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An integrated open source CAT based on Skin Model Shapes

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Abstract

The control of geometrical deviations and form variations throughout the product life-cycle is a fundamental task in geometric dimensioning and tolerancing. As product complexity increases, it has not only become necessary to rely on computers to process geometrical and non-geometrical information from early design stages but also to come up with more realistic shape representation. Most of computer-aided tolerancing (CAT) packages used nowadays are fully integrated to computer-aided design softwares like CATIA and SolidWorks and they allow to model 2D and 3D tolerances stack-up through worst-case or statistical models. These CAT systems are generally available as proprietary commercial software which can sometimes restrict their domain of application and slow the implementation of new paradigms like the Skin Model. The Skin Model is an abstract surface model that represents the interface between a workpiece and its environment whose implementation involves the modeling of finite instances of the Skin Model called Skin Model Shapes (SMS) that encompass different sources of deviations and constitute a non-ideal geometrical model. The aim of this work is to show the first phase of implementation of an integrated open source environment based on PolitoCAT and Salome to model Skin Model Shapes. An Unified Model Language (UML) based logical data model of the integrated system is presented, it is an extended version of current data models for geometric modeling that includes the objects and relationships to manage form variations at different design stages. The work carried out contributes to the conceptualization of Skin Model Shapes model and it constitutes a support on the implementation of SMS in an open source CAT. An example of this integration involving a Skin Model Shapes implementation is shown as an illustration of the functionality of the platform.

Keywords: UML; Skin Model Shapes; Tolerance Analysis;Computer-aided tolerancing;

1. Introduction

Each one of the workpieces subjected to a manufacturing process comes out of that process with defects, errors or deviations that were induced during the transformation of that workpiece into a functional part. The inevitable induced defects on single parts will impact the whole compound of parts when they interact in an assembly. The notion of defect, error and deviation carries implicitly a comparison to what is perfect, ideal, nominal. This is where the apparent dichotomy between the conceived object and the actual object arises. The existing CAD systems today rely on a nominal representation of parts constituted by shapes of perfect form described parametrically. This simplification is the starting point for a set of different activities like simulating, manufacturing and tolerancing parts and assemblies.

Even though today exist systems that admit the use of non-rigid parts in variation analysis, the vast majority continue on relying on rigid modeling, furthermore these systems are incapable of aggregating all the sources of variation of a workpiece in a single environment. In the next subsection a brief overview of Computer-Aided Tolerancing (CAT) software is presented.

1.1. Overview of CAT systems

The primary information that any CAT tool needs in order to work is the geometrical representation of parts and assemblies as solid models from CAD systems. It would be useless to think of a system that cannot benefit from the explicit and implicit information that comes from CAD models, and it is because this exchange of information is possible that today we can think of fully integrated CAT tools into the existing CAD

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and CAE softwares.

The frequent approach in CAT begins with the nominal geometric information obtained from CAD systems. The procedure starts with defining the individual parts in a CAD environment that are part of an assembly, then the specification of the tolerance types can be done on the features of interest in each part. Once all of the tolerances have been specified, the relationships between different parts can be defined. At this stage it is possible to accommodate the dimensional and geometric variations on the assembly, then the Key Product Characteristics (KPCs) can be specified and must be satisfied in order to fulfill the functional requirements of the system [13]. KPCs are specific features of a part or assembly whose variation has a significant impact on the functional requirements.

The compendium of activities in Geometrical Dimensioning and Tolerancing GD&T is of such an extent to cannot be all fully encompassed in a single CAD workbench nowadays. CATIA V5 Functional Tolerancing and Annotation (FT&A) is based on Topologically and Technologically Related Surfaces (TTRS) model in which 28 different configurations are defined with seven different surface classes considering the degrees of freedom that let surfaces globally unchanged [8]. The FT&A tool in CATIA helps the user in the correct use of standards by providing automatic annotation support and dimensioning and tolerancing rules verification [11]. New CAT systems are created based on existing ones, like the Quick GPS system [2] that is implemented using FT&A, Visual Basic for Application (VBA) and Component Application Architecture (CAA). The Quick GPS system allows automatic generation of tolerance data for single parts through a VBA procedure, then tolerance data are retrieved from Excel using CATIA V5 CAA. Quick GPS was created to assist the designer in the specification process.

