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A functional tolerance model: an approach to automate the inspection process

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ABSTRACT

Purpose: Purpose of this paper is the definition of a framework to describe the Technological Product Specifications (TPS) and the information associated with the geometric dimensioning and tolerancing to integrate the design concepts into a commercial inspection system.
Design/methodology/approach: A functional tolerance model provides a complete framework to define the geometric dimensioning and tolerancing and its relationship with the part geometry and the inspection process. This framework establishes a connection between a computer aided design and computer aided inspection system throughout the exportation of the information associated to the dimensions and tolerance of the part into a commercial CAI system.
Findings: They are mainly focused on the definition of a framework that describes the relationship between the entities of dimensions and tolerances with the geometry of the part. The information imported to a CAI system allows to develop the inspection process without the additional information provided by a physical drawing of the part.
Research limitations/implications: They regard the limited access to commercial CAI system and to the lack of protocols of exchange of data associated to the tolerances of the part.
Practical implications: They involve facilitation of the inspection process development. This implication allows realizing the inspection process reducing the time spent to define the geometry to inspect and the parameters that must be controlled.
Originality/value: The main value of this research is the development of a unique framework to extract the information related to the geometric dimensioning and tolerances and the geometry of the part in a common model. This model provides a complete definition and representation of the entities, attributes and relationship of design and inspection system.
Keywords: Automation engineering processes; Geometric Dimensioning and Tolerancing (GD&T); Inspection process

1. Introduction

The Concurrent Engineering has been accepted as one of the most influencing initiatives on the introduction of new products and processes within the last decade. In a globalize market, the development of low cost and high quality products pressures industries to improve and to optimize manufacturing processes. Industries must focus mainly on reducing the time for designing, manufacturing and inspecting. With the advances in manufacturing technologies and in computer aided systems, the integration of information given by the lifecycle of a product has been facilitated. The necessity to speed up the development of a product has led to replace the scheme of sequential processes by a simultaneous or concurrent scheme. The last has the purpose of overlapping the activities in order to reduce the development time. In this sense, the integration of the systems of design, manufacturing and inspection in a computer aided process planning platform, based on the concurrent engineering concept, will support the improvement and optimization of the inspection process planning throughout its automation.

The inspection process planning in coordinate measuring machines has the objective of defining and setting up an optimal and detailed inspection operation sequence to be carried out on an specific product. The definition of the inspection optimal sequence depends on the information extracted from three knowledge areas: design, manufacturing and inspection.

The design information includes a detailed characterization of the part geometrical specifications together with dimensioning specifications and tolerancing. This information has the purpose of referring the geometrical specifications, dimensioning and tolerancing of a computer geometric model. It allows the representation of a piece according to three levels: cells, dominions and bodies. These entities allow the definition of a group of primitives such as surfaces, splines and points [9].

The manufacturing information includes the information related to the type of process (cutting or forming) and to parameters used during the product manufacturing, e.g. machining advance, cutting depth, machine tool specifications, etc. The manufacturing processes are grouped into two processes: cutting processes (turning, milling, drilling, etc) and forming processes (bending, extrusion, forging, etc).

The inspection process information includes the specification of the inspection resources and capacities and characteristics of the production machines. At the moment, the integration between manufacturing and inspection process has been developed into two levels: information and machines. The first level involves the definition of the information associated to manufacturing and inspection process [3]. The second level involves the integration of a hardware available to develop the manufacturing and inspection process [6].

The following section describes the implication of the recognition of geometric patterns and tolerancing. Section 3 presents a brief state of the art about the knowledge based methodologies. Section 4 describes the functional tolerance model developed. Section 5 presents the implementation of the tolerance model in an informatics platform. Finally section 6 presents the conclusions of this research.

2. Recognition of the geometric patterns and tolerancing

A geometric specification of products and mechanical parts - Technologic Product Specification, TPS- is an aspect of great importance in the inspection process. This is due to the crucial information they provide regarding dimensioning, geometric and finishing specifications of a product. The incorporation of product geometric specifications to methodology TTRS - Technological and Topological Related Surfaces- makes it possible to use information related to the product geometry with a more rigorous level of detail.

Different research groups have focused their efforts on the development of methodologies that partially use TTRS to structure a functional model of tolerances [18]. Through international standards and other approaches, models of information have been developed to define both the inspection process [4, 5] and the knowledge models apply to automate the design of machining fixtures [10].

Modeling and representing information contained in GD&T (Geometric Dimensioning & Tolerancing) are of crucial importance in industry due to the advances in integrating manufacturing technologies. In this sense, an information model associated to the GD&T must provide a generic support through which it may be possible to include standards such as ASME 14.5M, STEP and DMIS.

