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Published in *Computers in Industry* 57:4 (May 2006), pp. 319–330; doi: 10.1016/j.compind.2005.09.004
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Submitted April 16, 2004; accepted September 12, 2005; published online November 23, 2005.

Modeling and Representation of Geometric Tolerances Information in Integrated Measurement Processes

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Abstract

Modeling and representation of geometric tolerances information across an enterprise is viable due to the advances in Internet technologies and increasing integration requirements from industry. In Integrated Measurement Processes (IMP), geometric tolerances data model must support different models from several well-defined standards: including ASME Y14.5M-1994, STEP, DMIS, and others. In this paper, we propose a layered conformance level geometric tolerances representation model. This model uses the widely applied ASME Y14.5M-1994 as its foundation layer by abstracting most information from this standard. The additional geometric tolerances information defined by DMIS and STEP is incorporated into this model to form corresponding conformance layers that support IMP. Thus, different application domains in an enterprise can use this data model to exchange product information. This model is further transformed with XML Schema that can be used to generate XML instance file to satisfy geometric tolerances representation requirements in IMP.

Keywords: geometric tolerances modeling and representation, integrated measurement processes, ASME Y14.5M-1994, STEP, DMIS

1. Introduction

Tolerancing is widely used in industry to define the allowable variation of parts from their ideal shape. The tolerance information plays a critical role in many steps of the product life cycle, such as design, manufacturing, inspection, assembly, and so on with different emphasis. Among many research efforts related with tolerance, tolerance modeling and representation is one of important and active research fields [1]. Modeling and representing tolerance information with a unified, unambiguous, computer and human understandable data model is essential in today's industry when we are in the age of Internet and e-business. The ultimate goal is to ensure product quality while reducing product cost.

Due to inevitable errors introduced in manufacturing processes, different measurement processes are used to inspect the part to verify if it is within or outside of specified geometric tolerancing zones. With the continuous diffusion of CAD/CAM technology, Integrated Measurement Processes (IMP) is emerging to integrate the inspection activities within already well-defined CAD/CAM systems to achieve higher efficiency and more data sharing. In this area, Feng identifies the application activity model to summarize some functional requirements and activities of IMP [2]; Zhao et al. suggest some important aspects and applicable technologies in IMP [3]; NIST presents an effort to integrate dimensional measurement machines' controller using I++ interface [4]. Fundamental to the IMP, is the requirement to provide a harmonized data model and represent it appropriately, including geometric tolerances information that can be understood well by computers and users.

Most of the CAD/CAM systems support the widely accepted ISO 10303—STandard for the Exchange of Product model data (STEP) to encapsulate tolerance data. STEP describes geometric tolerances information via EXPRESS using hierarchical structure. A similar data model is the ANSI/CAM-I 104.0-2001—Dimensional Measuring Interface Standard (DMIS) for measurement processes that describes geometric tolerances information with a flat structure. Though both the systems are well developed, they use different description mechanisms to satisfy the constraints of respective applications. A mechanism to integrate these two tolerance representation formats is essential. This paper presents a methodology for data modeling and representation of geometric tolerances information for IMP.

From system integration viewpoint, instead of point-to-point transformation, a neutral data file format is often presented to efficiently integrate heterogeneous application systems. Thus, the associated transformation cost can be reduced dramatically [5]. In this paper, we present XML (eXtensible Markup Language) as a neutral data file to represent geometric tolerances information due to the many inherent advantages of XML file.

The remainder of this paper is organized as follows. Section 2 reviews related work in this area and illustrates our motivation. Section 3 concisely describes the solution to address tolerance representation requirements in IMP using XML serial technologies. Section 4 presents a layered conformance level data model using a series of tables and EXPRESS-G diagrams. Section 5 illustrates the representation of that layered data model with XML Schema. Section 6 shows the process by which an example part can use our data model to construct a valid XML instance file to be used in IMP. Section 7 concludes this paper.

2. Literature review and motivation

So far, research work in geometric tolerances modeling and representation can be classified into two categories: system-dependent and system-independent methods. In the first category, research focus on modeling and representation of tolerance information within a geometric modeling system. In the second category, research focus on independently modeling and representing tolerance information. Since our work falls into the second category, we review the literature in this category. For the first category, interested readers can refer to Requicha's work in CSG (constructive solid geometry) [6–8] and recent work in CSG-Brep hybrid geometric modelers [9,10].

