INTERNATIONAL DESIGN CONFERENCE - DESIGN 2010
Dubrovnik - Croatia, May 17 - 20, 2010.

DECISION-AID FOR ACTUATOR SELECTION

T. Erbe, T. Stroehla, R. Theska and C. Weber

Keywords: decision-aid, requirement management, knowledge-intensive design, actuator-selection

1. Introduction

The generation of motions is a crucial task of technical systems. The trend of automation results in an increasing number of customised actuator systems. State-of-the-art gearless-drives are able to realize almost all motion patterns which previously necessitated drives in combination with transmission components, e.g. gears. The great advantage of gearless-drives is the simplification of the kinematic chain. This allows to shift piece costs from kinematics to development costs of easy (since inexpensively) producible control algorithms and control electronics. The trend towards the more prevalent use of gearless-drive systems will lead to price reductions of digital control-systems and electronics which go along with adaptability and frequently with a mass reduction [Kallenbach 2007].

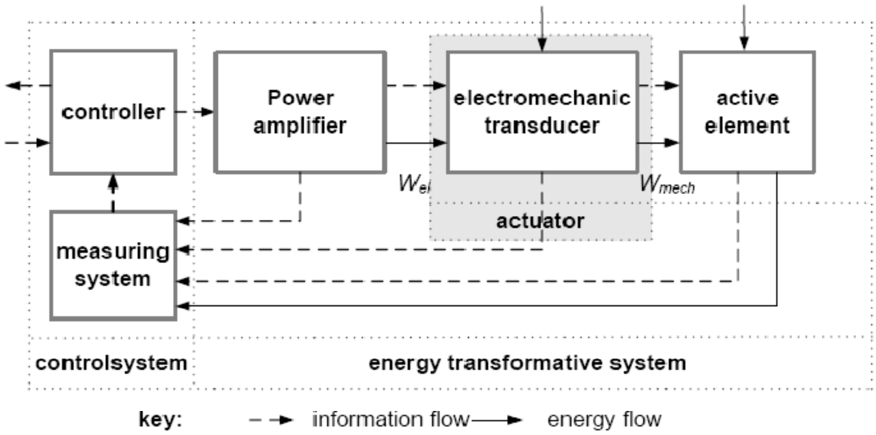

Figure 1. Structure of a gearless-drive system [Kallenbach 2008]

During the development of drive systems, the objective of the engineer is to select an actuator optimally suiting the given requirements. Depending on the application, these requirements can consist of a large variety of hardly comparable criteria like cycle time, efficiency, available space, vacuum-fitness, etc. This demands focusing on the important properties and the handling of inevitable trade-offs in the case of direct drives - not only of actuators, but basically of actuation principles .
The huge number of potential actuators and actuation principles as well as their respective properties and the inter-dependencies of these properties cannot all be considered at the same time by an engineer. Instead, the number of potential actuation principles, which are considered in more depth later on, has to be reduced as early as possible in the design process.
Though all actuation principles are scientifically well characterised and rule sets are available for selection and design, in practice, an early decision upon the central component is often preferred to

systematically searching the whole area of potential solutions. This can lead to suboptimal results if the engineer does not have applicable experience, deals with a novel product or market segment, if the actuator selection is based on design- or product-catalogues of individual manufacturers (and may in consequence be restricted to a few actuation principles) or if the actuator manufacturers have insufficient understanding of the specific design.
This becomes even more exigent if the design task is dealing with the cutting edge of present technology like ultra precision or low cost automation.
The research questions addressed in this paper are:

- How can principles of actuators be compared at an early stage of the design process?
- How can potential solutions be evaluated?
- Can actuation selection be supported by a design support tool and if so, how?

The selection method and tool presented in this paper are to be understood as an approach, not as a market-ready solution. The authors' focus is precision engineering dealing with positioning and high repeating accuracy in micro and nano scales. For this purpose, the main objective is to maximise the solution space and, to a lesser extent, to reduce the costs.

