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FUNCTION MODELING SUPPORTS CONCEPTUAL DESIGN OF INNOVATIVE PRODUCTS

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1. Introduction

The development of innovative products is based on the generation of new concepts. This can be done by well known systematic and intuitive methods [Pahl 1999, Chakrabarti 2002] with the result of numerous more or less adequate solution variants. For evaluation and selection of potential innovative solutions it is important to understand and predict their properties (primarily concerning function and behavior). To get this information based on facts in the early design phases the designer needs special methods and tools. Virtual prototyping is such a method and it can be applied even in early design phases. One essential base for this is functional modeling on a high level of abstraction. The product structure is given by a symbolic description of elements and couplings as well as their basic layout.
Innovative solutions are typically characterized by high performance, accuracy, dynamic behavior, small dimensions etc. Therefore the model has to include quantitative parameters of the function relevant elements, couplings and the basic layout in parametric mode. Then it can be used to check if the solution variant can be dimensioned in a required space, is over-constraint or has collisions.
Beside this task of analysis function modeling should be used also for variation and optimization of solution principles with the objective to generate a quantified layout as base for the next design phase of embodiment design.
The paper presents a computer supported tool for this purpose and shows applications of function modeling in the conceptual design phase dealing with the development of ultra high precision positioning and measuring machines and mechanisms. This constraint- and feature-based tool supports also the reuse of solution principles from different information sources and their adaptation to current requirements.

2. Constraint- and feature-based modeling of solution principles

An integrated computer-aided product design needs consistent models serving as digital prototypes. The objective of virtual prototyping is to analyze, to test, to optimize and to evaluate design results before the product is built.
A key level in the sequence of synthesis steps is the solution principle (Figure 1). It contains only the features relevant to the function and allows the simulation of the behavior and the variation of the structure. Solution principles (Figure 1b) consist of principle elements and couplings (e.g. joints). They are represented by predefined symbolic elements in the computer as features forming a constraint-based model [Brix 2001]. Base elements of the constraint-based model description are sets of objects, like geometric objects or parameters, and constraints, like incidence, distance or mathematical operations. Such a model description doesn't necessarily represent a consistent model. The consistency of the model can be achieved by a model evaluation with a constraint solver which

transforms the implicit (constraint-based) description of the model automatically into an explicit set of consistent model parameters (e.g. coordinates and parameter values) [Brix, Döring and Reeßing 2005]. For each change of certain parameters or geometric objects in the model the constraint solver generates an appropriate sequence of necessary calculations (Fig. 2).

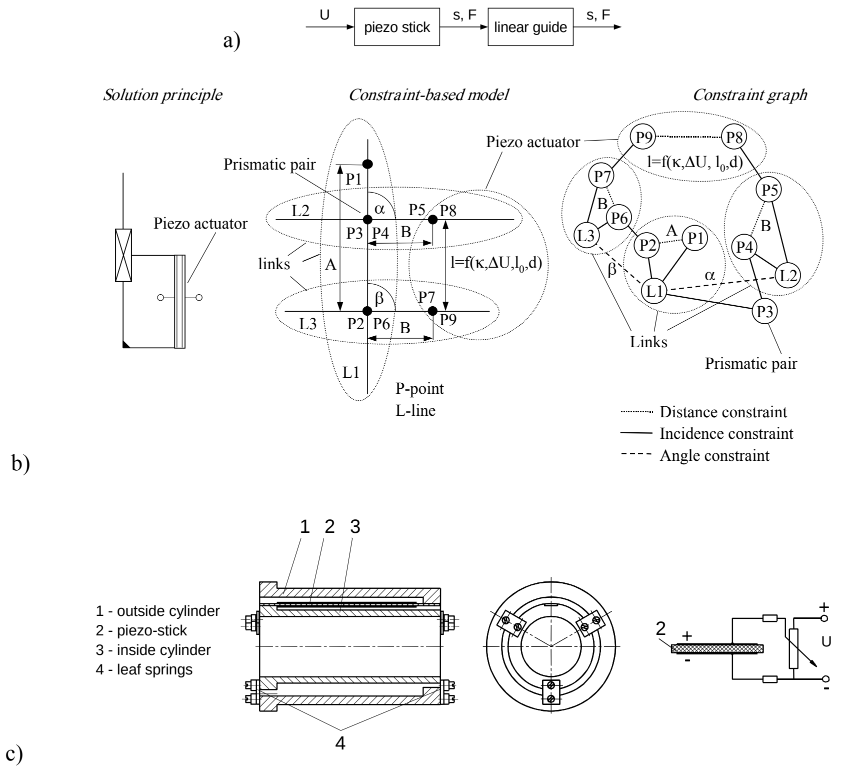

Figure 1. Model of a translation element, a) functional structure, b) solution principle with the corresponding model and graph, c) embodiment design