ANATOLE 3D is a software developed by Digital Product Simulation (DPS society) and AIRBUS that is also integrated into CATIA V5. It uses a robust solver based on a open source initiative for the management of uncertainties and risks [5] that allows for worst case, and statistical and sensitivity analysis. ANATOLE 3D considers only iso-constrained assemblies, so it is necessary to release some components when working with an over-constrained system [10]. ANATOLE 3D is based on rigid body and small displacement torsor (SDT). A dedicated module for modeling flexible assembly has been developed under the name of ANATOLEFLEX [9]. It also provides a deviation modeler where the description of geometrical variations can be performed

MECAmaster is another robust solution that allows to manage 3D variations from early design stages. It can compute 3D tolerances stacks-up and assist the designer on the identification of causes of variation. MECAmaster proposes two modeling modes, one using simple kinematic connections and another that takes into account surface-oriented contacts. MECAmaster also uses an automatic detection of over-constraint assemblies [6]. Other CAT softwares like 3DCS from Dimensional Control Systems, eM-ToolMate and VSA from Tecnomatix make use of a variational approach for tolerance analysis. These CATs focus mainly on tolerance analysis and on the automatic generation of tolerance schemes, generally based on Monte Carlo simulations [19]. Form deviation modeling as part of CAT is starting to gain importance as it allows a more realistic representation at the feature level. The use of proprietary softwares can restrict the quick implementation of new paradigms like the Skin Model, it complicates the access to the models and approaches, and makes it expensive for companies.

In the next section the concepts of Skin Model and Skin Model Shapes will be introduced. In section 3 a general view of the architecture of the system is presented and its components are described. In section 4 an illustration of the use of the system is shown using an industrial part, the process of generation of defects is detailed as well in this section. At the end, the limitations of the system are discussed.

2. Skin Model

2.1. The concept of Skin Model

The Skin Model is an infinite, theoretical model that can neither be explicitly represented nor implemented. It was introduced as a central part of GeoSpelling language [12] that emerges from the need of having a consistent, unambiguous, cross-domain language for specification and verification activities. GeoSpelling defines concepts regarding surface models and a series of operations for the manipulation of these models. The *Skin Model* is a virtual model of the physical interface of a workpiece and its environment and it was first imagined as a concept that could encompass all of the potential defects of a part.

The Skin model is considered as an infinite number of points that constitute a continuous surface. It can also be defined in opposition to the nominal model, an ideal representation of a part, as a non-ideal surface model. It is clear that the notion of infinite and numerical implementation are not compatible [3], so a finite Skin Model with engineering purposes needs to be defined. These finite representations are called Skin Model Shapes (SMS).

2.2. Skin Model Shapes

The Skin Model Shape can be defined as a finite and particular Skin Model representatives and also as specific finite outcomes of an Skin Model that comprises a possible non-ideal state of infinite possible states [16]. So the SMS can be seen as target instances of an infinite non-ideal surface model. Although there is not a prescribed representation scheme to draw a SMS from the Skin Model, emphasis has been put in the discrete representation of SMS [21].

Recently the simulation of SMS has gained importance, not only because it offers a reliable description of geometry but also because of the adoption of these concepts by the tolerancing community. The generation of particular representatives of the Skin Model is possible through a series of operations (partition, extraction, filtration, collection, association and construction) that are used to define a set of features. This approach has been used to model rotatory mechanisms [17], in conjunction with polytope approach [23] and for the Geometric Product Specification of gears [22], among others.

