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Object Structure of an Application for Tolerance Simulation of a Mechanical Unit in a CAD System

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Abstract: *The simulation modeling is the unique way to perform the inevitable 3D tolerance calculation in CAD supported design. A known functional model of a mechanical unit is used as platform for the proposed solution of dimensional problems. The emerging data organization and procedural components are analyzed. Some arising processing particularities of the incorporated formal approach of matrix operators are discussed. A set of related object classes for implementation of dimensional calculations in the context of used model and approach is proposed. Particular properties of the application are clarified.*

Keywords: *CAD, functional model, machine design, tolerance, object modeling.*

1. General notes

Dimensional and tolerance calculations represent unavoidable part of any mechanical design process. Some advanced CAD systems have as their own part or as companion software means to perform these calculations [1].

The intention of this work is to develop a stand-alone application, having capabilities to be applied to mechanical assembly descriptions of different origin, including paper technical documentation. Strongly following the idea that the 3D tolerance calculations of a mechanical assembly can be performed only using simulations, operational and procedural means for modeling of parts and joints precision were prepared. This preparation is founded on the theory of bases [2]. The theory expresses mechanical connections between parts in terms of reducing their virtual movements (degrees of freedom – DF) by expressing junctions, via contact surfaces, as purely geometric elements, called *bases*. A *base complex* is a coordinate system composed by bases. The space position of one part of the assembly is completely determined by this coordinate system.

The problems of tolerance analysis are solved using the representation of the spatial disposition of base complexes by means of dimensions and tolerances of parts and joints [3]. Primary data about the assembly can be extracted from its technical documentation or other representation and properly expanded (Fig. 1) to a consistent description, completing in this way the so-called *functional model* of the assembly, needed for the solution of the engineering tolerance problem.

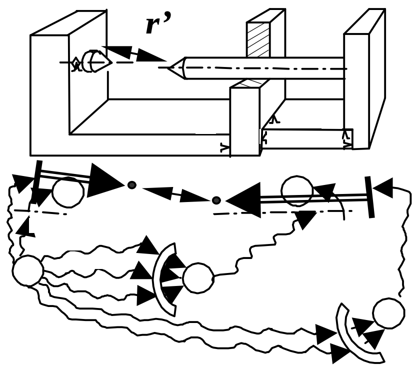

Fig. 1. The basic functional model of a unit

Due to the complex nonlinear influence of parts geometrical inaccuracies, the calculation is performed as a simulation of feasible samples of the assembly, depending on the parts and joins tolerances.

The aim of this paper is to present in details the whole process of data transformation from the original document (or other representation) trough different internal structures and their object implementation to the final calculation components – matrix operators and procedures for geometric relations.

2. Data representations

The technical documentation contains data for all properties, needed to guarantee the correct functioning of a mechanical assembly and data, necessary for its production as well.

Primary geometric data, concerning the functioning, describe geometric parameters such as linear and angular dimensions and their tolerances, geometric tolerances (form and position), properties of the surfaces etc. Independently from their primary type – scalars or vectors, they can be considered as an integrated vector representation of the "dimensional substance" of the assembly. This representation is needed for composing the geometric component of the functional model, which comprises a description of all contact surfaces between the parts.

Apart of this, the specific nature of contacts, determining possible movements and mutual position of solids should be described and considered as an essential part of the functional model. This mechanical data is necessary for the correct setting of the attachment of base complexes to the solids. The functional model is necessary and sufficient for any kind of tolerance calculations.

In this work, tolerance calculations are performed using coordinate transformations. The used matrices are of two types according to the different significance of the primary geometric data. The nominal mutual position of the joined parts is expressed separately by the “position” matrices *G***,** generally depending on the nominal dimensions. The transition matrices *T*, reflecting the influence of inaccuracies, express the tolerance of the nominal position separately. The transition matrices are derived from diverse type of tolerances in the primary geometric data using geometric procedures.