2. Actuator selection in the context of the design process

Managing and editing huge amounts of property data is a problem in different areas of engineering sciences. A well-known solution for this problem in a particular field of application is the *material selector* [Ashby 2006]. The basic concept of the material selector has been applied to actuator selection resulting in a limited number of particular ratios/indicators for all actuators and actuation principles.
Looking at the application area of actuators, however, the range of properties is considerably larger and much more heterogeneous than that of materials, as well as the number and complexity of inter-dependencies between those. In many cases, actuators capable of working in the same operating area are characterised by distinct and not directly comparable properties. Subsequently, the “vector” spaced by different properties is hyper-dimensional and extremely sparse. Due to this and due to the fact that only a small number of potential properties are specified at early design stages, two problems can be observed during actuator selection:

- Determination of multiple potential solutions without the possibility to evaluate them via the given requirements
- Determination of non-appropriate solutions without any information about possible alternative working principles that would almost suit the current requirements.

Currently, actuator selection is based on design or product catalogues of individual manufacturers. Most of them are specialised on particular actuation principles and drive system solutions like rotary drives. Basically, these catalogues inform about the performance spectrum of existing drives. The abilities of actuators are permanently improving, amongst other things by applying new materials with better properties. Most of all, new control systems and a permanently increasing amount of code that can be implemented into cheap micro-controllers enable considerable extensions of existing actuation principles.
In industrial applications, the catalogues mentioned above are often sufficient because the companies are interested in using existing, well-known and well-proven product lines, suppliers, support facilities, etc. In this manner they can use know-how built up over a long time (human resources, experiences) and non assignable properties like trust and reliability of the supplier.
The trend towards gearless-drive systems results in customer-tailored actuators, which allow the consideration of new and unconventional actuation principles like so-called smart actuators (e.g. piezo-, magnetostrictive-actuators, shape-memory-alloys, magneto- and electro-rheological-fluids, magnetic-shape-memory-alloys, etc.) or classical actuation principles beyond the common working range.
Furthermore, this necessitates a proper selection base for the best actuator, i.e. the one optimally suiting the given requirements, regarding technical constraints of all elements of the drive system, like power amplification, software, sensors, mechanisms and so on.

So far, there seems to be no support for the selection task. The huge number of requirements is difficult to handle, and the types and stocks of properties recorded in databases are often not comparable. The approach of the material selector is not adequate because of the heterogeneity of actuator properties (compared to those of materials). Furthermore, there is no approach to estimate new options of an actuator principle with regard to customer-tailored applications.

3. Concept of actuator selection

In order to establish a decision-aid, a new concept for actuator selection has been developed. The concept is based on:

I. a selection procedure based on
   - a classification via motion patterns and
   - a selection by an algorithm using the Skyline approach

II. a database with a sufficient amount of data sets, and

III. a frontend for the presentation of the results

The selection uses arbitrary parameters. Thus it allows to take different and – with regard to changes of specifications during the design process - varying parameters into account.

3.1 Selection procedure

The actuator selection according to the requirements, even if simplified to the selection of an actuation-principle, represents a multi-requirement optimisation problem (referred to as multidimensional in the following). The criteria are different in quality (e.g. installation space and degree of freedom) and values (e.g. different magnitude and unit of measurement) for which reason they can mostly not be converted into or compared to each other (fig. 2) [Erbe 2008].

3.1.1 Classification

In order to reduce the number of properties, the first step during the actuator selection is the classification by:

- 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) and
- ability to maintain position without actuator energy supply

The reduction of properties does not imply a loss of generality of the selection results. The parameters listed above present the necessary basics for any actuator system and are so called qualitative or discrete parameters. These parameters are defined from the beginning of the design process, as well as the required performance of the actuator. The use of this classification already restricts the range of actuation principles considerably; only those which are able to accomplish the required type of motion go to the next selection steps by means on quantitative parameters.

3.1.2 Skyline-approach

A holistic optimisation of actuator selection regarding all requirements separately is not feasible due to the fact that dependencies between them frequently result in contradicting trends during the optimisation.

A possible solution is the search for the set of optimal compromises. This set is called the Pareto-optimum (q. v. [Ehrgott 2005]).

For the interpretation of data-sets stored in a database, this method of finding the Pareto-optimum is often called Skyline-method, as explained in (Fig. 3a).