Using the ASME 14.5M standard, Zhao has modeled a group of tolerancing establishing several levels of hierarchization [20]. Besides, Islam has proposed a prototype system to represent tolerancing and functional dimensioning in a concurrent engineering environment through the conversion of the product function requirements in dimensioning specifications [11].

The information required to define geometric tolerancing in complex forms and machined parts is not available in early stages of the design process. However, by integrating tolerancing models it is possible to create a tool to analyze 3-D tolerancing based on standardized specifications in coordinate measuring machines [2, 19].

Taking into consideration the conceptual framework in which the inspection process takes place, this paper proposes the use of TTRS and TPS methodologies to define, within the 3D product design phase, the principal product geometric specifications (dimensioning, geometric and finishing tolerances). Then the definition and implementation of the product geometric specifications in a CAD system makes it possible to export the information related to tolerancing to a computer aided inspection system.

3. Knowledge based methodologies

During the last decade, the evolution in artificial intelligence techniques have taken the interest of several researchers in the so called multi-agent systems. The fundamentals of this technique consider an agent as an entity with useful attributes in a specific domain. These agents are perceived as entities that emulate the inferring processes of the human being. The multi-agent systems being developed at present cover a wide range of engineering fields. Thus, it is possible to find applications to them in designs of products [13] of fixtures [17] and in process planning [14].

According to the above, it is clear that a Knowledge Based System, KBS, or a Knowledge Based Engineering – KBE, can be implemented through the use of different techniques of knowledge representation, together with a reasoning or inference method.

It becomes clear as well that the KBS system development needs advanced techniques of programming to capture and re-use product and process knowledge in an integrated way. In this sense, it is necessary to analyze the probe of how to capture and represent knowledge for its use in a KBS system applied to a specific engineering area. Intense research has been carried out in recent years to establish a methodology that allows to capture and re-use the knowledge. As a result, several methodologies involving knowledge re-use and capture from different points of view has been developed. For example the architecture proposed by Hunter [9] establishes a different approach to develop a knowledge model.

The CommonKADS methodology covers all the process of KBS/KBE system development. It considers the use of tools and techniques for knowledge capture and representation [15]. It uses the UML language –Unified Modeling Language-. The main phases proposed in CommonKADS for modeling the knowledge are:

- Context model: It comprises three different models, i.e., organizations, tasks and agents.
- Knowledge model: It involves three sub models, i.e., dominion (static view or information structure), inference (reasoning process), task (application objectives).
- Communication model: It comprises the definition of information exchange procedures for knowledge transferring between agents.

On other hand, the MOKA methodology is a methodology based on CommonKADS developed by the automation of the engineering environments [16].The position proposed by MOKA is applied to engineering environments where a detailed procedure for a specific process design exists. Also, the knowledge is clearly identified. In this context, MOKA provides a framework for representing and storing the knowledge for KBE systems. Influenced by CommonKADS, its objective is to provide support to reduce the effort and risk associated with the development of KBE systems. The MOKA methodology defines knowledge at two levels. The first level captures knowledge in a semi-formal model classified into five types. The second level is a formal model that makes it possible to represent knowledge in a structured way, using the MML language (MOKA Modeling Language, MML).

Other investigations related to Knowledge Based Systems and knowledge modeling may be found in different areas, such as prediction of surface roughness in turning processes [1], fixture design for high speed machining [8], knowledge representation for CAPP systems [7] and metal forging [12].

4. Functional tolerance model

The functional tolerance model for geometric dimensioning and tolerances has been structured in three models directly related and two indirectly related. Figure 1 shows the structure of the knowledge unit that composes the functional tolerance model for GD&T. The Geometrical Knowledge Model and the Inspection Knowledge Model are two knowledge units that provide information to define the needed information to develop the functional tolerance model.

The geometrical model defines and describes the entities that constitute the topology for geometrical design. It is important to highlight that the entities are modeled using a common modeling language. Topology allows representing objects by detailing their boundaries and the connections between their different parts. The basic concepts associated to the topological object can be classified in three types of entities: cells, domains and body. A Cell is an entity limited by a basic geometry, and it is the most basic topology entity. A Domain is a set of connected cells of dimension "n" connected by cells of dimension "n-1". It is possible that a domain can contain only one cell. A Body is a set of domains not necessarily connected, i.e. the concrete object to model.