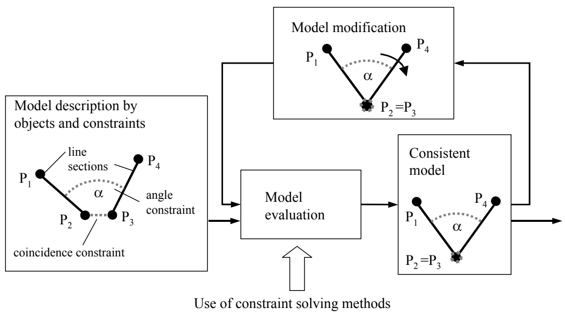

Figure 2. Sequence of constraint-based modeling

This concept is implemented in a software called MASP (Modeling and Analysis of Solution Principles) using a hybrid geometric constraint solver [Brix, Döring and Reeßing 2005]. The tool MASP supports the functional modeling by virtual prototyping and is an important part to preserve and to provide solution variants. The interactive modeling of solution principles is done by selecting symbols in the context of a chosen operation mode (e.g. create, delete, modify). For the first steps in embodiment design the software provides predefined, full parametric form elements. Figure 3 shows an example of a modeled mechanism in the design system MASP.

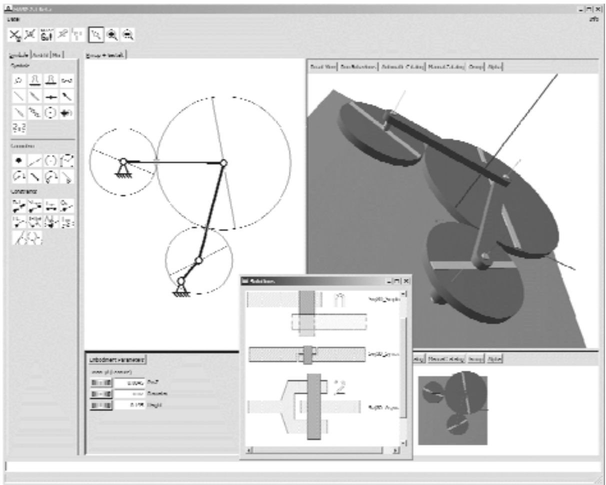

Figure 3. Design system MASP for the modeling and simulation of solution principles and embodiment designs

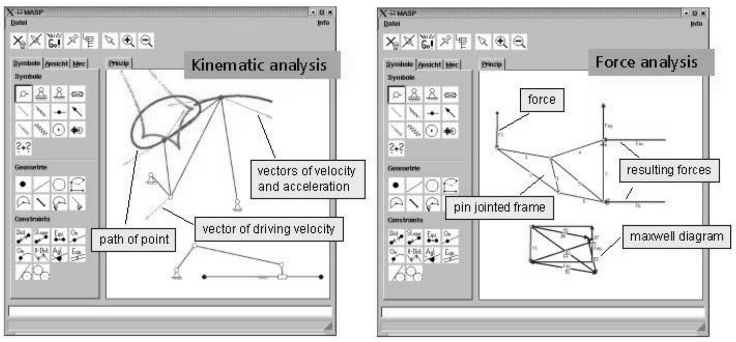

Figure 4. Calculations based on the evaluated constraint model

Integrated calculation modules (Figure 4) support kinematics analyses (determination of velocities, accelerations and the path of interesting points) and static analyses. The feature based parametric model and the constraint solving procedure can be used also for catalog-oriented configuration of technical systems with mechanical, electrical as well as optical elements and tolerance analyses [Brix 2001, Brix et al. 2003].

3. An example for function modeling of solution variants in the context of nanopositioning and nanomeasuring machines

Nanopositioning and nanomeasuring machines are multi-coordinate positioning and measuring machines with nanometer resolution. These systems have to meet stringent specifications in certain fields of application all to be maintained in precise positioning over increasingly wide areas. The equipment for this purpose includes mechanical, electrical, electronic and software components. Because of this the design must be carried out as a mechatronic project.

First of all it is necessary to describe the operations which must be carried out by the nanopositioning and nanomeasuring machine (NPM machines). The system should provide the user with the enabling technology for nanoscale and macroscopic objects with high precision [Jäger 2001]. In our case the machine should be used for testing and measuring of wafers for micro-electronic circuits and micro-optical lenses. This exemplary specification is a sample for other application areas. The machine has to meet the following main requirements:

- flexible configurability with respect to the required technological process,
- long-term stability of the construction and good dynamic behavior,
- realization of wide moving areas of 200mm x 200mm x 5mm and more as well as
- high adaptability for the different types of application areas.