A Skyline $S(P)$ is defined by those points within a set which are not dominated by other points P. One point – a particular data-set in the database – is said to dominate another point if its performance parameter is better in at least one dimension and equal in all of the remaining dimensions (cp. [Papadias 2005]).

$$S(P) = \{P_x \in P \mid \nexists\, P_y \in P : P_y \prec P_x\} \tag{1}$$

The performance is rated by the vector of the weighted criteria. This is comparable to the Pareto-optimum relating to one single point instead of an area of a potential solution (Fig. 3a).
The optimum in the Skyline-approach is arranged in the point of the origin. The Skyline equals the minimum of weighted criteria. In the case of actuators it is possible, but not necessarily common that the minimum of all properties is required.

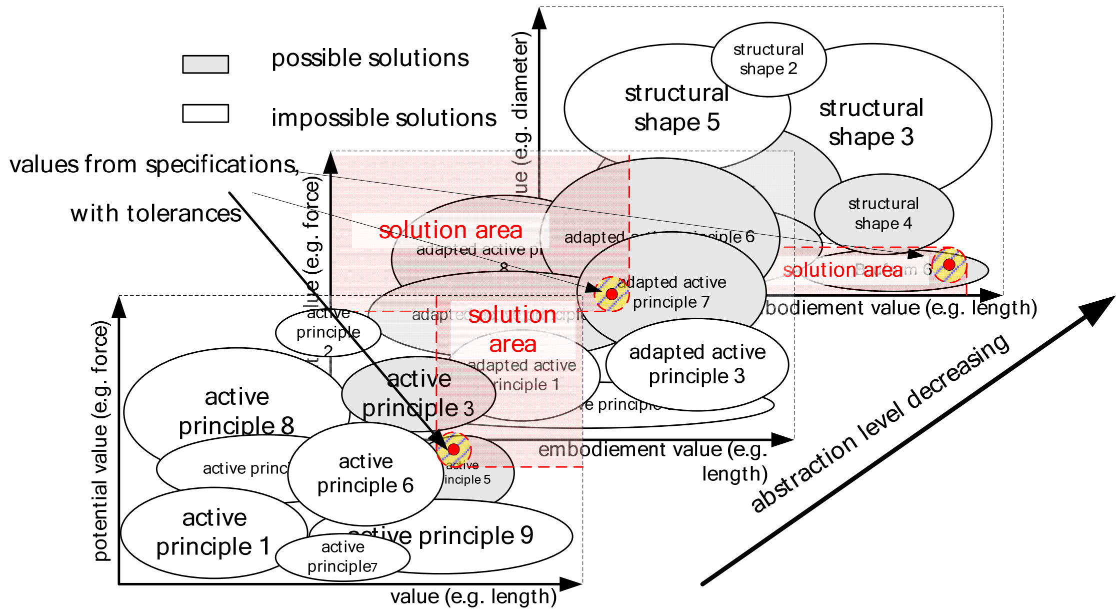

Figure 2. Visualisation of the concept. The diagrams in the chart represent cross-sections of the multi-dimensional vector space. In the implementing software, the optimisation is not done serially (cross-section by cross section), but parallel. The arrow symbolises the possibility to refine and adjust the selection-criteria during the design-process

Due to the fact that in the engineer's situation of actuator selection, concrete requirements are available, the optimum will not be the point of origin (that would lead to a minimisation of all requirements). A transformation of the hyper-dimensional vector space spanned by the requirements is not feasible because of the incomparability between those requirements in quality and quantity. By using another point than the point of origin as an optimum (Fig. 3b), requirements specified by discrete variables (e.g. circle-, square-, or rectangular shaped actuator cross-sections) can be taken into account.

