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Research Article

Development of An Open-Source Computational Tool for the Generation of Deviated Point Clouds from Nominal Models

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Abstract: Design for dimensional control refers to the engineering field concerned with variation management in different stages of product development. One of the key elements within the framework of design for dimensional control is the effective use of computational techniques for assisting the designer in defining the dimensional tolerances of mechanical parts. Despite the existence of commercial suites for computer-aided tolerancing, in general, they cannot be afforded by small businesses such as job shops and measurement service providers or be used in engineering courses in emerging economies. To bridge this gap, an open-source computational tool has been developed to assist the user with the specification of dimensional and geometrical controls. The proposed tool generates a point cloud from the nominal computer-aided design (CAD) model of the part and applies known virtual deviations to that original point cloud. Based on the modified/deviated point cloud, the user can perform virtual what-if analysis and improve the tolerancing process. This paper describes the implementation of the proposed method and presents the results of preliminary tolerance studies of some real components of the Sirius particle accelerator.

***Keywords*:** manufacturing engineering, computer-aided tolerancing, deviated point cloud generation

1. Introduction

Inaccuracies presented in machining processes cause inevitable dimensional and geometrical errors on the parts, which impact the assembly of mechanical systems and therefore require methods to control them. Consistent with the tenets of concurrent engineering, Leaney [1] introduced the term “design for dimensional control” (DDC) to refer to the manufacturing metrology discipline that recognizes and manages variation during design, manufacture, and assembly. DDC does not aim to eliminate variation, because it would not be possible, but rather to control it within reasonable limits, thereby allowing us to improve quality and reduce cost through controlled variation and robust design. To manage dimensional and geometrical variation, the DDC methodology is built upon some elements that include the use of geometric dimensioning and tolerancing (GD&T) and the use of computational tools for tolerance analysis.

The technical specification process of precision mechanical parts has evolved significantly with software packages related to computer-aided design (CAD), computer-aided manufacturing (CAM), computer-aided tolerancing (CAT) and digital mock-up categories. These suites allow not only the drawing of mechanical parts but also the assignment

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of dimensional and geometrical tolerances to the parts. For full control of the manufacturing process, these tolerances are added by the means of GD&T controls, using a common language to indicate how actual part features can depart from the nominal geometries listed in the design model. This engineering language is established in the ASME Y14.5-2018 standard and in a group of ISO standards, e.g., ISO 1101-2012, which allows the designer to mitigate ambiguous, uninformed, and incomplete specifications and to communicate with clarity the design intent. To support the decisions made during the design stage of a product, CAT tools have been developed and widely applied to predict the effects of form deviations on parts and assemblies and to ensure their functionality and manufacturability. This way, late product modifications, which are cost- and time-consuming, can be minimized and the product design process can be shortened [2].

Currently, dimensional and geometrical tolerances are applied to the model via annotations [3], a procedure known as the model-based definition. This way of assigning tolerances gives rise to two important issues. First, the tolerancing process is left exclusively in the charge of the designer, which could result in suboptimal tolerance specifications. Secondly, computational simulations that use the model will only consider the nominal characteristics of the part, neglecting form deviations that the manufacturing processes could have introduced to the part. If the specific manufacturing deviations are not considered in simulations, the assembly process under analysis cannot be accurately reproduced, and the simulation results will be incomplete [4]. In fact, simulations based only on the nominal values of a model can result in divergences between the simulation output and the actual output of a real assembly of a group of parts and their functional characteristics [5, 6]. These differences occur because of the stochastic and unpredictable nature of the manufacturing process itself [6]. Therefore, methods for including dimensional and geometrical deviations in the simulations have been explored and addressed by many researchers.

Henke et al. [7] presented two useful models for form errors of cylindrical features that were later employed by Summerhays et al. [8] to the specific problems of sampling plan and substitute geometry algorithm selection, particularly for tolerance analysis. Zhang et al. [9] proposed a method for the representation of geometrical errors, including form errors, based on the measurement data obtained from the machined surface (of an actual part prototype) using a coordinate measuring machine (CMM) with reasonable accuracy. Hofmann and Gröger [10] described the creation of points along the virtual surface of a part from virtually generated measuring data, indicating production process simulations as a potential candidate to represent the real (deviated) model. This approach does not depend on real prototypes for tolerance analysis purposes, but it depends on finite element simulations that are time-consuming, costly, and not integrated with tools that could apply ordinary dimensional and positional deviations for less complex tolerance analyses. Moreover, the authors did not provide details about the method for virtually discretizing the surfaces of the realistic model.