In the second category, Bjarke proposed the *Tolerance Chain* to represent the dimensional relations among surface features [11]. Though the *Tolerance Chain* was intended for dimensional tolerances, it is also applicable to geometric tolerances. Tsai and Cutkosky presented a graph-based representation scheme to represent geometric tolerances information across a part or assembly called a *Tolerance Network* [12]. Their data model is associated with the decomposition of a hierarchical product model and also uses nodes and arcs as in Bjarke's model.

Also, there are some research efforts that are closely related to the ANSI Y14.5 standard. Guilford and Turner classified several representational primitives for geometric tolerances based on ANSI Y14.5-1982 [13]. Zeid modeled tolerances with an attributed graph structure that represents ANSI Y14.5-1982 tolerance classes [14]. Feng and Eugene represented tolerance information in class diagrams with Unified Modeling Language [15].

Despite all those efforts, the most relevant and detailed prior work to this paper's focus is works from two well-known committees: STEP and DMIS. Currently, STEP is a de facto standard in CAD/CAM field and DMIS is a de facto standard in measurement processes among metrology groups. Since STEP's geometric tolerances information model is based on ISO standards while DMIS's model is based on ASME Y14.5M-1994, it is worthwhile to have a brief review of those two standards and then look into these two committees' work.

2.1. Related standards

The ASME Y14.5M-1994 is revised from the previous ANSI Y14.5M-1982 by introducing some new concepts and symbols and adapting to international standards. DMIS 4.0 uses this standard to model and represent geometric tolerances [16]. Geometric tolerances in ISO are mainly illustrated in ISO 1101:1983 [17]. Both standards specify the semantics and symbols to present tolerance information in engineering drawings. However, additional structure and encoding is still required to model and represent these tolerance definitions in computer-interpretable and human-understandable ways.

The main difference between the ASME and ISO standards relates to limits of size. The ASME standard is based on the "envelope principle" (Taylor Principle, Rule #1) [18] while the ISO standard is based on the Independency Principle [19]. Though two standards have different principles, most of the symbology is identical and ISO standard also allows user to apply the Taylor Principle to the toleranced feature either by reference to ASME Y14.5-1994 or by using symbol Ⓢ . Thus, this paper focuses solely on the ASME standard to build geometric tolerances foundation level.

2.2. Committee works

2.2.1. STEP geometric tolerances information model

STEP is a set of standards for a computer-interpretable representation and exchange of product data to provide a mechanism capable of describing product data throughout its life cycle while independent of any specific system [20]. STEP consists of different parts including description methods, integrated resources, and application protocols (AP), as well as implementation methods and abstract test suites. Geometric tolerances information model in STEP is based on ISO serial tolerance standards. Such information can be found in AIC 519 (Application Interpreted Constructs) [21] and some APS, such as AP224 [22]. It also uses some entities from Part 47 [23]. Its main focus is to meet the design phase requirements. Besides STEP work, there are some individual authors presented tolerance models, such as Feng and Yang's work [24] and the further refinement work from Tsai et al. [25] by adding mating relationship between parts and datum reference frame. All such information is documented using EXPRESS and EXPRESS-G, which provides an object-oriented information modeling way to describe hierarchical product data [26,27].

STEP AP219 is a new effort to retouch the geometric tolerances information model by referring to other STEP APs and AIC 519. Its scope is to specify information requirements for analyzing the data and reporting the results of dimensional inspections of solid parts or assemblies [28]. Current version of AP219 uses similar geometric tolerances information model as other APs and imports some attributes from another group's work—Dimensional Markup Language group (DML) [29]. DML's focus is to represent dimensional inspection results with XML based on some information from standards and practical considerations. Since AP219 is still under development, we hope our work can be useful for that committee.

2.2.2. DMIS geometric tolerances information model

DMIS is a standard created by the Consortium for Advanced Manufacturing International to enable dimensional measurement machines to communicate seamlessly with each other. Each tolerance in DMIS is represented individually using Backus-Naur Form in terms of tolerance nominal and tolerance actual [16]. Tolerance nominal modeling is based on the semantic interpretation of ASME Y14.5M-1994 standard. Tolerance actual modeling is based on tolerance nominal definition plus some unique terms related with inspection procedure, like *INTOL/OUTOL*, *lim*, and so on.