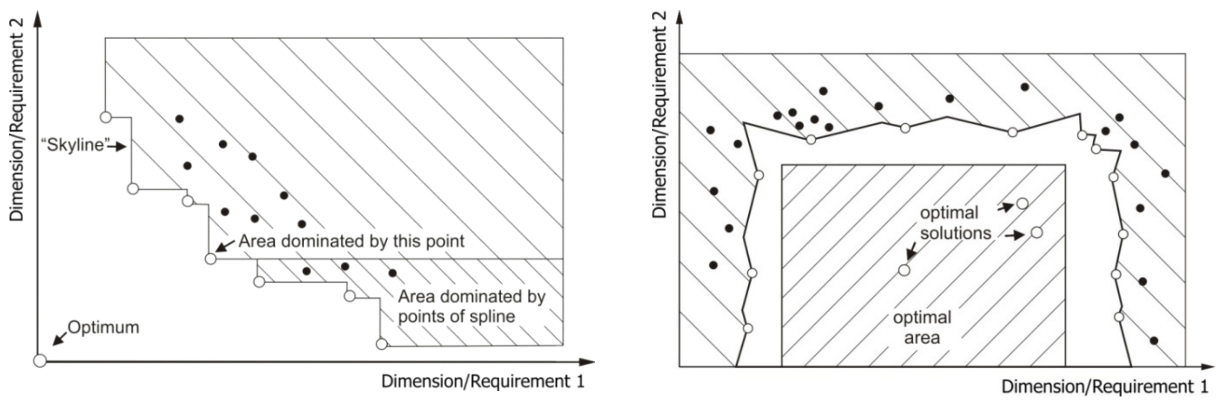

Figure 3. Illustration of a) the Skyline-approach, b) the "angle dominated" Skyline with requirement area/span

The boundary layer of areas of potential actuation-principles belongs to the result of the Skyline-approach. This is an advantage considering the fact that a great deal of actuation-principles with almost similar performance will not be displayed in a list of results during the selection. So, the result is a broad spectrum of different actuation-principles in contrast to an actuator-catalogue which may only deliver one.
Frequently occurring tasks are strict constraints to the solution space by requirements (e.g. value X, Y, Z above or below a certain value). This means that one point defines the boundary layer. Inside this area – i.e. matching the requirements – circumscribed by requirements, potential solutions (sets or subsets of actuation-principles) are conceivable.
The Skyline-approach can be extended by softening the dominance by a so called "angle of dominance". In a two-dimensional plot, this means that every point only dominates points beyond a certain angle referring to the requirements, which results in an "angle dominated" Skyline (Fig.3b).

$$P_x \prec P_y \wedge \left(|D_A| = 0 \vee |D_B| = 0 \vee \tan\alpha \geq \frac{\sqrt{\sum_{i \in D_A} (P_{y,i} - P_{x,i})^2}}{\sqrt{\sum_{i \in D_B} (P_{y,i} - P_{x,i})^2}} \right) \quad (2)$$

This is especially expedient if the angle of dominance is sensitive to actuation-principles. That means that solutions of the same actuation-principle will be more strongly dominated than those of alternative principles. This leads to two different angles of dominance, one for the own and one for alternative actuation-principles. This approach is further on called "two angle dominance Skyline".
With the two angle dominance approach it became necessary to scale the individual requirements (corresponding to "dimensions" of the mathematical formulation) with a weight vector. Otherwise too many data records of a dimension of a relatively small range of values could be in the angle of dominance. In each dimension the weight vector is set to the same distance between the maximum value and the minimum value. A tolerance range for all parameters is used as well.

$$P_x \prec P_y \wedge \left(|D_A| = 0 \vee |D_B| = 0 \vee \tan\alpha \geq \frac{\sqrt{\sum_{i \in D_A} (P_{y,i} - P_{x,i})^2} - \varepsilon}{\sqrt{\sum_{i \in D_B} (P_{y,i} - P_{x,i})^2}} \right) \quad (3)$$

In a first prototype of an actuator selection tool this choice of the weight vector delivered good results compared to a few conventional case studies made before (even if comparison with work done before is not a real proof of concept it was done to get a first idea of weight vector influence).
By adaptation of the Skyline approach to a so called dynamic Skyline it is moreover possible to evaluate the distance of solutions around a preferred dataset (cp. [Dellis 2007]).