Once the 3D part models can be represented by specifying a set of surfaces known as the non-uniform rational basis spline (NURBS), Schneider [11] suggests that the measured 3D raw data can be used to create a CAD model that behaves as an approximation of the real geometries of the part. The model is rebuilt with an algorithm known as the NURBS Surface Reconstruction Algorithm [12]. This method may be considered a solution to one of the issues mentioned earlier, but it requires the production of a physical prototype for testing and evaluating the geometrical content. To handle this limitation, some methods based on the analysis of how the tolerances affect each other as a whole (tolerance stack-up) are already known. These techniques were introduced by Feng [13], and are part of a broader suite of techniques known as Variation Analysis. It is used to evaluate how the presence of errors in the model after the manufacturing process can affect future assemblies, thus providing a better tolerancing process. Despite that, these stack-up techniques are limited to simple surfaces and geometrical characteristics.

On the other hand, some commercial tools can provide good support for product and process development, allowing early prediction of the effects of dimensional and geometrical deviations on the assembled part [14]. For example, the EVOLVE software suite allows the designer to perform a “what-if” analysis of dimensional tolerances and hence improve the overall consistency of the tolerancing process [15, 16], and the TECNOMATIX® software enables the user to identify dimensional issues early in the design cycle by using linear equations or the Monte Carlo method, which was used by Barbero et al. [17] within a CAT-based methodology for the assessment of assembly tolerances, including a so-called dimensional hierarchization matrix and a tolerance optimization algorithm. The effective application of CAT software for tolerance analysis was described by Petruccioli et al. [18], who performed a sensitivity analysis of tolerances on some engine assembly operations in order to identify the main contributors to variation. Through CAT simulation, the authors reported that some tolerance intervals could be relaxed, thus reducing the manufacturing costs without putting at risk the functional requirements of the assembled component, whereas others needed to be shrunk in order to improve the assembly performance. On the other hand, Ziegler and Wartzack [19] presented an approach to adopt sensitivity analysis methods on current tolerance simulations, which was tested in the clearance evaluation of a fictional plain bearing. Idriss et al. [20] proposed a method based on sensitivity analysis to allow designers to identify the dimensions of the non-conformity rate in order to reduce the total number of key characteristics indicated on the drawings without loss of quality.

The creation of digital twins that virtually replicate the attributes of pipe spools, extensively found in the oil and gas industry, was reported by Fernandes et al. [21]. Using the VisVA™ - Visualization Variation Systems Analysis - computer-aided engineering (CAE) software, the digital twins were explored in the design stage of the development of pipe spools to estimate and understand the dimensional variations and to predict the behaviour of their subsets when joining them to each other. The authors concluded that the use of digital twins to investigate the geometry quality of pipe spools potentially allows the pipe shop to estimate the variation and capability of the original processes and, if required, redefine the fabrication and measurement plans, create alternative assembly sequences and propose design changes in full consonance with the best GD&T practices. Schluer et al. [22] presented a geometric-based approach to tolerance analysis for robust design of flexible assemblies, which embedded an in-house solution to create non-ideal geometries from the CAD model. In general, however, small businesses in Brazil, such as job shops and measurement service providers, cannot afford commercial tools like the one previously mentioned. From the teaching point of view, manufacturing metrology topics such as the management of dimensional and geometrical variations cannot be properly addressed in engineering courses because of the high acquisition cost of the commercial tools or the limited options for educational institutions.

Given the characteristics of the existing methods for virtually producing non-nominal models of complex parts, a computational tool has been developed for tolerance planning and analysis aiming to assist the designer with the specification of dimensional and geometrical tolerances. This way, the user can conduct tolerance analysis without the need to produce and measure a physical prototype or to use complex methods based on finite element simulations. The proposed tool is particularly relevant for the high-precision components of the fourth-generation synchrotron light source called Sirius, located in the city of Campinas, Brazil. The remaining portion of this paper details the implementation of the proposed computational tool and presents the results of preliminary tolerance studies carried out with the current version of the program.

2. Implementation of the computational tool

The computational tool called EGGTol, an acronym for Error Generator for Geometrical Tolerancing has been conceptualized and implemented to virtually produce non-nominal models of mechanical parts for assessing their dimensional and geometrical relations. This section describes the basic concept of the proposed tool, the implementation details, and the deviation modules.