2.3. Motivations

From the previous literature review, we realize that there is not an existing suitable way to model and represent geometric tolerances in IMP currently. STEP and DMIS address this issue from their respective viewpoint with limited scope and information and are dominant in design and inspection domains individually. Also, we lack a data model to include as much geometric tolerances information as possible from ASME Y14.5M-1994. Such information appears in feature control frame and some notations in the standard as discussed in Section 4.1 and should be included in the data model obviously. Thus, a new data structure is needed to model and represent geometric tolerances information in IMP

to catch maximum possible information from ASME Y14.5M-1994 and incorporate these two committees' work. Other requirements for such a data structure include:

- It should represent tolerance information in an objected-oriented way to meet different application domains' requirements by taking information from appropriate layer.
- It should be defined in a format to make it computer interpretable and human-understandable. The semantic meanings can be traced to relevant standards.
- It should consider the new trends in industry. In such a situation, web-based applications are often used to exchange product data in distributed manufacturing environments [30–32]. Thus, the data format should be web-applicable.

3. Solution based on XML and XML Schema

In this section, we first justify the choice of XML-related technologies to represent tolerance information in IMP, and then a solution based on those technologies is proposed with concise illustrations. This solution is then detailed in Sections 4 and 5.

3.1. Why XML-related technologies

The use of the Internet, the World Wide Web, and XML is a de facto requirement in new system integration projects that address application interoperability and data exchange [30–32]. There are two reasons for this. One reason is that the ubiquity and acceptance of the Internet and World Wide Web provide the furthest-reaching and lowest-cost integration platform in the world. Another reason is the advantages of using XML since it is W3C's recommendation, half-structured and presentation-free and so on. Also, XML bindings of EXPRESS schema and corresponding data are standard implementation methods for STEP [33].

For the XML to be more robust, an XML Schema file is needed to define the data structure of XML data. After a user constructs an XML instance file, its validity can be pre-checked with the schema before it is passed to another system.

After comparing several available XML Schemas in the market, XML Schema [34] becomes the choice of our approach to represent tolerance information in IMP. The reasons to choose XML Schema over others are as follows:

- XML Schema itself uses XML syntax to take advantage of XML benefits.
- It supports a rich set of built-in datatypes and allows user to define their own datatypes.
- It supports datatype inheritance, which is suitable for object-oriented modeling.
- It provides some data constraints.
- It supports namespace hooks, thus provides a systematic way to manage schema files by putting different kinds of schema files in different namespaces.

3.2. Solution

According to the properties of XML Schema and requirements to represent tolerance in IMP, this paper shows how to represent tolerance information by using XML Schema in

multiple-layered conformance levels to meet different application domains' requirements. Based on the XML Schema file, users can construct an appropriate XML instance data file to meet requirements. Such an XML instance file can be used in IMP and is suitable for web-based application throughout the Internet.

4. Layered conformance level data modeling

In this section, we follow the process of data modeling [24] by first creating data requirements based on ASME Y14.5M-1994 standard, then abstracting those information in tables and documenting them with EXPRESS-G diagram to provide a formal object-oriented and graphical view of geometric tolerances information [27]. Since the development of geometric tolerances information model in DMIS is based on ASME Y14.5M-1994, it is modeled as the second layer. The geometric tolerances representation in IMP is modeled in the third layer since it needs to include information from both DMIS and STEP.

4.1. Foundation layer

As mentioned above, the ASME Y14.5M-1994 standard is used as foundation layer. In this standard, 14 types of geometric tolerances are defined. They are form (straightness, flatness, circularity, and cylindricity), profile (profile of a line and profile of a surface), orientation (angularity, perpendicularity, and parallelism), location (position, concentricity, and symmetry), and runout (circular runout and total runout). Each type has an implicit or explicit 2-D or 3-D tolerance zone type. Tolerance zone types in 3-D include parallel planes, square/rectangular, cylinder, spherical, uniform boundary, and conical and concentric cylinders. Tolerance zone types in 2-D include parallel lines, circular, uniform boundary, concentric circles [35].

From this standard, all 14 types of geometric tolerances information are specified via a feature control frame. Figure 1 shows a typical feature control frame and possible symbols that may appear in it [35].