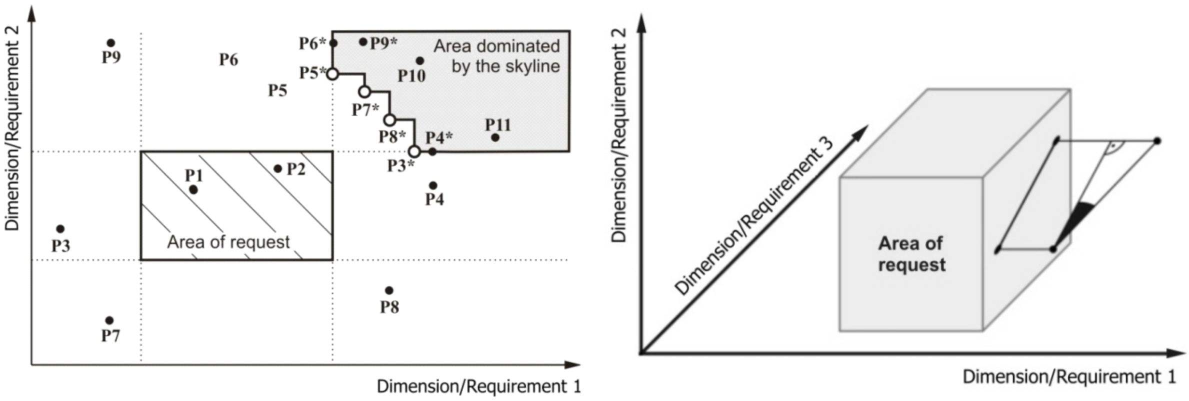

Figure 4. a) Illustration of the dynamic Skyline, b) Illustration of the angle of dominance

The dynamic Skyline starts from the concept of selecting only the maximum (and/or minimum) values with the Skyline approach. The Skyline algorithm is still based on the maximisation (and/or the minimisation), it works however on transformed data records. The number of dimensions can differ

between the transformed and the original data sets. Each new dimension of the transformed data set is defined by a function. In principle these functions can use the values of all dimensions of the data set before transformation for the computation of the transformed data set. That means that the new values can be computed from the old values of the respective data set. After this pre-processing the transformed data sets are processed by the basic Skyline approach.
This means that the transformed data sets are based on a q-dimensional area $D^*=(d_1^*, d_2^*, \ldots, d_q^*)$. Every transformed data set is calculated in the particular dimensions by functions out of the original data sets.

$$P_i^* = (p_{i,1}^*, p_{i,2}^* \ldots, p_{i,q}^*);\ p_{i,1}^* = F_1^*(P_i),\ p_{i,2}^* = F_2^*(P_i), \ldots, p_{i,q}^* = F_q^*(P_i)p_{i,q}^*) \tag{4}$$

The number of dimensions does not change and in each case the functions only determine the distance to a preferential data record. The dynamic Skyline looks for data records, which resemble a preferential one.
In practice this results almost exclusively in simple distance functions (Fig. 4).
The presented decision-aid uses basic-, "two angle dominated"- and dynamic Skyline algorithms. This results in:

- All actuators out of the database within the area of request spanned by requirements are presented
- Number and type of parameter can be chosen arbitrarily (within the limits of classification)
- All actuators out of the database that do not fit – in part or in total - the given requirements are presented with weights –called relevance in the sequel- depending on an average distance to the given requirements
- Actuators of the same actuation-principle are more strongly penalised than those of alternative principles

A selection is possible on the basis of all parameters in the database independent of composition. Data sets with missing entries at a particular parameter are not sorted out.
A relevance between 100% (fits to all requirements) and 0% (no requirement matches the dataset) is assigned to every data set.

3.2 The database

As mentioned before, a database was developed to contain as many examples as possible of different actuation-principles. The data sets have been extracted from different catalogues, missing parameters have been calculated as far as possible (e. g. power density, out of power and volume data) or had to be left blank. For the sake of comparability the database contains data of different actuators that are produced by different manufacturers, but all are structured with respect to the same parameters. The aim was not only to get as many examples as possible but also to get a diversity of the examples. For example, not every DC Motor on the market was inserted into the database. Instead the particular attention was directed to a broad range of products with extreme configurations and diversity of manufacturers.
The created database contains about 2500 examples of actuators of different working principles collected from different manufacturers. At first the database classifies actuators by their type of motion – translatory or rotational. Around 1000 examples of rotary motors and 1500 translatory examples are affiliated in the database.
The current amount of datasets is considered as "sufficient" because the areas of different active principles are distinguishable (cp.fig. 5, 6).
The second classification is based on the actuation-principle. Table 1 provides an overview of the active principles that are covered and currently (albeit with varying detailing) included.