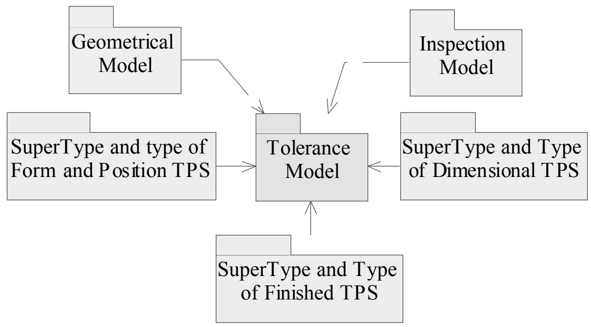

Fig. 1. The functional tolerance model

The form and position TPS submodel establishes a framework to describe the associated attributes to form and position tolerances. This framework allows to link the geometric features of the part with both form and position tolerance. This information has been presented in Figure 2.

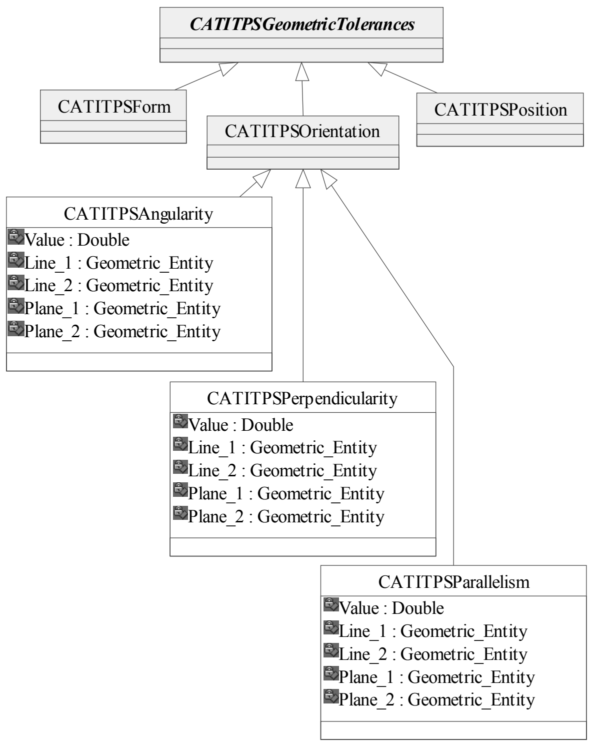

Fig. 2. Architecture of form and position TPS

This figure shows the architecture for this submodel.

- The Orientation Geometric Tolerances submodel includes the specification of tolerances associated to other elements by orientations. The definition of the angularity, parallelism and perpendicularity tolerances require the specification of the attribute related to the geometric features of the part.
- The Form Geometric Tolerances submodel defines a set of features related to straightness, flatness, circularity, cylindricity, and profile for lines and surfaces. The attributes of those features are related to geometric features (lines, splines and surfaces) and numerical tolerance values.
- The Position Geometric Tolerances defines a set of features for the position of the elements in respect of other elements. The position, concentricity, symmetry and run out tolerances need some attribute to declare the position of geometric tolerances (lines, splines, planes, cylinders, etc.)

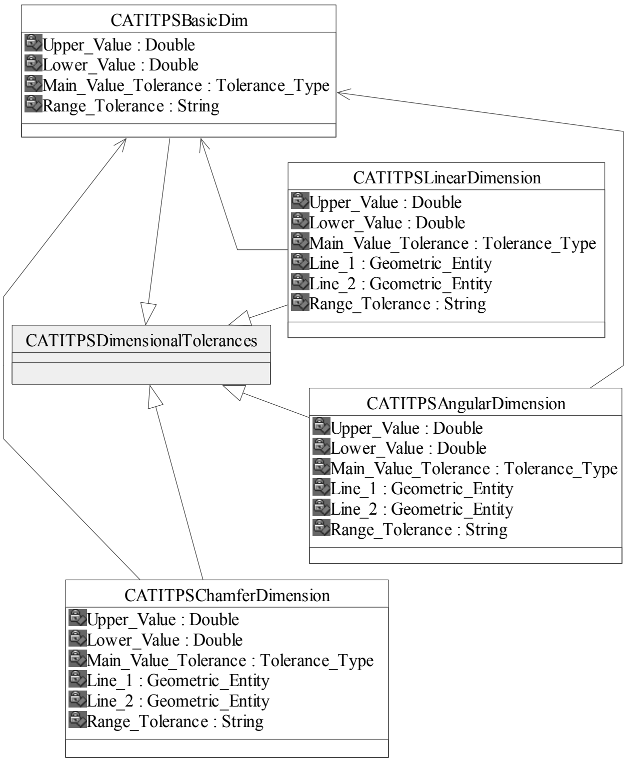

Fig. 3. The dimensional TPS architecture

The supertype and type of dimensional TPS submodel represents the main features of the part dimensioning. These features are associated with the geometrical features of the part. Each of the dimensional features is linked to a line, circle or curve of the part.