2.1 *Basic concept*

The proposed concept relies on four main functionalities, which are: importation and interpretation of the nominal model of the part; discretization of the nominal surfaces from the imported model; virtual application of predefined manufacturing errors to the original (nominal) discretized point cloud; and exportation of the virtually deviated point cloud in a format similar to that obtained by any coordinate measuring system. Figure 1 illustrates the methodology proposed for a dimensional tolerance assignment and analysis using EGGTol, in which three additional steps associated with the use of EGGTol in the conventional product design framework are considered. The proposed tool virtually generates deviations from the nominal part model (the output is a deviated point cloud that reproduces the measurement of real surfaces) and third-party CAT software suites can be used to evaluate the GD&T characteristics defined by the designer (some CAT packages for tolerance evaluation can be downloaded free of charge). Within this iterative scheme, tolerances can be better defined in the early stages of product development. In addition, considerable time and cost reductions are expected because there is no need to manufacture real prototypes in order to generate the virtual deviated models.

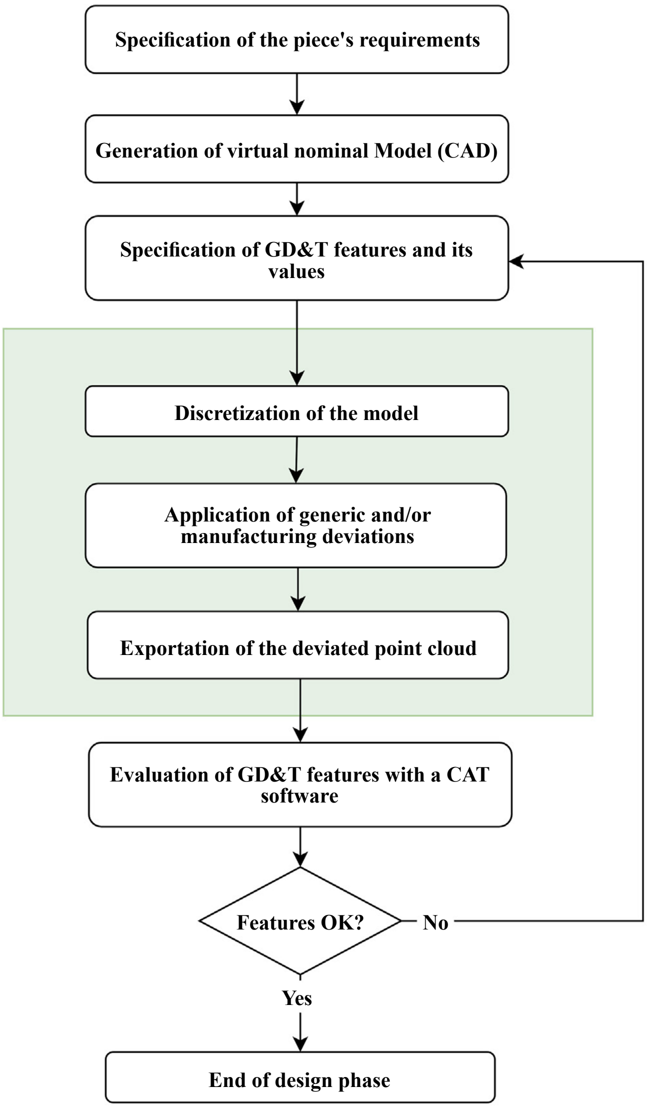

Figure 1. Proposed workflow for tolerance assignment and analysis with the use of EGGTol

2.2 *Implementation details*

The computational tool has been entirely written in Python programming language using the object-oriented scheme, and the source code is freely available in the public domain (GitHub remote repository) under the GNU Lesser General Public License, version 3. Currently, the developed tool features reading routines and interpretation processes for IGES files. It also includes the generation of point clouds in a generalized way from the nominal model. This resource can be applied both to flat surfaces limited by any polygon or free form and to any other complex curve that can be specified by a NURBS curve. Figure 2 illustrates the result of a complete high-density point generation performed on an exemplary part model using the discretization functionality of the proposed computational tool. Note that both flat and curved elements were discretized.

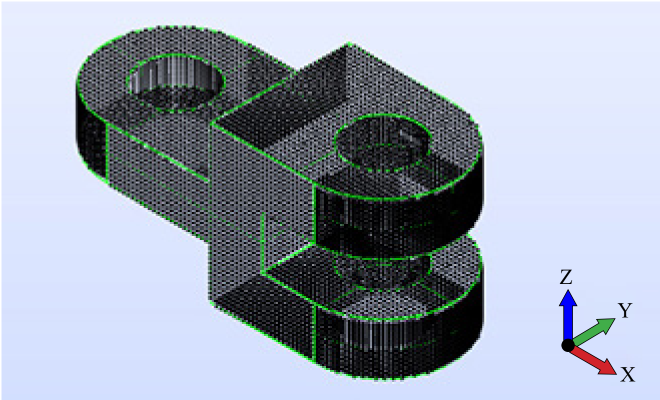

Figure 2. A high-density point cloud obtained from the nominal model of an exemplary part using the discretization function (extracted points exhibited in dark gray and surface edges highlighted in green)