Table 1. Actuation-principles of actuators currently enclosed in the database

rotary active principles	translatory active principles
DC-Motors	solenoids
EC-Motors	piezo stack drives
stepper motors	piezo-hybrid drives
three-phase synchronous motors	piezo-steppers
brushless servo motors	ultrasonic piezo linear motors
rotational pneumatic drives	pneumatic cylinders
rotational hydraulic drives	synchronous linear motors
torque motors	voice coil drives
rotary solenoids	magnetostrictive actuators
rotational piezo drives	magneto rheological drives
reluctance motors	hydraulic cylinders
	shape memory actuators

To achieve comparability the following determinations/assumptions regarding parameters have been made:

- The casing volume is presumed to be cuboid, hence the diameter of cylindrical actuators and width of cuboidal actuators are abstracted to a "generalised cross section dimension".
- Only nominal power and energy is considered for power and force values.

Furthermore, costs of actuators are not considered because it proved impossible to compare the costs of actuators by a universal and consistent scale. In certain cases this could be imaginable but only with further premises and restrictions according to the number of covered actuation-principles [Egbuna09]. If the costs have to be taken into account this has to be done by relative cost ratios for specified drive systems (cp. Fig 1.) considering lot size dependencies too. This is, however, not possible for the selection of the actuation-principle alone. Moreover, consideration of costs poses the problem of confining them, as mentioned before the piece costs are not the matter of expense (reliability, delivering time, etc). Nevertheless, an entry for costs is already implemented in the database, even if it is not used in the selection algorithm yet.

3.3 The Frontend

One of the challenging targets is the visualisation of the results. Because of the multi-dimensional character of the optimisation task it cannot be visualised in a simple (two-dimensional) manner. Some different visualising methods depending on the demands of the end user – scientists, customer, students, etc. - have been evaluated. The aim was to visualise as many parameters and their inter-dependencies as possible in a simple way. Further on, the plot itself has a significant influence on the reception of the results by the user (cp. Fig. 5).

As a result, a cloud of actuators was formed showing the region of their functionality. Albeit apparently better, the logarithmic plot proved to be difficult to interpret during first basic usability tests. The first reason was, that a comparison defines the need to distinguish different active principles which is difficult in the dense cloud.