Analyzing these requirements and existing systems a relative multi-coordinate movement between the object to be measured or tested and a tool is necessary. One fundamental concept to accomplish this objective is the arrangement of object and tool corresponding to the 3D-version of Abbe's principle [Theska et al. 2004, Rujil 2002]. Figure 5 shows the Abbe point as a virtual intersection point of the three interferometer beams and the cantilever tip. In this case the object carried by the 3D-mirror is moving in three directions (x, y and z). However other combinations of moving components between object and tool are possible.

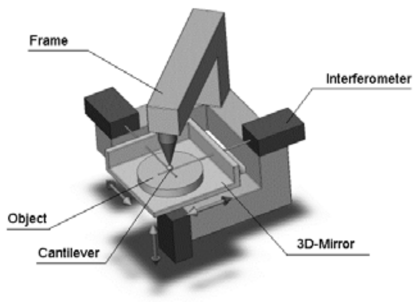

Figure 5. Principle of the measuring system

The layout of the machine is stepwise established as a virtual prototype beginning in the phase of technical principles. In this phase selected components from the configuration matrix will be combined generating a number of different variants. The development of the technical principle is crucial for the whole machine design. This phase allows to find the most critical error sources and crucial components of the whole machine and the measurement circle early. Error calculations and the development of adjustment strategies can also be carried out.

If highest precision is desired it is necessary to apply design principles (especially the principles of small error arrangement, of function separation, of force transmission, of symmetry and of well-defined contact design) in all phases of the design process especially in technical principles. Therefore design principles and their compliance are the most important criteria.

Two possible solutions are shown in Figure 6. The serial arrangement uses linear guides and a planar drive system. Its dimensions are compact but the long force flow (because of gravity and driving forces) leads to bending and torsion. Therefore the parallel arrangement fulfils the principle of force transmission better and is preferred. The vertical moving axis is directly connected to the base through planar bearings. As a result the force flow is direct but the lateral dimensions are larger.

These estimations must be checked and evaluated in relation to the requirements. The objective is to simulate properties like accuracy, dynamic behavior as early as possible using virtual prototypes and optimize the dominating parameters to save time and effort in the several phases of the design process and the bodily realization. The predominant questions are the analysis, simulation and optimization of motion concepts to find preliminary layouts. The use of special software tools (like Matlab, SAM, WorkingModel, Watt) helps to find a good solution principle and determines some basic embodiment design parameters.

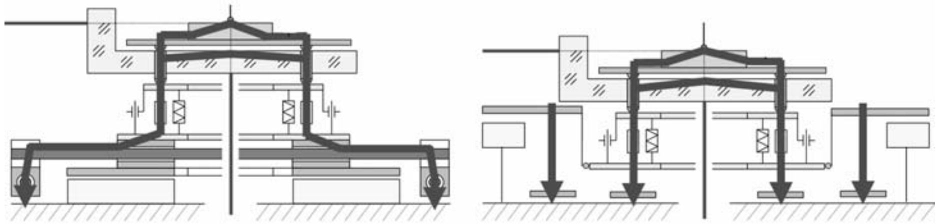

Figure 6. Serial (left) and parallel (right) designs with force flow (red) shown

For the design of the NPM machine concept the design tool MASP is also used. This design system enables the designer to model and simulate different guide and drive concepts of a NPM machine. MASP uses a constraint-based method to describe kinematic geometries [Brix 2005, Höhne 2004]. Figure 7 shows the preliminary designs of both variants.

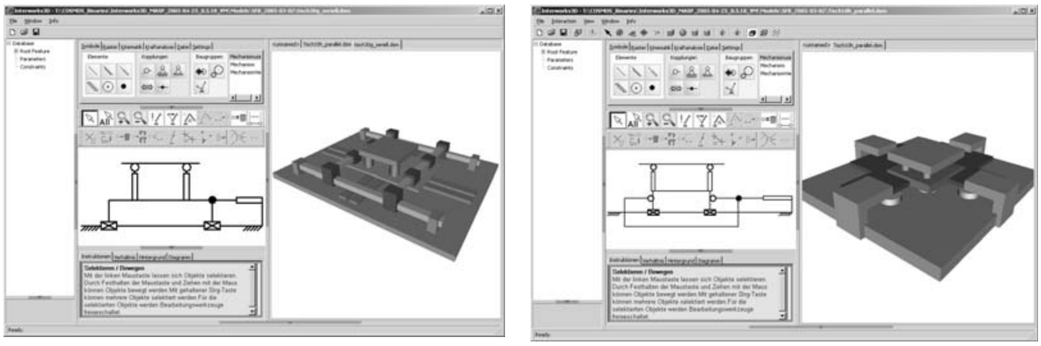

Figure 7. MASP with the motion concepts of the serial (left) and parallel (right) designs