2.2.1. *Deviation modeling*

The deviation modeling is generally conceived at two different stages according to information that is available at a certain stage in the design process [21]. It is divided into *Prediction stage* and *Observation stage*. In the prediction stage it is assumed that information available about the defects is based on previous knowledge. A further classification in this stage is done by the type of defect to be modeled: a systematic, reproducible type of default or a random one. There exist several methods to model each one of those type of defects. The systematic defects can be modeled through decomposition methods like: Discrete Cosine Transform (DCT) [20], and Discrete Fourier Transform (DFT). The random deviations can be modeled through the Gaussian family methods, random fields, among others [18].

3. General Architecture

PolitoCAT is an open source software based also on Open Cascade Kernel for Tolerance Analysis using polytopes and prismatic polyhedra [7]. PolitoCAT comes with a mathematical solver called Politopix developed in C++ under GNU LGPL/GPL license. Politopix is a polyhedral modeling tool that allows the operations of Minkowski sums and intersections of operands in n-dimensions. PolitoCAT along Politopix have been used as a stand alone software for the tolerance analysis of iso-constrained and over-constrained assemblies. Generally, a STEP file is imported into the software where the operands for individual features can be generated as well as the contact features involved in a mechanical system as it is shown in Fig.1. PolitoCAT usually works with substitute surfaces, an ideal surface associated to the real manufactured surface but where the form defects are neglected [4].

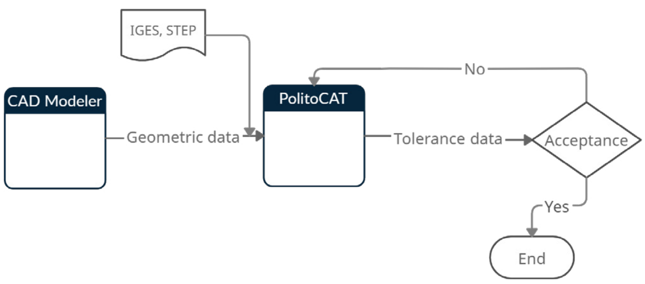


Fig. 1. Previous system process flow

The integration of the capabilities of PolitoCAT and the form deviation generator inside the Salome platform allows to execute most of the tolerancing activities in only one integrated open source environment. The continuous and discrete geometry models are available in a single place which provides the traceability of the geometric requirements throughout the design process.

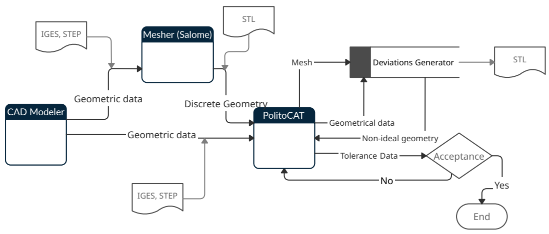


Fig. 2. New system process flow

The geometrical information can as well come from external sources for both the CAD model and the discrete model. For the case of the CAD model, the information can come in any of the recognized formats for exchanging geometrical information. For the the discrete model, the external data can be STL files obtained from measurements or manufacturing process simulations. The new system counts with a module for the generations of deviations as it can be seen in Fig.2.

The correct integration of the OpenCascade based platforms (Salome and PolitoCAT) demands the description of the type of objects and their interactions. In the framework of this project Unified Modeling Language (UML) is used to not only capture the knowledge in both systems but also to have a consistent representation of objects. UML is based on the object-oriented paradigm which makes things easier for the posterior development. In Fig.3 it can be seen an example of a class diagram that aims at integrating the deviation generator module with existing objects in PolitoCAT. The single toleranced features on each part of an assembly or sub-assembly are partitions of the nominal geometry. A mesh is generated and associated to each one of these partitioned features. A single toleranced featured object has as attributes: a name, the nature of the feature, the nominal geometry, the invariance class, the situation elements, the type of feature (i.e.ideal, non-ideal), and a label concerning the source of the discrete data. The data could come from measurements, simulations, or from a tessellating or meshing tool. Deviations could be generated for both ideal and non-ideal features(i.e. a previous SMS). The deviation method to use depends on the attributes mentioned above, and for the prediction case, on the type of deviations to generate (systematic or random).