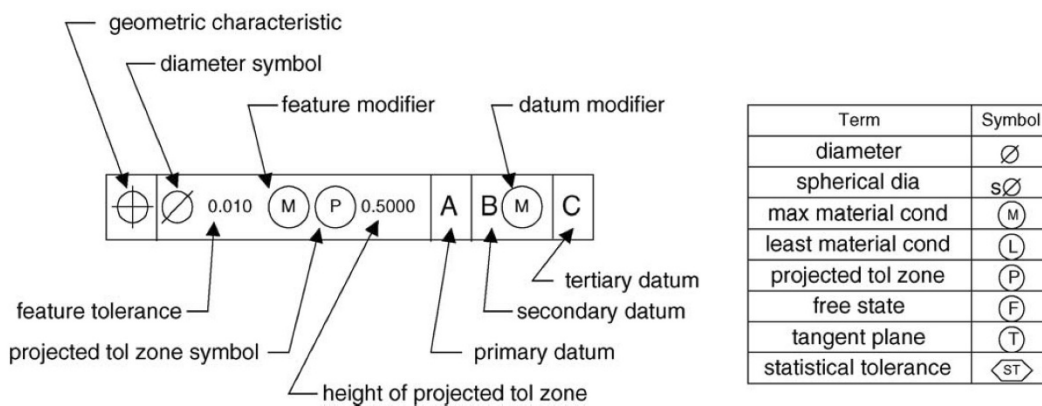


Figure 1. A typical feature control frame and its possible symbols

This information is summarized in Table 1 and is quite complete. In this table, Level 0 includes the necessary information for all geometric tolerances. Information of Level 1 and Level 2 often appears in the second compartment of a feature control frame. They are both optional, but Level 1 can be applied to all tolerance types. Information of Level 3 appears in the third compartment of a feature control frame and specifies the datum-related information. Information on the Level 4 appears in the second line of feature control frame under the same geometric tolerance type. Information on the Level 5 is very specific to a certain geometric tolerance and should be incorporated case by case.

Levels	Data elements	Apply to	Required
Level 0	Name	All	Yes
	Value	All	Yes
	Unit	All	Yes
	Applied feature	All	Yes
	Tolerance zone type	All	Yes
	Label	All	Yes
Level 1	Free state	All	No
	Statistical tolerance	All	No
	Significant digits	All	No
	Description	All	No
Level 2	Feature material condition	Feature with size	No
	Projected tolerance zone	Orientation	No
	Tangent plane	Orientation	No
	Maximum allowable tolerance	Feature at MMC/LMC	No
Level 3	Referenced datum	Orientation, location and runout	No
	Datum material condition	Datum feature	No
Level 4	Unit tolerance zone	Flatness and straightness	No
	Composite tolerance	Position and profile	No
Level 5	Specific information	Such as all around or partial profile tolerance	No

4.2. DMIS layer

Though geometric tolerances representation in DMIS is based on ASME Y14.5M-1994, it is specifically modeled for dimensional inspection purpose. Hence, DMIS introduces some new concepts into its tolerance model. A similar approach can be used to summarize geometric tolerances information in DMIS. The information summarized in Table 2 is unique for DMIS, for other geometric tolerances information, refer to Table 1.

In Table 2, Level 0 includes additional necessary information for all geometric tolerances that appears in DMIS. Information of Level 1 is optional and applied to certain types of tolerance. Information on Level 2 is very specific to a certain geometric tolerance that needs to be analyzed and incorporated case by case.

Table 2. Specific geometric tolerances information summary in DMIS

Levels	Data elements	Apply to	Required
Level 0	Category	All	Yes
	Inspection result indicator	All tolerance actual	Yes
Level 1	Lim	Toleranced feature with size at MMC/LMC	No
	Parpln	Orientation tolerance	No
	Lotol, uptol	Profile tolerance	No
Level 2	Specific information	Such as AVGDEV value for surface profile tolerance actual	No

4.3. IMP layer

In IMP, geometric tolerances modeling should also include information from STEP to make the model more complete. The geometric tolerances modeling in STEP can be found in AIC 519 and some application protocols that need geometric tolerances information, such as AP224. Study of the above materials indicated that the geometric tolerances information summarized in Tables 1 and 2 can cover most of the information from STEP and only few information related to some specific tolerance types is missing. See Table 3 for detailed information.