With this program it is possible to simulate the clearance in the guides and the resulting deflections from the ideal guiding line. If mechanisms are used as guides or couplings it is possible to calculate their motions and resulting forces in joints. The preliminary design can be exported to CAD programs for further development.

4. Retrieval and reuse of solution variants in the Digital Mechanism and Gear Library (DMG-Lib)

Important for the virtual prototyping in early phases of the design process is the reuse and the retrieval of approved solution variants. One suitable procedure for this is the retrieval and reuse of solutions from different information sources and their adaptation to current requirements. Thereby the most important problem is, that the existing worldwide knowledge in the form of books, articles, drawings, photographs, sketches, patents, functional models etc. is mostly scattered, difficult to access and does not comply with today's requirements concerning a rapid information retrieval. For the field of mechanisms and gears a long term research project to eliminate these disadvantages exists. The aim is the development of a digital, internet-based library which contains large amounts of the worldwide knowledge about mechanisms and gears. The name of the project is DMG-Lib (www.dmg-lib.org). It will support research and development projects and encourage the reuse of existing solutions by a dynamic and problem oriented representation of the knowledge. The aim of the project is not only the collection of different sources, but also the enhancement of the digitized sources. An example for this is the provision of constraint based models of described solutions. Before the models can be used, they have to be extracted from the very different sources and must be stored in a unified representation.

The extraction of solution principles from figures or photographs (originating from books, patents, databases, screenshots of some software etc.) can be carried out with MASP (Figure 8) which includes also methods of image processing and pattern recognition. Figure 8a shows a drawing taken from [Grübler 1917]. Since in MASP the extraction of solution principles is connected with the motion

simulation, the behavior of the defined mechanism can be tested interactively to check if it behaves as expected. This is important to minimize the number of errors in the mechanism database.
To improve the understandability of drawings or even photographs the generation of an animation is in MASP also possible. The animation rendering algorithm can visualize the mechanism in different representation styles, for instance in the abstract style (Figure 8) or the original style (Figure 9). Furthermore it is possible to enrich the images with additional information obtained from the analyses (e.g. vectors which visualize kinematic parameters).

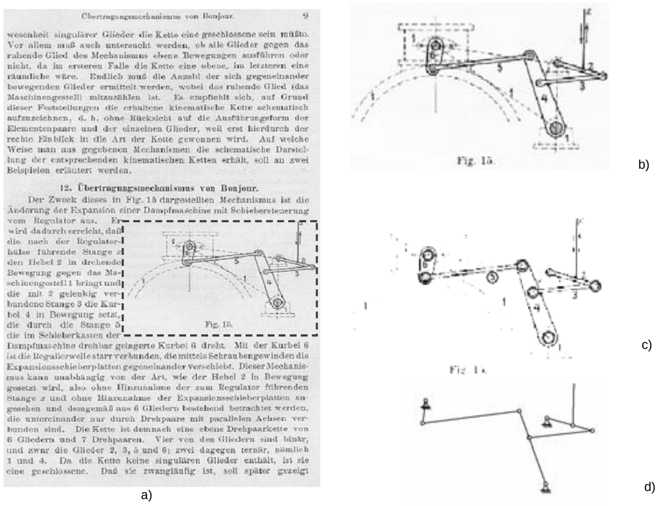

Figure 8. Process of the extraction of a solution principle from an image in a book with MASP

a) shows the book page with the drawing and b) the image after some image processing. To support fast positioning of the symbols for revolute pairs circles are proposed by a pattern matching algorithm e.g. by red circles as shown in c). Then the symbols are added interactively. The extracted solution principle in d) can now be added to the database.

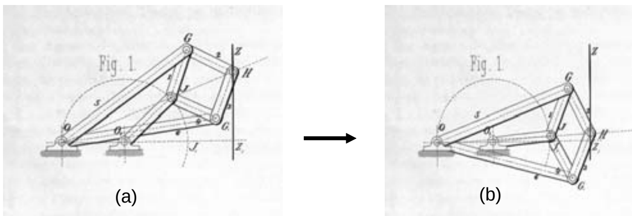

Figure 9. A figure taken from [Hülsenberg 1877]

a) shows the mechanism in the original position and b) the mechanism in a new position but rendered in the style extracted from the original image.