The basic entities proposed on the dimensional TPS submodel are:

- The linear dimension entity which describes the basic values of the tolerance (upper and lower values), the tolerance type, the range of the tolerance and the restricted geometric entity.
- The angular dimension entity which describes the angularity between two geometric elements.
- The basic dimension entity which describes the dimensional value associated to any tolerance. In this case, the linear, angular and chamfer dimensions are linked to the basic dimension entity. The basic dimension entity makes it possible to define the information needed to complete the declaration of each dimensional tolerance. To declare the basic dimension, it is necessary to define the geometric entity that is affected to a tolerance.

Figure 3 shows the architecture of the dimensional tolerances framework.

The supertype and type of finishing TPS submodel describes the finishing parameters and values of the restricted geometry entities of the part. The main features and structure included in this submodel are presented in Figure 4. The parameters and values of finishing features are expressed through the entity that affects a single profile of the part.

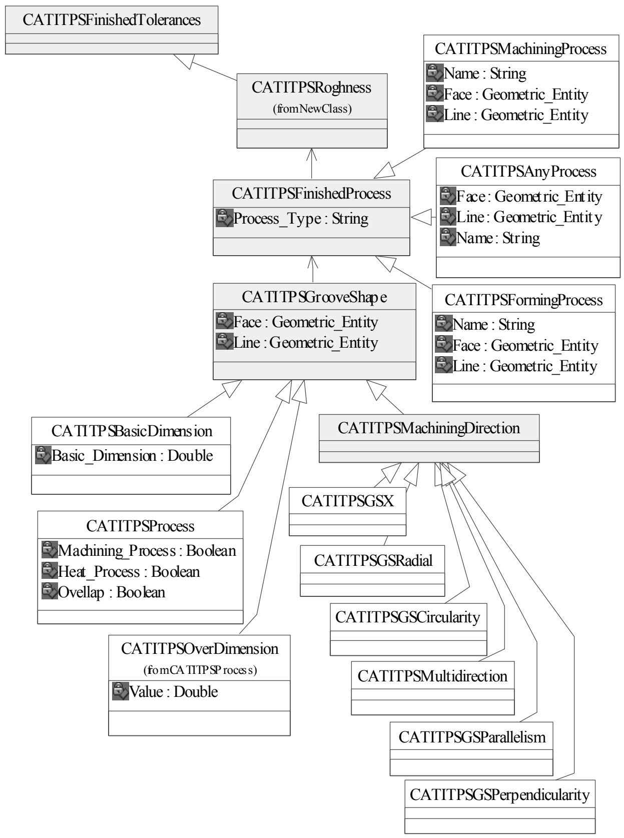

Fig. 4. Entities and parameters for finishing tolerances

In order to declare the finishing tolerances, the information related to the geometry of the part to inspect should be defined. In this context, the finishing tolerance submodel is linked to the geometrical model through the definition of the individual identifiers. These identifiers provide the information about the geometric element restricted.

Table 1.
Features of the tolerance model

Submodel	Super type and type of feature
Supertype and type of form and position TPS	▪ CATITPSGeometricTolerances
	▪ CATITPSForm
	▪ CATITPSStraighness
	▪ CATITPSFlatness
	▪ CATITPSPosition
	▪ CATITPDOrientation
	▪ CATITPSAngularity
	▪ CATITPSParallelism
	▪ CATITPSPerpendicularity
Supertype and type of dimensional TPS	▪ CATITPSDimensionalTolerances
	▪ CATITPSLinearDimension
	▪ CATITPSAngularDimension
	▪ CATITPSSecondLinear Dim
	▪ CATITPSChamferDimension
	▪ CATITPSBasicDim
Supertype and type of finishing TPS	▪ CATITPSRoughness
	▪ CATITPSFinishingProcess
	▪ CATITPSMachiningProcess
	▪ CATITPSFormingProcess
	▪ CATITPSAnyProcess
	▪ CATITPSGrooveShape
	▪ CATITPSMachiningDirection

The additional information about the distribution of the marks or type of manufacturing process is obtained through the single attributes declared on roughness (finishing) symbols. Figure 5

shows the information needed to establish the declaration of the finishing tolerances in the program application.

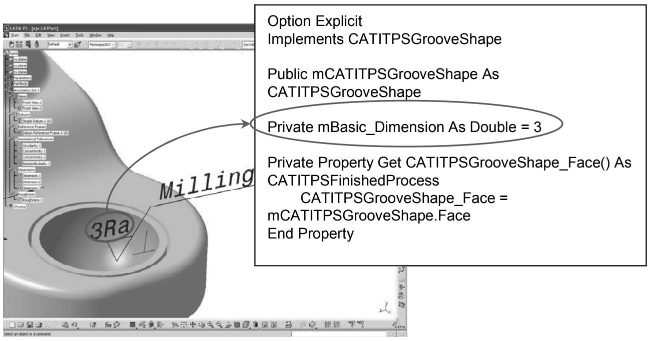

Fig. 5. Declaration of finishing tolerance parameters

The main features of the tolerance model are presented in Table 1.