The proposed system integrates the cross-platform solution Salome with PolitoCAT and a SMS feature generator. Salome is an Open Source platform that allows the integration of customized CAD applications [14]. It can be seen as a cross-platform solution for pre and post-processing numer-

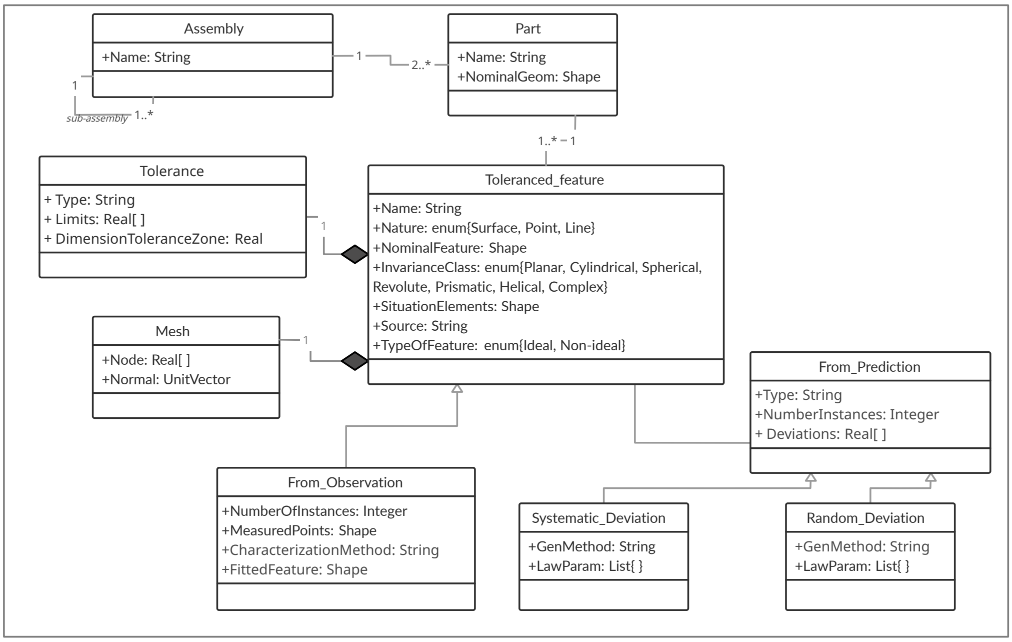


Fig. 3. Class diagram deviation generator

ical simulation. Salome is based on OPEN CASCADE 3D kernel and it is fully supported by the same. It counts with different modules included on the installation: a *Geometry* module that accounts for the creation, modification, importation/exportation, reparation and measurement of CAD models, a *Mesh* module that includes a great variety of meshing algorithms, and allows importing/exporting meshes, modifying mesh data and check quality of meshes.

The deviation generator module is programmed using C++ and makes part of the PolitoCAT environment. It uses OpenCascade classes for the manipulation of the geometry. It allows the user to choose the type of deviation method to use, and set the parameters of the desired law.

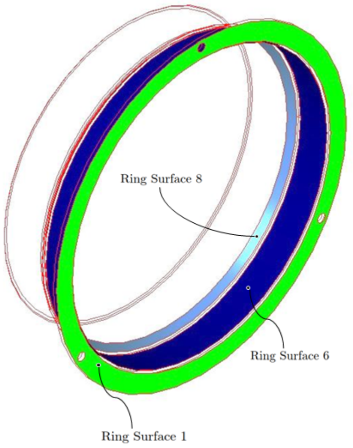
4. Example of generation of SMS

The part used is a support ring modeled in a external software and imported in STEP format in PolitoCAT. A manual partition of all the features in the part was done and 18 features belonging to four different invariance classes were identified as seen in Fig.4a. Once the partitioning was done, the meshes for each one of the features were generated as seen in Fig.4b. The mesh is globally consistent but the individual meshes could be defined with different density detail, which is the case on the example. Once the part has been meshed, both the STEP CAD model and each one of the meshes in STL format are used in PolitoCAT to generate the geometrical deviations where traceability of the CAD model, the toleranced features and the meshes is ensured.