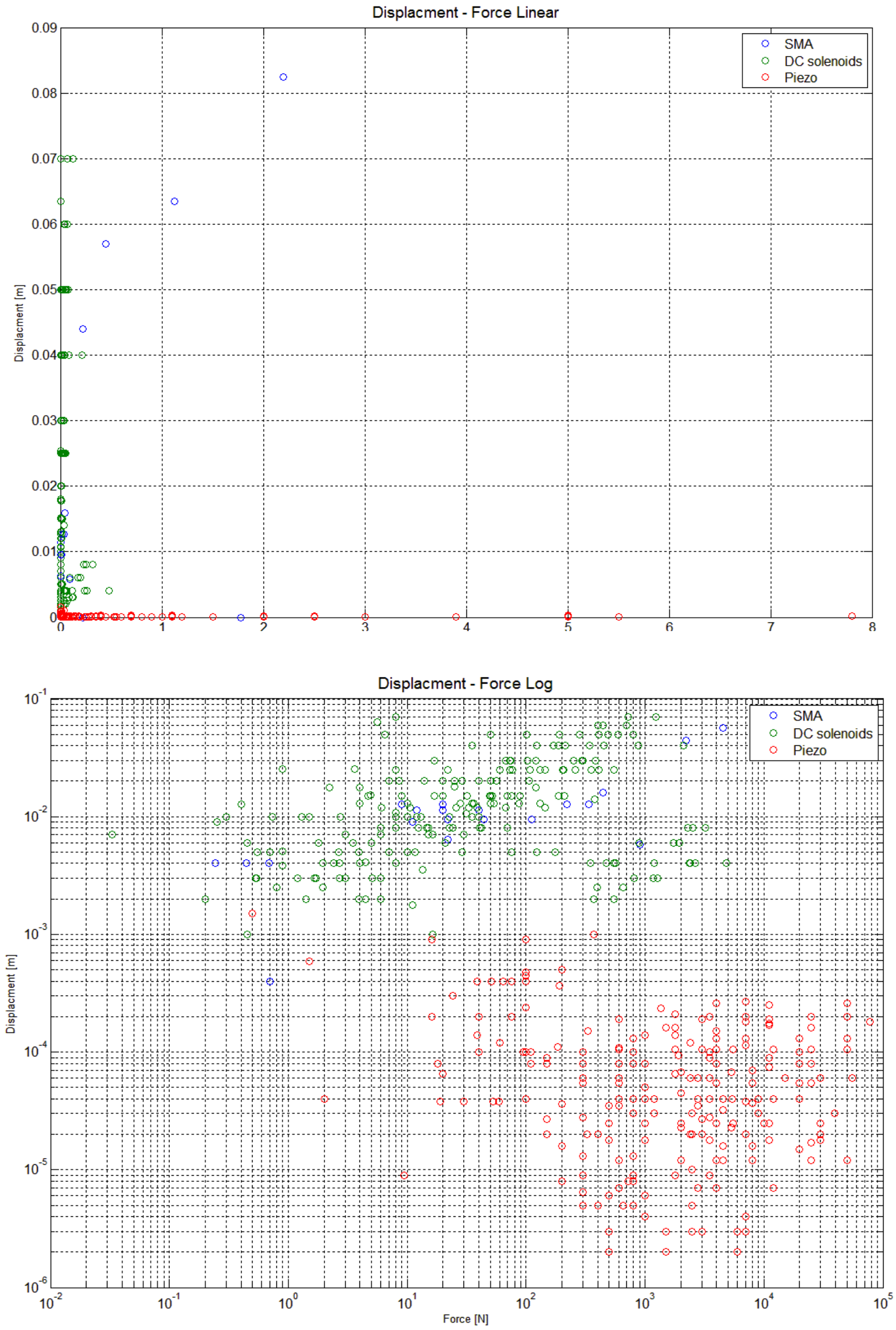

Figure 5. Illustration of the data sets of an assortment of translatory actuation-principles in a logarithmic (below) and a linear manner (above)

The second reason was the desire for manipulation of the plot itself. Therefore an improved version of the frontend has been created (limited to German language, cp. Fig. 6).

The validity of different actuation-principles can be recognised by overlapping areas in the figure 5. Furthermore a list of the results is presented and a third parameter can be addressed by the bubble size. Parameters (including the calculated relevance) can be assigned to coordinate axes and changed arbitrarily, as well as the parameter of bubble size, zooming is also possible. Actuators with more than 60% relevance will be presented in the plot and the table.

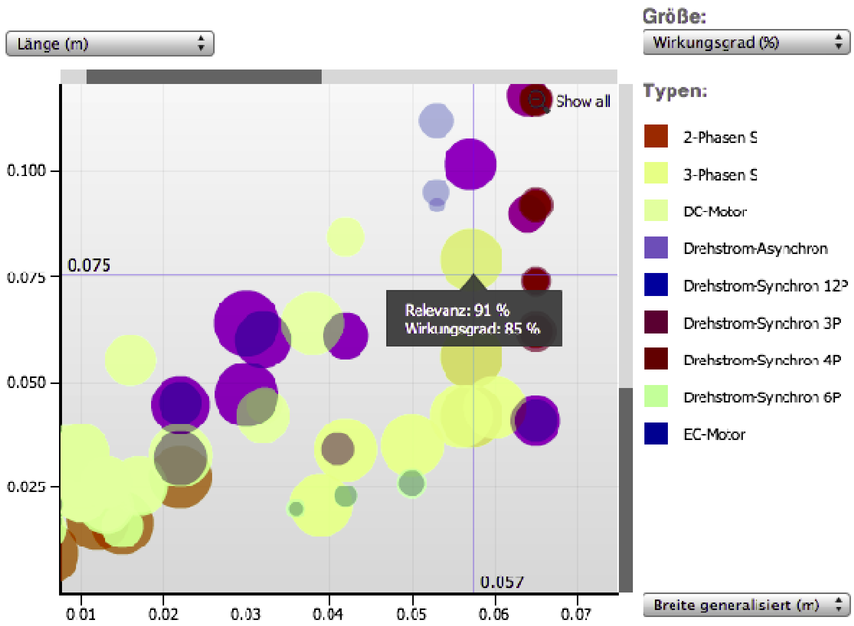

Figure 6. Above: Illustration of the data sets of rotational actuation principles, Y-axis representing length, X-axis representing width, bubble sizes representing efficiency factors

