the piezo actuator-model (reduced)

Whether and when requirements can be redistributed or weakened depends on the particular case. As the decision on the suitability of an actuator can be reduced to:

- the applicability of the type of energy conversion itself (magnetism, heat, etc.) or
- ratios between properties and characteristics (specific sizes, densities, stiffness, aspect ratios etc.)

the starting points for the evaluation of the suitability of an actuator principle are physical or technological limitations. Changing characteristics is (physically) limited, which must be considered. For example, the density of functional materials (e.g. transformer plate metal, piezo ceramic) can not be reduced easily to half of the original value. Also, air gaps in the nm range are technically hard to achieve.

6 DISCUSSION AND CONLUSIONS

The intention of the approach presented in this paper was to give the designer the opportunity to identify his/her options of influence on a known actuator design with respect to new requirements and not to give design rules for developing new actuators from scratch. It provides a supplement to the existing actuator selection tools and approaches. Approach and measures how to meet conflicting objectives were discussed. However, general rules for suitable trade-offs are hard to formulate due to the variety of possible sets of requirements.

The proposed model represents the relations between characteristics and properties for a special type of technical solutions - actuators. This was possible because the relations are well described for most of the actuation principles. Basically a comparable approach is conceivable for other application areas where a large number of potential solutions exists and the solutions are well understood and described.

The presented approach seems to be similar to a design structure matrix, but differs in purpose and use. The purpose is the assessment of the accessibility of outputs by quantitative changes of characteristics in the early design stages. For this purpose, either the characteristics influencing the desired outputs are determined or the impact of the changes of characteristics on the output values can be estimated. Changing the structure - if possible at all - is, however, reserved for specialised actuator developers.

The reasoning shown allows the designer to identify convenient characteristics and to assess them on a qualitative basis. A quantification of individual dependencies by using appropriate literature is possible.

Ongoing research will be focused on software implementation and interlinking of the models of different actuation principles and how to link them to (existing) actuator/design catalogues. The implementation of mathematical equations for the relations to support the decision making process is also subject of current research. Linked to that, an important question is which benefits the calculation can offer, using the values of parameters known in the early stages of the design process.

In the future the systematisation, the study of physical and - if possible - technological limitations as decision-making criteria is of particular interest. In this context, recent investigations suggest that the consideration of scaling effects is very important, too.

Physical and technological limitations (e.g. ceramic grain sizes, magnetic/Weiss domains, heat losses …) are non-linear relationships and can affect the decision model significantly, especially in the design of microsystems. Although the models presented here are still valid, the extent of the influence of these limitations will be subject to further investigations.

ACKNOWLEDGEMENTS

The authors would like to thank the members of the Collaborative Research Centre 622 “Nanomeasuring and Nanopositioning Machines” and the German Research Foundation (DFG) for their support.

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