2.3 *Deviation modules*

To artificially add geometrical deviations to the discretized point cloud, EGGTol has been designed to contain two main modules, one for adding generic deviations and the other for adding simulated manufacturing deviations. The module for generic deviations is already implemented and introduces dimensional and positional deviations to the extracted nominal dataset in a completely controllable and predefined way. The module for simulating manufacturing deviations is currently being developed and is planned to apply deviations to the discretized surface following the actual shape and magnitude associated with specific machining operations. Details about these modules are provided in this section, including the process of obtaining the turning deviation model and the simulation of real diameter deviations in rounded surfaces:

Generic deviations. In its current version, the proposed tool has seven modules for deviating a dataset in a specific way, that is translation, rotation, bending, torsion, ovality, periodic, and random deviations. The result obtained from each module in a simple discretized model can be seen in Figure 3. It is possible to vary some well-defined characteristics of the model through the application of one or more deviation modules. For example, the presence of random-generated errors modifies the flatness of any surface of the model and/or introduces measurement errors. With the application of translational errors, it is possible to simulate size deviations from flat and cylindrical elements (e.g., to control the diameter of a hole). Operations involving rotation can cause perpendicularity errors between surfaces and symmetry axes. The torsion and bending modules can simulate systematic errors associated with geometrical deflections of lathes, as in the case of the presence of a flexion profile on some faces of a machined part due to inaccuracies in the machine structure. In their turn, the periodic and ovality modules can simulate, respectively, roughness and ovality.

Simulated manufacturing deviations. Several papers [23-26] have described the use of artificial neural networks (ANN) to create models of manufacturing process deviations with promising results. For this reason, in order to implement a module for simulating the deviations in a manufacturing process, the method of modelling with ANN was considered. The first and, for now, only process chosen to have its deviation patterns modelled was turning, and the methodology for extracting the model based on an experimental approach [27] was strictly followed. In short, the applied procedures were as follows:

i. Definition of the required instrumentation and experimental setup capable of extracting the diametral deviations of a real turned part changing some controllable variables. The experimental setup comprised a cylindrical part with 75 mm in diameter and 250 mm in length made of C45 steel, clamped down on the chuck of the machine tool, a ROMI CNC MULTIPLIC 30D lathe equipped with a Fanuc Series 21i-T.
ii. Execution of the designed setup, in which, for each planned condition, the controllable variable was changed and a part was machined; then, the diameter of each part was measured with a micrometre in five different positions to determine the within-part diameter variation (output of the model).
iii. Composition of the training vectors, which form a simple Elman Recurrent ANN with six nodes in the input layer, i.e., the controllable factors (tool condition, cutting depth, feed rate, spindle speed, L/D rate

and Li/L rate; where L is the length of the part, D is the diameter of the part, and Li is the position along the main axis), a hidden layer with five nodes, and a single node in the output layer, i.e., the within-part diameter variation. Table 1 shows an excerpt from the training vectors for the ANN. The ANN was trained and stored in the source code.

iv. Loading into the program of the stored model in the form of an ANN and using the turning deviation module to generate deviation values according to cutting parameters informed by the user and part geometry.

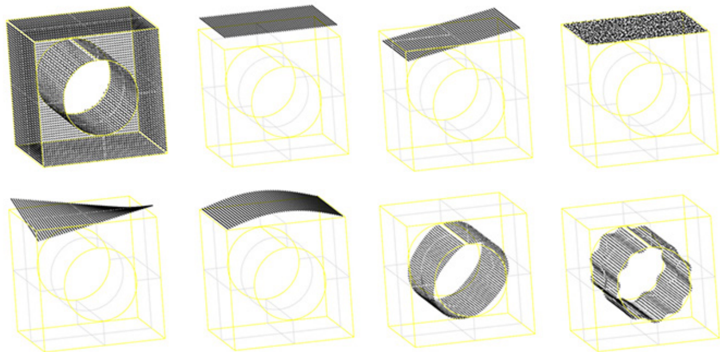

Figure 3. Virtual point clouds created with the discretization and generic modules. Top, from left to right: nominal discretized part, translation, rotation and random deviation. Bottom, from left to right: torsion, bending, ovality and periodic deviation.