The method uses matrix product of type *GT,* where *G* may be considered as modeling the stable “position” component and *T* is expressing the tolerance influence. So, the simulation consists in multiple calculation of the expression:

$$r' = \prod_{i=1}^{n} (G_i\, T_i)r \,, \tag{1}$$

where r' is an assembly dimension (between two parts, see Fig. 1) with its tolerance, r is the position of one of its components, referred to one of the supporting parts and $\Pi\, G_i\, T_i$ is the matrix product of series of position G_i and transition T_i transformations, which follows the pathway to the second supporting part. Each couple G_iT_i is composed with a concrete set of toleranced part dimensions and in this way expresses a feasible sample of the *i*-th part and its junctions. Thus, the simulation is a multiple generation of matrices T_i and calculation of expression (1).

The matrices G_i express the position of base complexes. If these base complexes are composed of geometric elements of more than one part, then they depend on some of the *T* matrices. There is not a direct transformation giving the relationship between the data, included in the functional model and the matrix operators *G* and *T***,** which can by applied for the final calculations. So, project decisions for different forms of internal representation of data and their distribution over a number of object layers should be done.

3. Project decisions

The tolerance calculations are ever performed on a subset of the functional model, including parts and joints between elements of the simulated dimension r'. Moreover, not all geometric data of the mentioned parts and joints are taken into consideration for the derived matrices *G* and *T*. When using the application for a particular simulation, primary data from the functional model can be acquired additionally if missing. That is why, the primary data of the functional model and all intermediate data as well are considered and build *as dynamic structures.*

As mentioned, the functional model comprises two types of relevant data about the assembly: the geometric and the mechanical ones. These two different types of primary data are acquired in diverse ways.

The geometric data persist in the documentation and/or any other representation explicitly and can be extracted or derived in automated or semi-interactive way. On the contrary, the mechanical information concerning the DF is implicit and should be deduced via user expertise. This can be done only in interactive mode. Thus, for their internal representation, *geometric and mechanical data are organized in separate structures.*

With regard to the integrity of the functional model, which combines the geometric and the mechanical data, appropriate procedural connection between these two representations is included. It concerns the attachment of the coordinate systems to the solids.

The way of attachment of base complexes to the parts follows the principles of the theory of bases, and depends on both mechanical and geometric data. As the matrices G and T are composed in terms of these coordinate systems, the final calculation components are result of multiple procedures as: detection of the particular case of base complex, its composition, geometric relations between components, and detection of tolerance depending positions. As a result, matrix operators G and T should be always considered as values, obtained by appropriate composition of low-level procedures. That is, *G and T should be generated dynamically.* (Some of them, being constant during the simulation process, can be retained as unique instances.)

The practical use of the application considers data, presented following the standards of technical documentation. The engineering meaning of tolerance calculations is to satisfy quality requirements using standardized tolerances. The ordinary solution is to apply an incorporated or external database with standardized tolerances. In the real practice, each particular tolerance depends on more than one (as defined in the corresponding standards) parameter and should be estimated and scaled applying expertise. That is the reason to leave *the scale of tolerances freely defined by the user.*

4. Data structures and procedures

In order to distribute data and procedures in an effective object hierarchy, data structures and procedures are discussed separately. The objective is to classify the initial data and the available solutions.

4.1. Geometric functional data

Geometric data (form, dimensions, position) of the *contact surfaces* are part of the functional model. They are organized in a separate structure – a list CS of contact surfaces. The elements of this list contain data about the form type (point, plane, cylinder, cone, sphere etc.), the own form dimensions and the disposition of the surface in a chosen coordinate system. Procedures, referred to this data stricture, are: definition of initial geometric data – point, line, plane; geometrical relations: coincidence, parallelism, perpendicularity and intersection. The relations are based on primary vector procedures – sum, difference, dot and cross product, multiplication by scalar, module and normalization. Higher order surfaces are represented by their linear representatives as required by the theory of bases.