An engineering designer often searches for certain functionality to solve a current mechanical design problem. He wants to retrieve a certain mechanism or a set of mechanisms which are optimized using a certain software later. Therefore extended search possibilities are needed, e.g. stroke-based search and a search using keywords to describe certain properties.
For a stroke-based search the designer may make a stroke to describe his idea of the path of a point or a transfer function. This stroke can be compared by matching algorithms with curves obtained from mechanism analyses stored in the database (Figure 10). During the analysis of a mechanism special properties may be detected, e.g. the number of instantaneous dwells, ranges with linear movement. The use of fuzzy logic may allow to map certain properties like numbers or ratios to keywords. For

example the number of certain elements could be mapped to terms like “less complex” or “very complex”. Nevertheless to describe the user’s intent, numbers like the “degree of complexity” could be used directly too. A further example for such a number is the ratio which describes the relative size of the working area of a special point (according to the area needed by the whole mechanism).

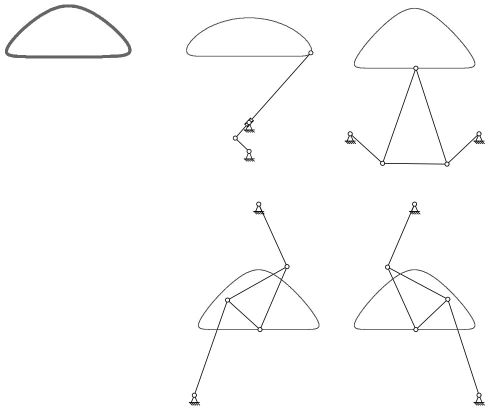

Figure 10. Stroke of a desired path (upper left) and four mechanisms which may be used to generate such a path

(The two lower mechanisms are found according to the Roberts-Chebyshev theorem.)

Based on the database the structure of stored mechanisms is searchable too. The demanded structure can be entered interactively using MASP. In this way, users could be able to check if some structures are already described. Furthermore a person, who has to check how innovative a patent is, could find according occurrences in a variety of sources. The most important property of this search process is, that it is independent on names which may be very different regarding languages, history and even schools. A very important use case of the search for certain structures occurs in the DMG-Lib itself. When a certain structure is found again (maybe as graph or subgraph), the according sources can be linked by a cross reference which gives users the possibility to get further information from other sources.

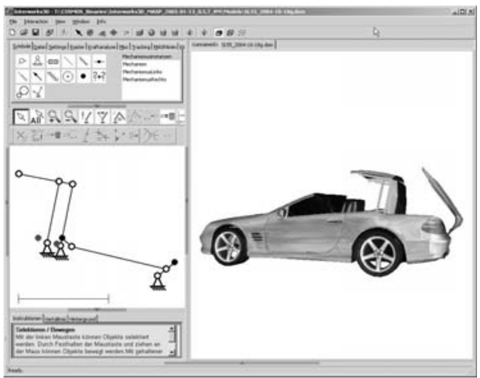

Figure 11. Design system MASP with modeled mechanism to move a hard top and integration of the corresponding embodiment design into an existing CAD model of a car

After the retrieval and selection of mechanisms which fit the needs of the designer a parameter optimization can be applied. This may be done externally by the software of the user. For this, the DMG-Lib will provide export/import interfaces to avoid that the user has to rebuild a mechanism interactively in his own software.

The embodiment design of retrieved solution principles can be done in MASP. The modeled embodiment design is bidirectionally connected with the solution principle and can be integrated also into existing CAD models (Figure 11). Thereby MASP supports function modeling during the conceptional design phase.

5. Conclusion and further work

The paper presents a function modeling approach in the phase of conceptual design using a constraint- and feature-based parametric description of solution principles. This is the base of the software tool MASP, which enables the user to test the functionality of design concepts in respect to following properties: static and kinematic behavior, required space, behavior under tolerance and disturbing influences, collision, over-determination.

Case studies of nanopositioning and measuring machines as well as mechanisms show applications and effects of function modeling at abstract levels in the design process. This follows the tendency to shift important design decisions from the concrete to the conceptual design phase. It is also shown, that the system MASP is able to support retrieval, reuse und adaptation of existing solution principles for current and innovative design tasks. Further work is focused on: the extension of the model to a phase-overlapping multi-stage modeling, building up the DMG-Lib database, connection of function modeling and CAD-based embodiment design.

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