Table 1. List of training vectors for the ANN

Training vectors	Factors						Response
	Tool condition	Cutting depth (mm)	Feed rate (mm/rev)	Spindle speed (RPM)	L/D	Li/L	Diameter error (mm)
1	0	0.5	0.10	800	2.567	0.90	0.021
2	0	0.5	0.10	800	2.567	0.74	0.021
...							
13	0	1.5	0.20	1400	2.674	0.53	0.017
14	0	1.5	0.20	1400	2.674	0.27	0.007
15	0	1.5	0.20	1400	2.674	0.07	0.018
...							
25	1	1.0	0.20	800	2.831	0.07	0.025
26	1	1.5	0.10	1000	2.917	0.09	0.033
...							
45	1	1.5	0.15	800	3.209	0.07	0.033

Figure 4 shows the generation of a virtually deviated point cloud from a cylindrical part by the turning deviation module. One can note the generation of a specific profile in the dataset on the left of the image, and the input parameters requested to the user on the right, which are related to the machining conditions. The method of modelling with ANN has some limitations regarding the range of the input data, though. The model provides accurate responses only if the given input data is within the range of the trained dataset. Therefore, the input parameters shown in Figure 4 are limited to the trained range, and the proposed tool does not automatically limit the geometry, but it is recommended to maintain the L/D rate within the trained range. Nevertheless, there is an intent to expand the geometries and materials of this experiment, which would lead to more reliable responses on a broader spectrum of input parameters.

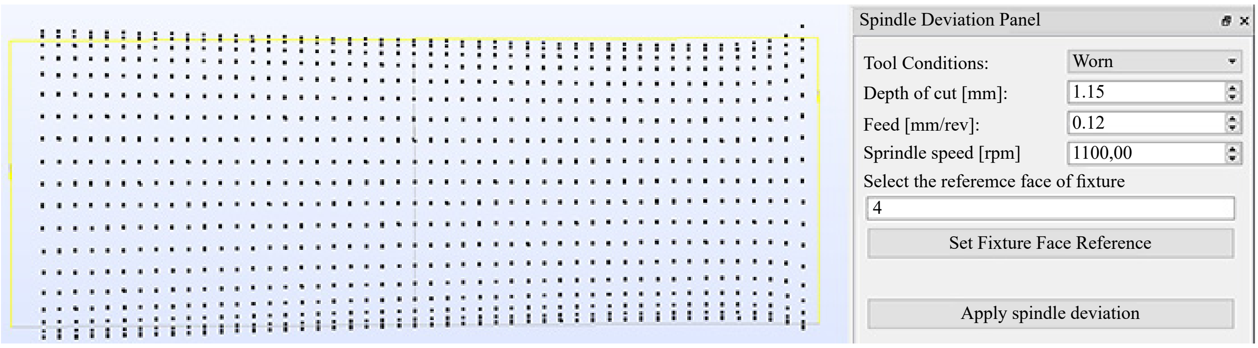

Figure 4. Spindle deviation panel and a deviated virtual part. The amplitude of the shift was multiplied by a factor of 100 for better visualization of the generated profile

3. Application cases

In order to assess the performance of the proposed computational tool in real-world applications, tolerance analyses were performed for measurement cases associated with the fourth-generation synchrotron light source called Sirius, located in the city of Campinas, Brazil. The first application case was focused on checking the consistency of the virtual point clouds generated by EGGTol from a precision mechanical component by comparing two different part designs with dissimilar, albeit known properties. The measurement problem and the results of this comparative study are shown in Section 3.1. The second application case, involving a more complex analysis, was intended to explore the full potential of the data generated with EGGTol in a cause-and-effect study (see Section 3.2).

3.1 *Performance evaluation of two different part designs*

The main components of particle accelerators are the magnets, which guide the particles along the desired trajectory. To work properly, the magnets need to be correctly located within the installation volume. For the Sirius particle accelerator, the permissible relative positional error between adjacent storage ring magnets is 0.04 mm (placed on the same support) and 0.08 mm (placed on separate supports) in both horizontal and vertical directions. To assist the metrologists in accurately aligning the magnets, laser trackers are used. A reference network of points is surveyed in the working volume of the particle accelerator and later used to locate the laser tracker stations. In the case of the Sirius project, the measured points on the magnets, called fiducials, are materialized by removable target holders for spherically mounted retroreflectors (SMR) of 38.1 mm in diameter. The target holders needed to be redesigned, motivated by large manufacturing deviations that caused alignment errors of the magnets beyond the specification limits.

The most probable explanation for the large deviations from the first version was the geometry of the seats (contact faces between the target holder and magnets). The hypothesis was that the position deviation for the center of the SMR could be improved by changing the seats to kinematic mounts. Figure 5 shows the original (left) and modified (right) CAD models of the target holder, with tolerances. The correspondence between the corner points and the functional axes of the magnets is calibrated through a special procedure called fiducialization (involving dimensional and magnetic measurements). The manufacturing deviations for the modified target holders were kept to 0.005 mm, thus having a small effect on the final position determination of the magnets' centerlines [28].