5. Implementation of the tolerance model framework

In the next section, the implementation of Geometric Dimensioning and Tolerancing in a computer application system is presented.

The tolerance model framework provides a group of interfaces designed to describe the technological product specification entities of the part to be inspected. In this sense, a main requirement in the implementation of the tolerance model is the definition of the geometric interfaces.

The geometric interfaces describe the features that represent the geometry of the part. For example, a tridimensional geometry such as a cylinder can contain information related to forms, dimensions, tolerances and other attributes. In this case the tolerance model is linked with the geometric interfaces to establish a virtual connection for accessing the information provided by the geometry of the part.

Due to this reason, the implementation of the tolerance model in a computer platform has been developed in two stages. The first one provides a complete framework to define the architecture of the three dimensional geometry. This framework includes the definition of the geometrical ontology that establishes the conceptualization of all entities considered. The entities have been structured in three basic entities.

The first entity is a cell. According to the dimension of the space in which the geometric design is modeled, there are four types of cells. Table 2 shows the cell type for different space design dimensions. The generic identifier is defined for each geometry of the part. For example, a point in the part is associated to one identifier. This identifier contains the information about the boundary entities and the geometric tolerances. This information is used to integrate the geometry and the geometric dimensioning and tolerancing features.

The second entity is a domain. A domain is a set of n-dimensional cells linked to n-1 dimensional cells. Also, a domain is useful to manipulate the boundaries of an upper dimension cell all together.

Table 2.
Cells dimensions and program identifiers

Space design dimension	Cell type	Related geometry	Generic Identifier
0	Vertex	Point	CATITPSPoint
1	Edge	Curve	CATITPSCurve
2	Face	Surface	CATITPSSurface
3	Volume	3D Space	CATITPSSpace

The third entity is a Body. This entity can be built through a group of n-domains. The geometry also makes it possible to define a group of primitive entities, such as surfaces, splines and points. These basic entities are linked to the features defined in Table 1, in a three dimensional graphics system. Figure 6 shows the definition of the geometric and dimensional tolerances in a three dimensional system.

The importing of both geometrical dimensioning and tolerancing is carried out through the program realized in Visual Basic in CATIA V5. The result of the application of this program is a STEP file that contains the GD&T information associated with the part geometry.

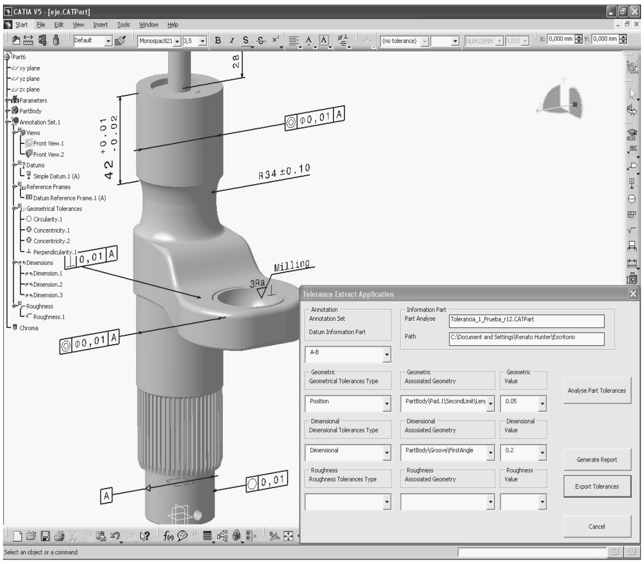

Fig. 6. Definition and importation of GD&T from CAD to CAI system

The second phase is the definition of the knowledge based system structure. This structure involves the definition of two modules. The first module, extracts the topological and geometric information associated to the part to be inspected. In this module, a group of identifiers is defined for each feature of the geometry, such as surfaces, faces and lines. These identifiers are linked to a single GD&T marker. These markers contain a set of attributes that define all the properties of the tolerances to be inspected. Figure 7 shows the identifier associated to a cylindrical surface.

The information provided by the CATITPSFace_50 identifier includes a geometric (concentricity) and dimension tolerance (+0.01/-0.02). In this context, the CATITPSFace_50 provides a definition of the TTRS features of the part. Through the definition of the TTRS identifier, it is possible to define the geometry associated to the TTRS identifier and the relationship of the boundary geometric of this identifier, i.e. a cylindrical surface in the case of CATITPSFace_50 identifiers.