4. Conclusions and outlook

The presented concept enables the consideration of trade-offs between different requirements for actuator selection. It is possible to identify not only one optimal actuation-principle – which is unlikely due to the void vector-space anyway – but also all alternative principle solutions which are close to the optimum. Thus, an optimal compromise (or a set of them) can be found as well. Requirements different in quality and quantity, as well as strict restrictions, can be taken into account. This results in an adaptive solution to the respective actuator selection task. The areas of application of different actuation-principles can be distinguished. This, to a certain extent, makes an active principle selection possible, albeit the present choice of a database is still sub-optimal. It has to be maintained continuously and needs many data-sets to create reliable delimitations of valid areas of the active principles.

To a certain extent, the described procedure leads to more diversity by anticipating the potential adaptation and "softening" of requirements during the ongoing design process. The choice of an appropriate degree of softening could, however, be made more reliable at the best if based on experienced data but still remains subjective.

A potential cure is a mathematical formulation of each actuation-principle [Rosenbaum 2008]. First attempts representing solenoids by a set of equations which are only dependent on material parameters were successful.

Nevertheless, unexpected difficulties did appear during the ongoing research. It proved to be a central issue to visualise the results because engineers have "pictorial minds".

Furthermore, searching for an optimum by assigning weighting coefficients to the requirements in order to get an "optimal" solution is a well-known procedure to engineers. Currently there are no weighting coefficients implemented in the decision-aid. The problem in implanting the weighting coefficients is: On one hand the weighting coefficients can be chosen arbitrarily (at least to a certain extent), on the other hand, many actuation-principles have specific properties that cannot be assigned to others (e.g. magnetic fields). This could also be achieved by adoption and adjustment of weighting coefficients – arbitrarily again – according to sub-goals in order to find an optimal actuation-principle.

To what extend the weighting coefficients could enhance or expand the feasibility of the decision-aid will be addressed in future work.

Studies of usability and consequential optimisation of graphical representation will be another objective of future research.

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.

References

Kallenbach, E., Radler, O., Rosenbaum, S.: Development Trends of Electromagnetic Actuators. Workshop zum 15. Firmenjubiläum der Saia-Burgess Dresden GmbH, 21.06.2007, Dresden.

Kallenbach, E. and Stölting, H., ed.: Handbook of Fractional-Horsepower Drives, 1st ed. Springer, Berlin, 2008.

Erbe, T.; Król, J.; Ströhla, T.; Theska, R.: Selection of precision actuators by novel function-structure-correspondences (2008). 23rd Annual Meeting of the American Society for Precision Engineering and the 12th ICPE, October 19 - 24, 2008, Portland, Oregon.

Ashby, M. F.: Materials selection in mechanical design. Spektrum Akademischer Verlag, 2006.

Ehrgott, M.: Multicriteria optimization. Springer. Berlin [u.a.], 2005.

Papadias, D., Tao, Y.; Fu, G., Seeger, B.: Skyline Computation in Database Systems, ACM Transactions on Database Systems, 2005.

Rosenbaum, S., Radler, O., Hüfner, T., Ströhla, T.: Issues in the Design of Electromagnetic Actuators Using Circuit Models and Hysteresis Simulation. 2008 ASME International Design Engineering Technical Conferences (IDETC) and Computers and Information in Engineering Conference (CIE), 03.-06.08.2008, Brooklyn, NY, USA, Proceedings (DETC2008-49107).

Dellis, E. und Seeger, B.: Efficient Computation of Reverse Skyline Queries. In VLDB ’07, 2007.

Egbuna, C., Basson, A. H.: Electric Actuator Selection Design Aid for Low Cost Automation. ICED09, Stanford University, 24-27.08. 2009.

Dipl.-Ing. Torsten Erbe
Research Assistant
Ilmenau University of Technology, Institute of Design and Precision Engineering (IMGK), Department of Engineering Design
PO-Box 100565, 98684 Ilmenau, Germany
Telephone: +49 (0) 3677 / 69 3897
Email: torsten.erbe@tu-ilmenau.de
URL: http://www.tu-ilmenau.de