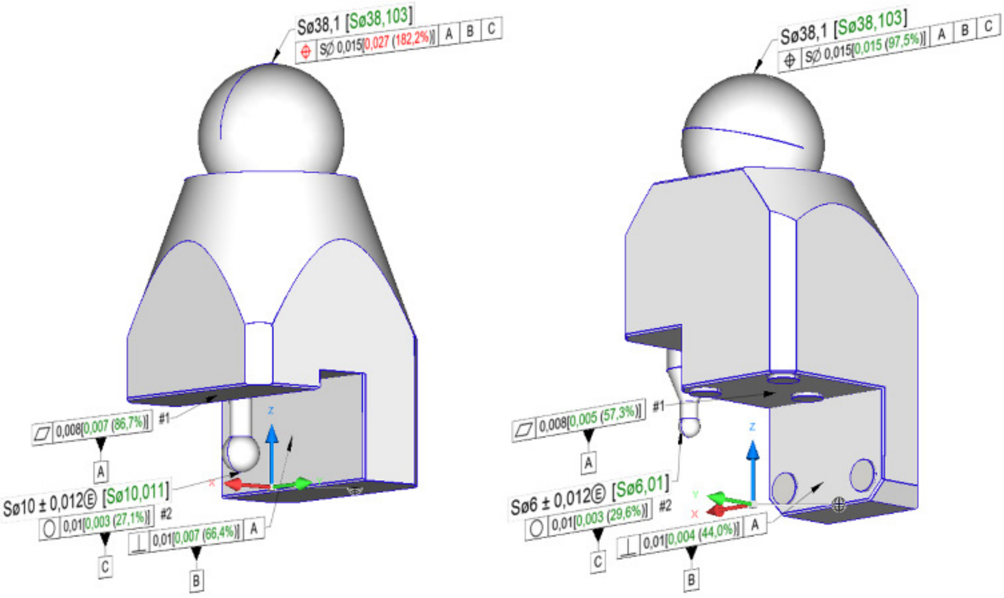

Figure 5. CAD models of the original (left) and modified (right) Sirius target holders containing the results obtained from the comparative study performed in the software EVOLVE SMARTPROFILE® from KOTEM)

To demonstrate the design improvements in terms of tolerance assessment, different simulated errors were specified and applied to the extracted datum elements of both the original model and the modified model of the component using the EGGTol functionalities. The value of the artificial errors applied to each datum element is presented in Table 2. Since the contact areas of the target holder were diminished in the modified design, the effect on the SMR position was expected to be reduced. In fact, for the position tolerance associated with the SMR, as shown in Figure 5, the actual result was 0.027 mm for the original design and 0.015 mm for the modified design, an improvement of approximately 44%. The reported deviations for the other specified tolerances (perpendicularity, flatness, circularity, and feature of size) were found to be kept at least to the same value as the modified design.

Table 2. Simulated errors applied to the extracted datum elements of both original and modified designs

	Translation	Rotation	Bending	Torsion
Datum A	0.002	0.007	0.000	0.003
Datum B	0.003	0.010	0.002	0.000
Datum C	0.004	0.000	0.000	0.000

3.2 *Causality study of deviations upon a Beam Position Monitor support*

The Beam Position Monitor (BPM), detailed by Kwon [20] and highlighted in Figure 6 (left) with its support, is responsible for measuring the electron beam position that is crossing perpendicular to the measurement plane, composed of four capacitive probes (pick-ups) pointed to the center of the vacuum chamber. The position information is then used in a closed-loop control to correct the electron orbit through the manipulation of the magnet's current. Since the correction algorithms depend on the relative position of the BPM from adjacent magnets sharing the same base, the alignment and positioning are crucial to a consistent operation of the accelerator. The BPM mechanical position is steered by the support, which contains some GD&T controls that were examined using the proposed computational tool.

The process of tolerance analysis using the proposed tool is as follows: (a) import the CAD model, (b) discretize the model's surfaces, (c) apply deviation to the point cloud referring to surfaces of interest, (d) save the resulting point cloud, and (e) evaluate it in a CAT suite, such as the EVOLVE package (from KOTEM). The tolerance analysis steps can be correlated with some questions:

i. Given the GD&T characteristics, what would happen to the surfaces of interest when the datums are subject to deviations close to or outside the tolerance limits?
ii. Would the nature of a deviation (e.g., flexion versus torsion) in a datum affect the surface of interest?
iii. Is it feasible to optimize the tolerances of an already designed part to better fit its application?