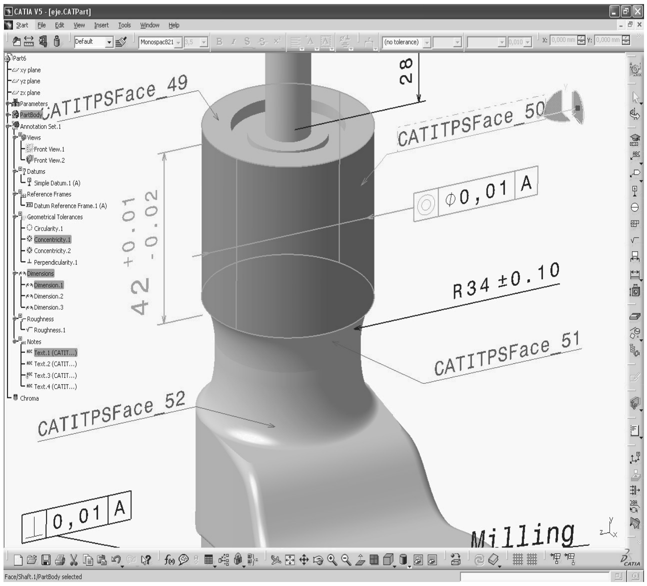

Fig. 7. Identifiers associated to geometric part

This process is called topological information extraction from the part. The information extracted is associated (to geometric element) to identify those areas or parts to be inspected those that are affected by dimensional or tolerance restrictions. In this context, the information on geometrical dimensioning and tolerancing is used to assist inspection process planning.

The second module uses the information extracted in the first module to develop the inspection process and the inspection fixture design in an integrated framework. The information related to develop the inspection process involves the definition of the inspection elements, dimensional or geometric tolerances, the inspection sequence and inspection resources (CMM, probe head and Styli).

The information related to the fixture design involves the virtual representation of the fixture and the conditions of the inspection process environment (visualization of the tool path, virtual representation of the CMM and the fixture component). Using a functional perspective, provides a significant advantage to share, reuse and store the knowledge implied in the fixture design process. These advantages have been used to develop a knowledge model as a base for the generation of the knowledge based engineering (KBE) applied to fixture design. This approach provides a definition of the knowledge model for the fixture design process and its implementation in a computer integrated architecture into CAX systems.

The architecture of the virtual fixture design system is made up with four main modules. The first one executes the functional analysis of the virtual representation of the fixture design and establishes the connection with the inspection resources (CMM, tools, fixture components, etc.).

On the second module, the result of this functional analysis for the virtual fixture representation is used to define a detailed model of the fixture design and its inspection environment.

The third module uses the detailed model to establish the validation of the environment of virtual inspection process through the analysis of the tool path interference, load and unload metal parts and fixture components, the cost and time analysis expended to design, to build and assembly the fixture.

Finally, sections of this knowledge model have been reused for building other applications in the environment of virtual simulation of fixture design, as machining fixtures.

The application of theses concepts to the domain of fixture design allows the planning and virtual simulation of the inspection process to be supported, and it brings the benefits of implementation of the tolerance model to capture, formalization and reuse the tolerancing information in other computer applications.

The information for geometric dimensioning and tolerances is exported from the CAD to CAI system through the STEP AP 203 protocol (Application protocol: Configuration controlled design). The structure of the knowledge based system is shown in Figure 8.

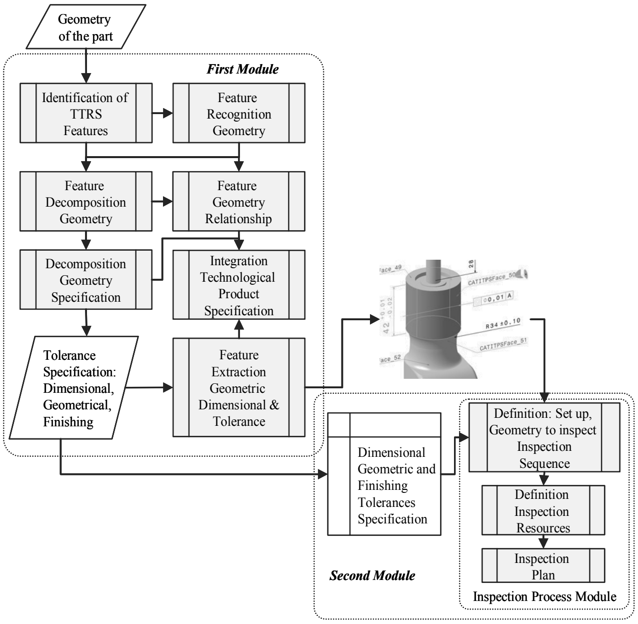

Fig. 8. Structure of the KBS inspection system

A knowledge unit of inspection is defined to develop the inspection process. The inspection knowledge unit involves defining the information concerning three main areas.