Inside PolitoCAT the meshes were associated to the each one of the toleranced features according to the partition process carried out before. During this operation all the edges are identified and the internal ones are suppressed for next operations. An internal edge is one that limits a face that is inside a tolerance element (i.e, edges created in CAD for solids of revolution).

Once this is done, the generation of deviations for each feature can be made. In this paper, only random deviations were generated to exemplify the use of the system in the prediction stage. Among the deviation methods for generating random deviations, the random Gaussian fields was chosen as the method is capable of generating perturbations on any type of surface. Random fields are a type of generalized stochastic process and is popular for modeling spatially varying uncertainties. The 3D random Gaussian method can be seen as a specific case of a random field. It is widely used in geology, hydrology and image processing. The random fields [1] take into account the spatial correlation among the elements of the mesh which translates into a more realistic modelization and visualization of the results. Gaussian fields are completely characterized by a mean function and a covariance matrix. The field is homogeneous if the mean and the variance are constant. A discrete approximation of a random field can be expressed as [15]:

$$\delta(x) = \mu + \sigma \cdot M \cdot N^{(1/2)} \cdot \epsilon \qquad (1)$$

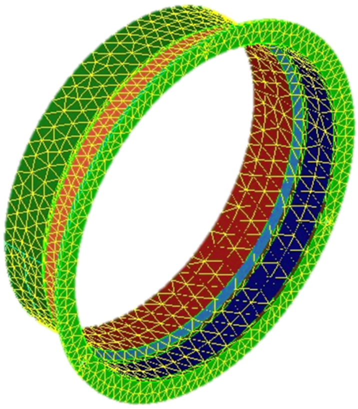


Part
Name: Support Ring

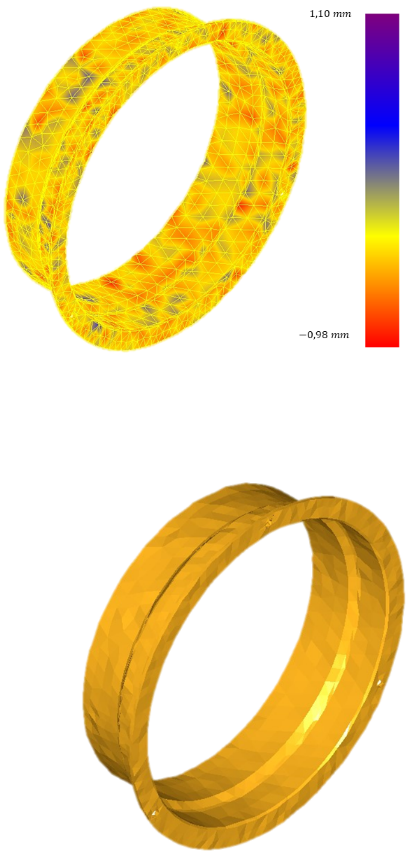
Partition list	
Name	***Invariance class***
Ring Surface 1	Planar
Ring Surface 2	Cylindrical
Ring Surface 3	Cylindrical
Ring Surface 4	Cylindrical
Ring Surface 5	Revolute
Ring Surface 6	Cylindrical
Ring Surface 7	Revolute
Ring Surface 8	Revolute
Ring Surface 9	Cylindrical
Ring Surface 10	Planar
Ring Surface 11	Revolute
Ring Surface 12	Cylindrical
Ring Surface 13	Revolute
Ring Surface 14	Revolute
Ring Surface 15	Cylindrical
Ring Surface 16	Cylindrical
Ring Surface 17	Planar
Ring Surface 18	Cylindrical

Partition list	
Invariance class	***number***
Cylindrical	9
Revolute	6(4 conical, 2 toric)
Planar	3