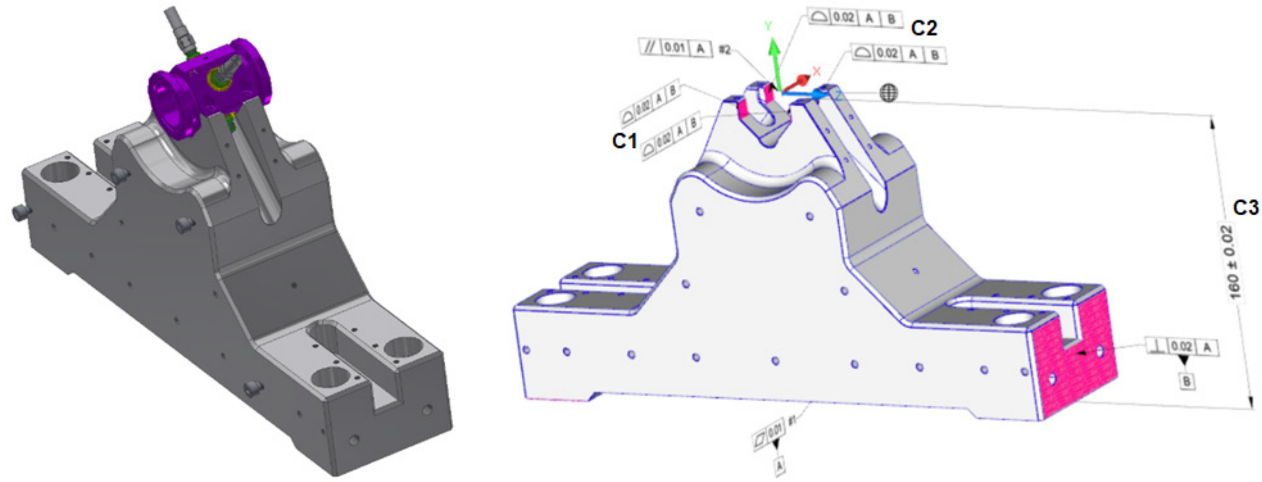

Figure 6. CAD model of the beam position monitor mounted on the support (left image) and an example of the high density deviated point clouds, highlighted in pink, extracted from the surfaces of interest (right image)

Figure 6 (right) indicates the two datum planes (A and B) and three characteristics referenced to the datums: the vertical stopper for the BPM (C1, two profile tolerances), the horizontal stopper (C2, two profile tolerances) and the height (C3, dimensional tolerance). Since these characteristics are strictly related to the quality of the BPM positioning, their deviations (caused by errors on the datums) were chosen as the variables of interest. To evaluate the effect of the deviation applied to the datums, three factors were considered: the magnitude of deviation applied to datum A (factor F_1), the magnitude of deviation applied to datum B (factor F_2), and the type of deviation applied (factor F_3). Then, three levels were chosen for F_1 and F_2 (0.005 mm, 0.010 mm, 0.020 mm), and two levels were chosen for F_3 (flexion, torsion). Hence, the effects of deviations larger and smaller than the specified tolerances for the datums would be investigated for 18 runs (full factorial design). The results are presented in Table 3, where deviations greater than the given tolerance for the specific feature are highlighted in gray.

Table 3. Applied deviations on the datums and the effect on the surfaces of interest

Trial	Factors *(mm)			Surfaces (mm)		
	F_1*	F_2*	F_3	C1	C2	C3
1	0.005	0.005	Flexion	0.010	0.000	-0.017
2	0.005	0.005	Torsion	0.001	0.003	-0.004
3	0.005	0.010	Flexion	0.021	0.000	-0.017
4	0.005	0.010	Torsion	0.006	0.003	-0.004
5	0.005	0.020	Flexion	0.042	0.000	-0.017
6	0.005	0.020	Torsion	0.016	0.003	-0.004
7	0.010	0.005	Flexion	0.010	0.000	0.000
8	0.010	0.005	Torsion	0.003	0.006	-0.009
9	0.010	0.010	Flexion	0.021	0.000	0.000
10	0.010	0.010	Torsion	0.002	0.006	-0.009
11	0.010	0.020	Flexion	0.042	0.000	0.000
12	0.010	0.020	Torsion	0.012	0.006	-0.009
13	0.020	0.005	Flexion	0.010	0.000	0.000
14	0.020	0.005	Torsion	0.022	0.011	-0.017
15	0.020	0.010	Flexion	0.021	0.000	0.000
16	0.020	0.010	Torsion	0.026	0.011	-0.017
17	0.020	0.020	Flexion	0.042	0.000	0.000
18	0.020	0.020	Torsion	0.038	0.011	-0.017