Table 3. Specific geometric tolerances information summary in STEP AP224

Level	Data elements	Apply to	Required
Level 1	Unit tolerance zone	Orientation	No
	Affected plane	Symmetry, position, parallelism, perpendicularity, line profile, straightness	No
	Runout angle	Runout	No
	Value qualifier	Position, concentricity	No

4.4. EXPRESS-G model

Based on the information from Tables 1–3, EXPRESS-G is chosen to abstract the tolerance modeling requirement in IMP. By abstracting data information from above tables into a formal EXPRESS-G representation model, it makes the next step to represent it with XML-related technology more convenient.

Figures 2–5 shows a graphical model of layered conformance level for geometric tolerances. In these diagrams, entities with lightest gray conform to the ASME Y14.5M-1994 standard layer (foundation layer); entities with medium gray conform to DMIS 04.0 layer; entities with maximum gray conform to IMP layer. In ASME Y14.5M-1994 layer, we initially create an entity *geometric_tolerance* based on Level 0 and Level 1 information from Table 1. Subsequently, we classify the entity according to datum information. Finally, we model individual geometric tolerances.

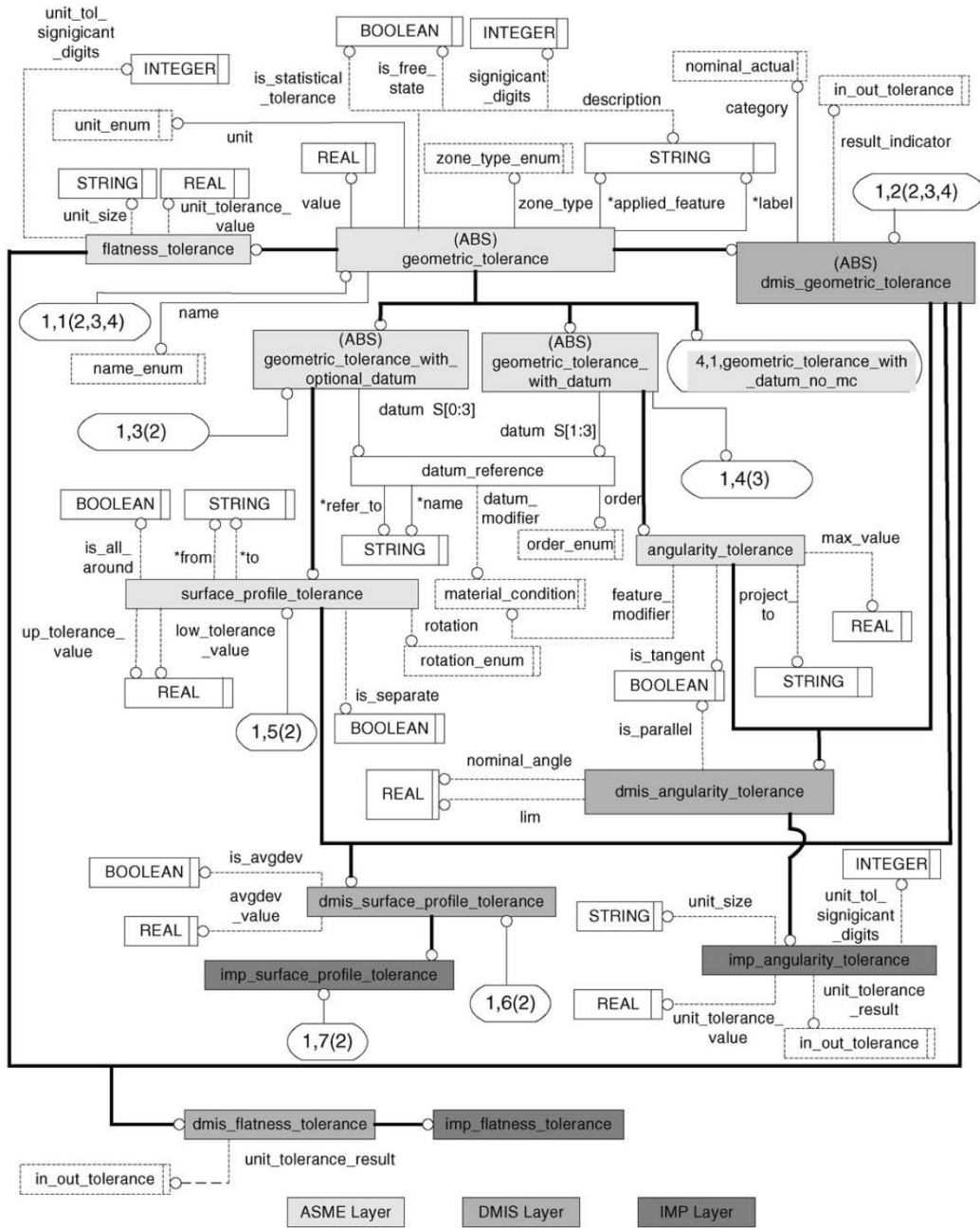
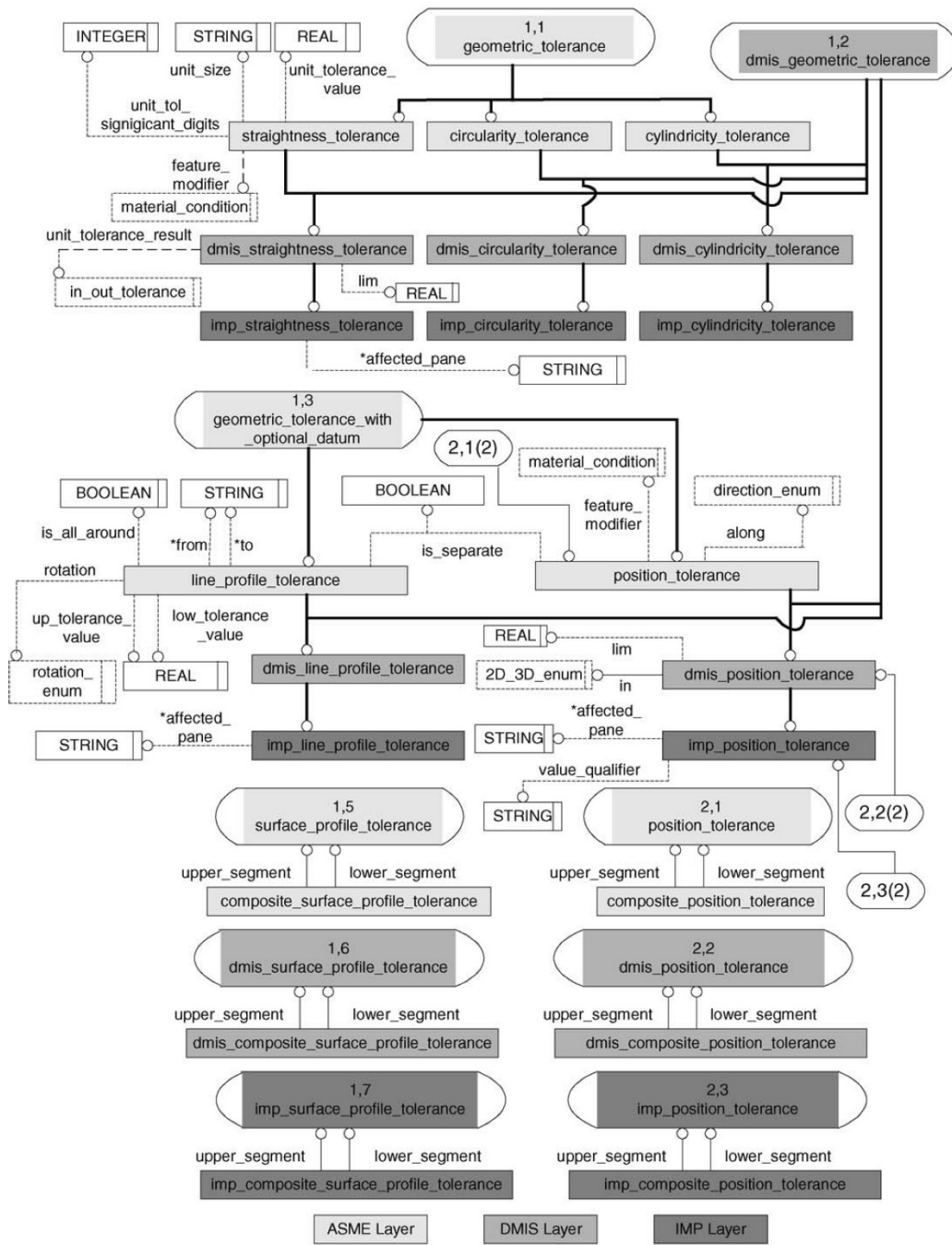