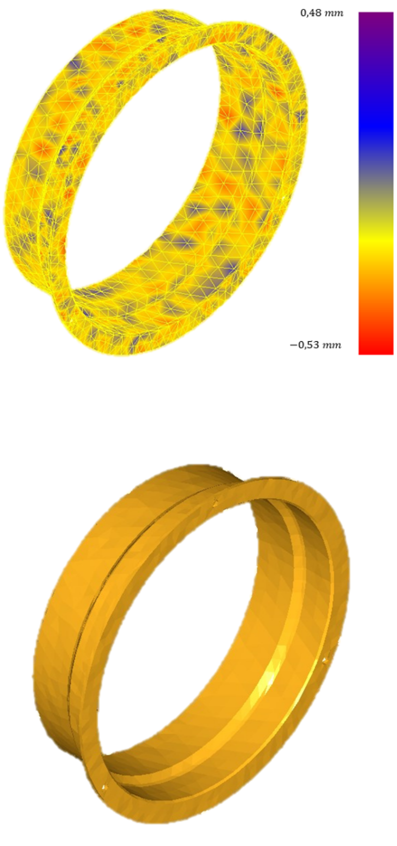
(a) Partition operation



(b) Part - Meshed ring



(c) Random fields with lp = 10



(d) Random fields with lp = 50

Fig. 4. Deviation Generation - Random fields

Where μ and σ are the mean and the standard variation respectively, M and N come from a square auto-correlation matrix that can be expressed as $R_{ij} = \rho(x_i, x_j)$. This auto-correlation function is sometimes referred to as the kernel function. The kernel function can assume different expressions, the most common and the one used in this article is the square exponential function that can be written as:

$$R_{ij} = \rho(x_i, x_j) = e^{\frac{\|x_i - x_j\|^2}{l_p}} \tag{2}$$

In Eq.2 the distance l_p corresponds to the correlation length that helps to the adjustment of correlation strength between two random variables in two points $\boldsymbol{x_i}$, $\boldsymbol{x_j}$ and could be calibrated through the analysis of experimental data. If l_p is small, the two random variables are strongly correlated if the distance between $\boldsymbol{x_i}$ and $\boldsymbol{x_j}$ is small. Inversely if l_p is large, the random variables are strongly correlated if the distance between $\boldsymbol{x_i}$ and $\boldsymbol{x_j}$ is large. $\boldsymbol{M}$ and $\boldsymbol{N}$ correspond to the eigenvectors and eigenvalues of the decomposition of the auto-correlation matrix $\boldsymbol{R_{ij}}$. Finally, $\boldsymbol{\epsilon}$ is the vector containing N independent Gaussian random variables.

The algorithm for obtaining the random fields was programmed in C++ and it makes part of the deviation feature generator module that is under development for PolitoCAT. The results of the non-ideal model are presented in Fig.4 and show the non-ideal geometry after being subjected to a random perturbation using random fields. For this method a series of parameters can be modified: the standard deviation (σ), correlation length (l_p), initial mean vector (μ) and kernel estimation. This can lead to achieving a more realistic distribution and level of the defects. For the specific case, the images correspond to the values of the correlation parameter of 10 and 50, a mean and standard deviation of zero and one respectively. There are two ways of visualizing the results, by color degrading or simply the shaded deviated geometry.

5. Limitations and conclusions

In this article, we presented the initial stage of the implementation of the integrated open source CAT based on Open Cascade 3D kernel. PolitoCAT is generally used to perform tolerance analysis using polyhedra. The generator added to it can be used to generate non-ideal geometry instances that can later be used in other CAT systems to perform analysis, synthesis or sensitivity studies. The user can also remain inside the same environment to perform tolerance analysis using PolitoCAT tools. The SMS generator could be enriched with any other method for geometric deviations modeling. Since it is an open source tool, users could include their own routine for defect parametrization (or settings) into the software. into the software. At this point the software does not allow to model more than one type of deviations per feature and it is restricted to a discrete representation scheme. Although the system is thought to manage data coming from measurements, all the simulations done until now were done only with meshes obtained from CAD softwares.

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