Percentual contribution analysis of each factor of the response variables was performed to draw a better comprehension of the collected data. The percentual contribution of a factor, in the absence of error contribution due to variance (the measurement simulation, in this case, has no variance sources), is given by:

$$P_F = \frac{SS_{Fi}}{SS_T} \tag{1}$$

where SS_{Fi} represents the sum of squares of the i_{th} factor, and SS_T is the sum of squares of every factor and their interactions. The results of the percentual contribution analysis of the pure factor (F_i, i=1, 2, 3) and factor interactions (F_{ijk}, i, j, k=1, 2, 3) to each of the surfaces of interest are provided in Table 4.

Some qualitative and quantitative conclusions can be drawn from the results presented in the tables. In Table 3, there are some combinations of deviations within the respective tolerances that led to surface C1 being out of tolerance (highlighted in gray). This is an indication that the chosen tolerances for datums A and B may not have been the most suitable to meet the functional requirement of the vertical stopper (C1). By analyzing the percentual contribution columns of Table 4 one can note that factor F_2 (i.e., deviation applied to datum B) affected the most the vertical stopper of the part, while F_3 (i.e., type of deviation applied) was the most critical for profile error associated with the horizontal stopper (C2) and the interaction of factors F_1 and F_2 was the major source of vertical deviation (C3). In fact, based on the simulation results, the designer could revisit the orientation control associated with datum B, e.g., assigning a smaller tolerance value, or including an additional flatness tolerance to control the surface form. However, since this application case was associated with a design-frozen part, changes in the tolerancing process were not possible at all. Instead, the main objective of this application case was to demonstrate the usefulness of the proposed tool in a tolerance analysis process, which could be regarded as achieved.

Table 4. Sum of squares (SS) and Percentual contribution (P) of each factor and interactions in different conducted analyses

Factor	**Deviation analysis**					
	C1		C2		C3	
	SS (e^{-4})	*P*	*SS* (e^{-4})	*P*	SS (e^{-4})	*P*
F_1	4.87	14.51	0.49	16.44	1.12	12.17
F_2	16.2	48.33	0.00	0.00	0.00	0.00
F_3	4.80	14.32	2.00	67.11	0.84	9.18
F_{12}	4.87	14.51	0.49	16.44	7.24	78.65
F_{13}	2.62	7.82	0.00	0.00	0.00	0.00
F_{23}	0.08	0.26	0.00	0.00	0.00	0.00
F_{123}	0.08	0.26	0.00	0.00	0.00	0.00
Total	91.3	100	2.98	100	9.20	100

4. Concluding remarks

GD&T is an indispensable design tool for communicating the design intent and therefore manufacturing components consistent with the required function. In today's manufacturing scene, the use of computer-aided techniques, such as CAD and CAM, has spread across industries, and many CAT tools for assisting the designer to specify accurate dimensional and geometrical controls even in the early stages of product development have been implemented and commercialized. However, these commercial tools may not be an option for job shops and educational institutions in countries like Brazil. In this context, an open-source computational tool has been developed in the Python language to support the designer in assigning dimensional and geometrical controls.

The operation of the proposed tool is based on four main functionalities: importing a CAD model; discretizing the part's curves and surfaces; applying artificial (virtual) deviations (that describe the actual pattern of manufacturing deviations on surfaces and curves) to the points; exporting the modified (deviated) dataset in a format readable by CAT evaluation packages. The modified dataset can be then evaluated in third-party CAT software, including the measurement software integrated with coordinate measuring systems, and a what-if analysis can be performed. This workflow was put into action in the design review of important components of the Sirius particle accelerator structure. The results observed in the application case were consistent with practical observations.

Given the effective outcomes obtained from the application cases of the proposed computational tool outlined in this paper, extensive tests are planned to be conducted with practical cases in a pilot program involving different technical sectors of the Brazilian Center for Research in Energy and Materials (CNPEM), such as the mechanical design group and the dimensional metrology group. The main objective of this pilot program is to demonstrate in a broader scenario the feasibility of virtual prototyping with the proposed method. Further developments will involve the inclusion of other manufacturing deviation modules as well since in the current development stage they are limited to turning operations.

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Statements and declarations

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Competing Interests

The authors declare no competing interests.

Availability of data and material

All data and materials are fully available without restriction.

Code availability

Not applicable.

Ethics approval

Not applicable.

Consent to participate

Not applicable.

Consent for publication

All authors have reached agreement for publication.

Author contributions

All authors contributed significantly to the research design and development. The first draft of the manuscript was written by Rodrigo Oliveira Neto and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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