4.2. Mechanical functional data

The material structure of the assembly is presented as solids and mechanical joints. The role of these two types of mechanical elements is different and they are organized in two separate structures.

The *joint pairs* between two contact surfaces s_i and s_j are described in a separate list JP. The list contains references to the list CS for each participating surface, references to the parts the surfaces belong to, the type of the junction, reduced DF, the boundaries of the contact area and the quoted tolerance of the joint.

The data about the parts are organized in separate list LP, containing the set {p} of parts. Each element of the list comprises the part identifier, a list of references to the possessed joints, optional list of dimensions and precision parameters. This option originates from the kind of the precision problem – to check or to prescribe the precision (the tolerances).

The base complexes (the coordinate systems) are attached to the parts, but the manner they should be established depends on the joints. The base complexes comprise the representatives of the contact surfaces depending on the type of junction between parts.

The data from the described lists JP and LP are necessary to determine the exact manner of participation of the surface representatives in a base complex. There exist eight possible schemes of composing the base complexes, which are entirely predetermined by the type of binary junctions, the mutual disposition of the surface representatives and the sign of the external normal, referring to each contact surface of the participating parts. Ohe matching to each particular base complex procedure (corresponding to one of the eight schemes [3, 4]) has to be detected and applied, thus identifying the geometric elements which assemble the complex and the appropriate geometric procedures to build it.

4.3. Composition of functional data

At last, the simulated structure, traditionally called *dimensional chain*, should be considered. As it is shown in Fig. 2, the structure represents a specific graph. The nodes are the assembly parts, connected by arcs – base complexes with corresponding DF. When a node is connected with other nodes by multiple junctions, each with less then 6 DF, a composite (constructed of more than one part) base complex is present. Such kind of base complex should be composed by means of geometric relations over simulated positions of connected (comporting) parts. The only way to detect such cases is to build and maintain a description of this graph.

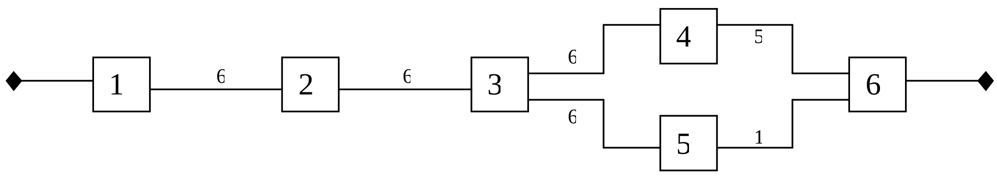

Fig. 2. Structure of the obtained dimension chain

In the example above (see also Fig. 1) part 6 is comported by two parts: 4 and 5. That means, during simulation, the components of incomplete base complexes between part pairs 5-6 and 4-6 should be calculated via separate matrix products $\Pi(G_i T_i)$, i = 1, 2, 3 , 4 and i = 1, 2, 3, 5. Afterwards, an additional service matrix G_s of these components has to be produced using the procedure, corresponding to the particular case of base complex. One additional matrix T_s of joint tolerances of the triplet 4-5-6 should be composed as well. The whole simulation shall be presented by the product $G_s T_s G_6$. Thus, the simulation is controlled using the graph description.

It can be seen that the matrix calculations require procedural approach as each composite base-complex necessitate expressing the precise value of its corresponding *G* matrix as function of the inaccuracies of other parts. That reflects in two types of matrix objects on the operational level: first – the "preset" matrices *G* for the position of the part-to-part 6 DF joints and second – the "late calculated" matrices which simulate the inaccuracy *T* and the position *G* of the composite base-complexes.