- The inspection process knowledge unit defines the activities and object (rules) implied in the development of the inspection process, and also involves the definition of the elements to be inspected of the part (elements that have been associated to dimensional or tolerance restrictions), the inspection sequence and the assignment of resources for the execution of the inspection process.
- The inspection resources knowledge unit describes a detailed view of the types, forms and dimensions of the available inspection resources involving in the inspection process, such as CMM, probe head, styli and fixture resources.
- The inspection fixture knowledge unit defines the information and rules needed to establish an initial solution for the inspection fixture configuration. The fixture knowledge unit describes the framework of a knowledge based engineering system application for fixture design automation. The methodological framework allows a hierarchical structure to be defined for a group of sub-models, which describes the knowledge field of fixture design.

To develop the inspection process, the information flow that exists among the activities involved in this process have been analyzed. The main activities and the information of the inspection process were described previously and they have been modeled using the IDEF0 methodology. Finally, the STEP file generated can be read by a CAI system (PC-DMIS was used). The CAI system represents the geometry of the part to be inspected but also shows the information related to the geometric dimensioning and tolerancing associated to constraint geometry in the part to be inspected.

The visualization of the GD&T in a CAI system is a three dimensional representation. Also the geometric dimensioning and tolerancing information can be represented in an Excel file. This file contains the information of the identifier (name), tolerance type (flatness, circularity, cylindricity, concentricity, symmetry, perpendicularity, etc.) and the numerical value assigned to tolerances.

The integration of the GD&T information into a CAI system makes it possible to start the inspection process without additional design process information. Then, the inspection resources (probe heads and styli) and the inspection sequence must be defined, using the information provided by a prototype application. The part elements to be inspected are defined by the geometric dimensioning and tolerancing restrictions visualized in the CAI system.

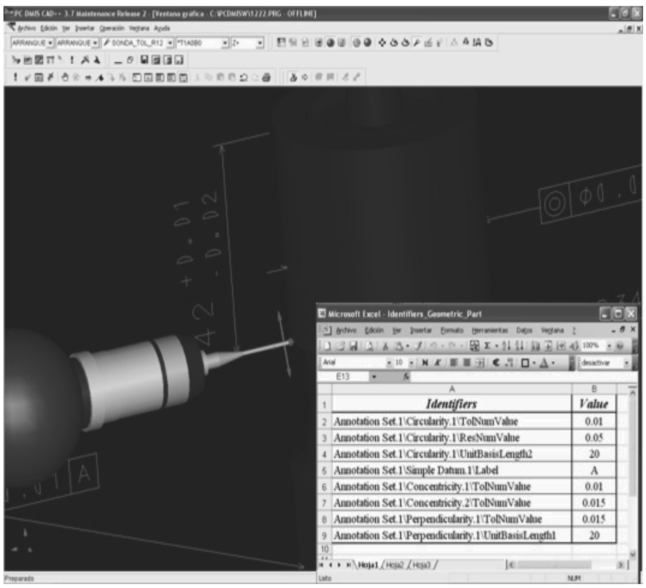

Fig. 9. Visualization of the part and GD&T in a CAI system

The geometric dimensioning & tolerancing features represented in the CAI system cannot be modified and manipulated inside this system. According to this implementation, the GD&T specifications are engaged with geometrical objects independently of the geometry to be inspected. However, the modification of the geometric dimensioning & tolerancing features can be developed into the CAD system used to design the part geometry. Figure 9 shows the representation of the imported STEP file and the GD&T Excel file generated with the prototype application.

6. Conclusions

A functional tolerance model has been developed to integrate the technological product specification with the inspection process in a concurrent environment. This model has been developed using the entities and attributes defined by application product interfaces of a commercial CAD system.

The functional tolerance model developed is a part of a complete knowledge model that defines and represents the information related to the inspection process. In this sense, the functional tolerance model provides information to develop two main activities in the inspection process. The first one is the definition of an inspection fixture design activity. The second one is the definition of the information needed to identify the geometry to be inspected.

The concept used to develop a unique environment for analyzing and integrating the GD&T tasks and inspection process planning has been presented. These concepts allow us to conceptualize and systematize the information about GD&T in an integrated framework.

The specific conclusions of this research are focused on the following points.