5. Object structure

The structures and procedures discussed above leads to a distribution into a convenient object hierarchy (Fig.3). One base class is *Point* with homogeneous coordinates as data and all vector procedures as methods. Every geometric element has a base point, so the abstract class *Surface* is derivative from *Point* and has as derivatives all geometric elements needed for the functional model. The procedures for geometric relations are implemented here as methods. Joint pairs are another class JP, which derive from *Surface* having additional data and methods to access them. The class *Part* has to contain specific data for parts and in addition, to produce own matrices *G* and *T* according to the position of the part in the dimension chain. The class *Matrix* contains a 4x4 transformation matrix and the procedure for matrix product as a method. Thus, the implementation comprises a multiple heritance from class JP and class *Matrix*. Procedures for building different types of position and transition matrices according to the specific composition of base complexes are implemented as methods.

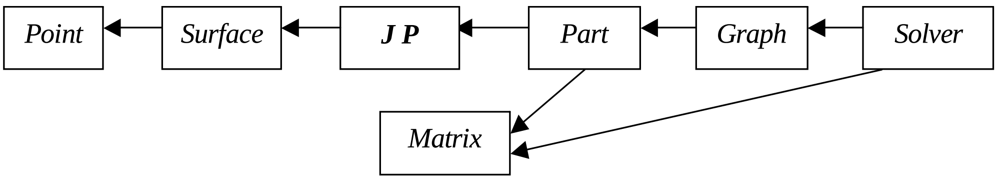

Fig. 3. Object hierarchy corresponding to the structured data and their processing

A specific container *Graph* is implemented to maintain all data of the dimensional structure of the assembly (implementation of the functional model) and all possible its subsets as a representation of separate dimensional chains. The class *Solver* is based on this container and has as its own methods procedures for: finding a path in the graph, detecting the cases of base complexes, building a description of the dimensional chain, performing the simulation, accumulation of simulation results for statistical treatment.

6. Data acquisition and simulation

A particular simulation problem is defined giving the geometrical elements of the simulated parameter and the parts these elements belong to. This can be done independently of the current state (complete or partial) of the functional model. Being derivative from the class *Graph*, an object of class *Solver* can support its own procedure for data acquisition up to the state of description, sufficient for problem solving. On the other hand, having an initial description as an instance of *Graph*, an object *Solver*, automatically or prompting for missing data, can build the relevant description, corresponding to the concrete given problem. In general, input data can be of arbitrary type and succession. Thus, generated instances of type JP and *Part* have to be stored in standard containers and their relations should be mapped separately in an appropriate sub-structure of *Graph*.

When the primary data origin from a CAD system allowing data exports for solid models of parts and for their joints, the data acquisition can be almost entirely automated. The only procedure to be executed in interactive mode is an additional confirmation of the DF of joints. This inconvenience is due to expertise, needed for precise recognition of mechanical properties of the product (possible movements, principle of action etc.)

7. Conclusion

Departing from a commonly used functional model of an assembly, data and procedural components of solution of dimensional problems have been analyzed. The requirements of simulation method for dimensional and tolerance calculations using the formal approach of matrix transformations are discussed and compared with the capacity of the functional model. A concise object hierarchy to cover data acquisition and solution of tolerance problems using simulation are proposed.

The realization of this application as a standalone program module premises its use in the engineering practice independently from the available source of primary geometric data. Moreover, the separate acquisition and organization of necessary mechanical data without a requirement for complete geometric representation, makes possible the use of such a module within CAD systems during the early conceptual stage of mechanical units.

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Обектна структура на приложение за симулационен размерно-точностен анализ в CAD система

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(Р е з ю м е)

За решаването на размерно-точностни задачи се предлага използването на функционален модел на механична конструкция, отчитащ взаимната обвързаност на механичните и геометричните параметри на детайлите и сглобките. Предлага се автономно приложение, ползващо геометрични данни с вход от CAD системи, реализиращо изчисленията чрез симулационно моделиране. Направен е анализ на връзката между функционалния модел, произхода и разпределението на данните, изчислителния подход на матричните оператори и наложителните процедурни компоненти. Представена е съответстващата на това описание йерархична обектна структура за програмно реализиране на автоматизиран модул за размерно-точностни изчисления. Обсъдени са някои особености на реализацията.