- A new approach for associating the geometric and dimensional tolerances with the geometry to be inspected is presented. In this case, a set of identifiers are defined to link the GD&T and the different levels of the part geometry.
- The geometric, dimensional and finishing tolerances have been modeled using a TTRS methodology.
- A total of three submodels has been defined in the functional tolerance model. These models provide information about the dimensional, geometrical and finishing tolerances of the part. These submodels contain around fifty entities that contain a wide range of information related to references surfaces, values and datum.
- The definition of a tolerance model involves the definition of a geometrical model. This model contains a complete definition of the entities that represent the three-dimensional entities of a part. The geometrical model has been developed according to the API of a commercial CAD system.
- The inspection knowledge model has been developed to validate the implementation of the functional tolerance model. The inspection knowledge model contains the information needed to develop the inspection process. This information is associated with set up, tolerance type to be inspected, accessibility of the inspection elements, inspection tool path and the definition of the inspection operation sequences.
- The tolerance model and the inspection process have been defined and integrated using a standard modeling language, Unified Modeling Language (UML).

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References

[1] N. Abburi, U. Dixit, A knowledge-based system for the prediction of surface roughness in turning process, Robotics and Computer-Integrated Manufacturing 22 (2006) 363-372.

[2] B. Anselmetti, H. Louati, Generation of manufacturing tolerancing with ISO standards, International Journal of Machine Tools and Manufacture 45 (2005) 1124-1131.

[3] J. Barreiro, J. Labarga, A. Vizán, J. Ríos, Information model for the integration of inspection activity in a concurrent engineering framework, International Journal of Machine Tools and Manufacturing 43 (2003) 797-809.

[4] J. Barreiro, J. Labarga, A. Vizán, J. Ríos, Functional model for the development of an inspection integration framework, International Journal of Machine Tools and Manufacture 43 (2003) 1621-1632.

[5] J. Barreiro, S. Martinez, J. Labarga, E. Cuesta,Validation of an information model for inspection with CMM, International Journal of Machine Tools and Manufacture 45 (2005) 819-829.

[6] A. Chen, T. Kurfess, Integrated inspection and process control for machining a circular contour on a two-axis vertical turning lathe, International Journal Manufacturing Research 1 (2006) 101-117.

[7] C. Grabowik, R. Knosala, The method of knowledge representation for a CAPP system, Journal of Materials Processing Technology 133 (2003) 90-98.

[8] R. Hunter, Definition and integration of requirements and manufacturing functions in a KBE system applied to machining fixture design. PhD Thesis, Polytechnic University of Madrid, 2004 (in Spanish).

[9] R. Hunter, M. Guzman, J. Möller, J. Pérez, Implementation of a tolerance model in a computer aided design and inspection system, Journal of Achievements in Materials and Manufacturing Engineering 17 (2006) 345-348.

[10] R. Hunter, A. Vizán, J. Pérez, J. Ríos, Knowledge model as integral way to reuse the knowledge for fixture design process, Journal of Materials Processing Technology 164-165 (2005) 1510-1518.

[11] M. Islam, Functional dimensioning and tolerancing software for concurrent engineering applications', Computers in Industry 54 (2004) 169-190.

[12] J. Kulon, D. Mynors, P. Broomhead, A knowledge-based engineering design tool for metal forging, Journal of Materials Processing Technology 177 (2006) 331-335.
[13] H. Liu, M. Tang, Evolutionary design in a multi-agent design environment, Applied Soft Computing 6 (2006) 207-220.
[14] A. Nassehi, S. Newmanb, R. Allena, The application of multi-agent systems for STEP-NC computer aided process planning of prismatic components, International Journal of Machine Tools and Manufacture 46 (2006) 559-574.
[15] G. Schreiber, H. Akkermans, A. Anjewierden, R. de Hoog, N. Shadbolt, W. Van de Velde, B. Wielinga, Knowledge engineering and management. The commonKADS methodology, The MIT Press, 2001.
[16] M. Stokes, Managing engineering knowledge: MOKA methodology for knowledge based engineering applications, ASME Press, 2001.
[17] V. Subramaniam, S. Kumar, K. Seow, A multi-agent approach to fixture design, Journal of Intelligent Manufacturing 12 (2001) 31-42.
[18] H. Toulorge, A. Riviere, A. Bellacicco, R. Sellakh, Towards a digital functional assistance process for tolerancing, Journal of Computing and Information Science in Engineering 3 (2003) 39-44.
[19] S. Zhang, A. Ajmal, J. Wootton, A. Chisholm, A feature-based inspection process planning system for co-ordinate measuring machine (CMM), Journal of Materials Processing Technology 107 (2000) 111-118.
[20] X. Zhao, T. Kethara, R. Wilhelm, Modeling and representation of geometric tolerances information in integrated measurement process, Computers In Industry 57 (2006) 319-330.