Figure 2. Layered conformance level of geometric tolerances model in IMP (1 of 4)



Note : * means a uniqueness constraint is applied

Figure 3. Layered conformance level of geometric tolerances model in IMP (2 of 4)

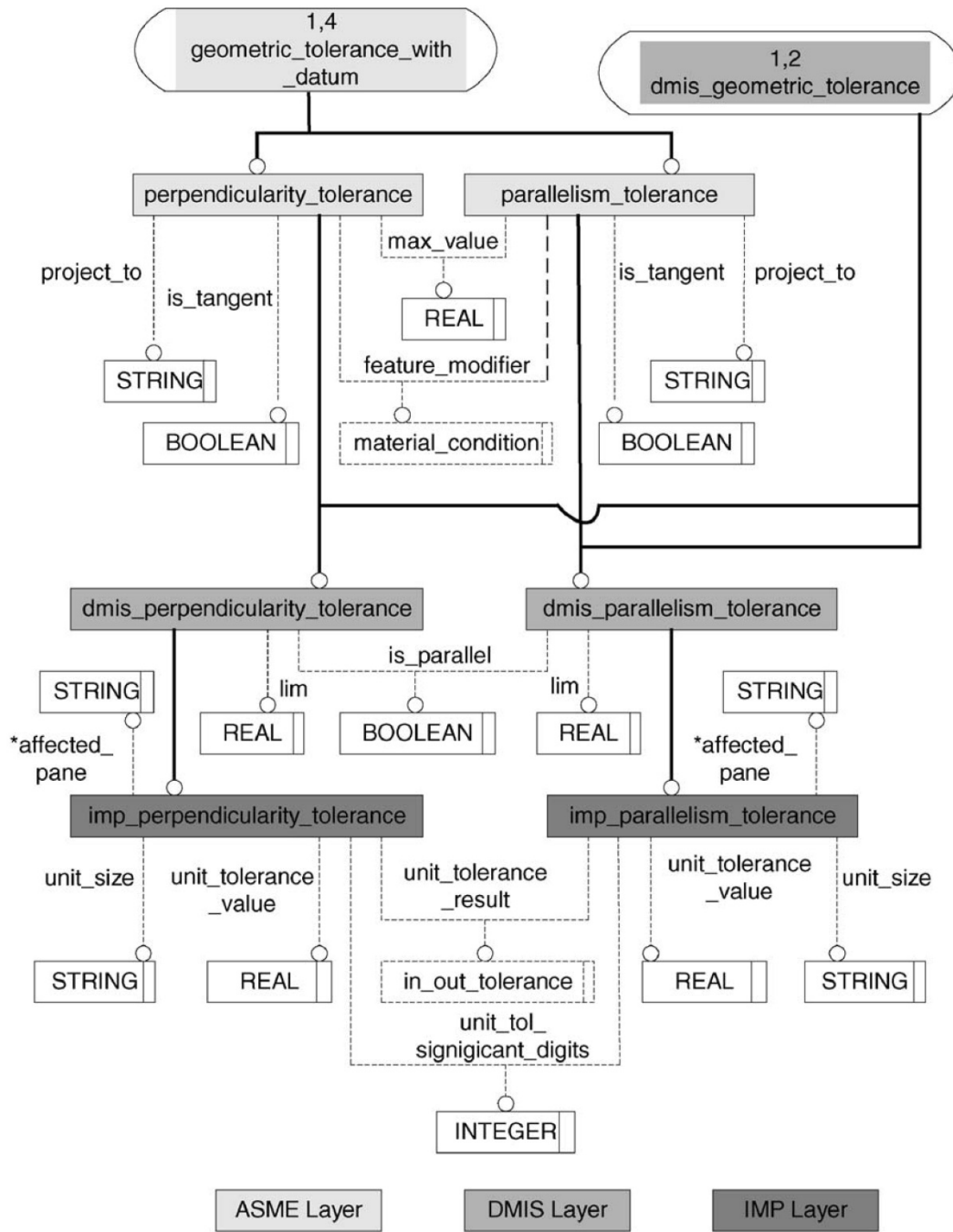
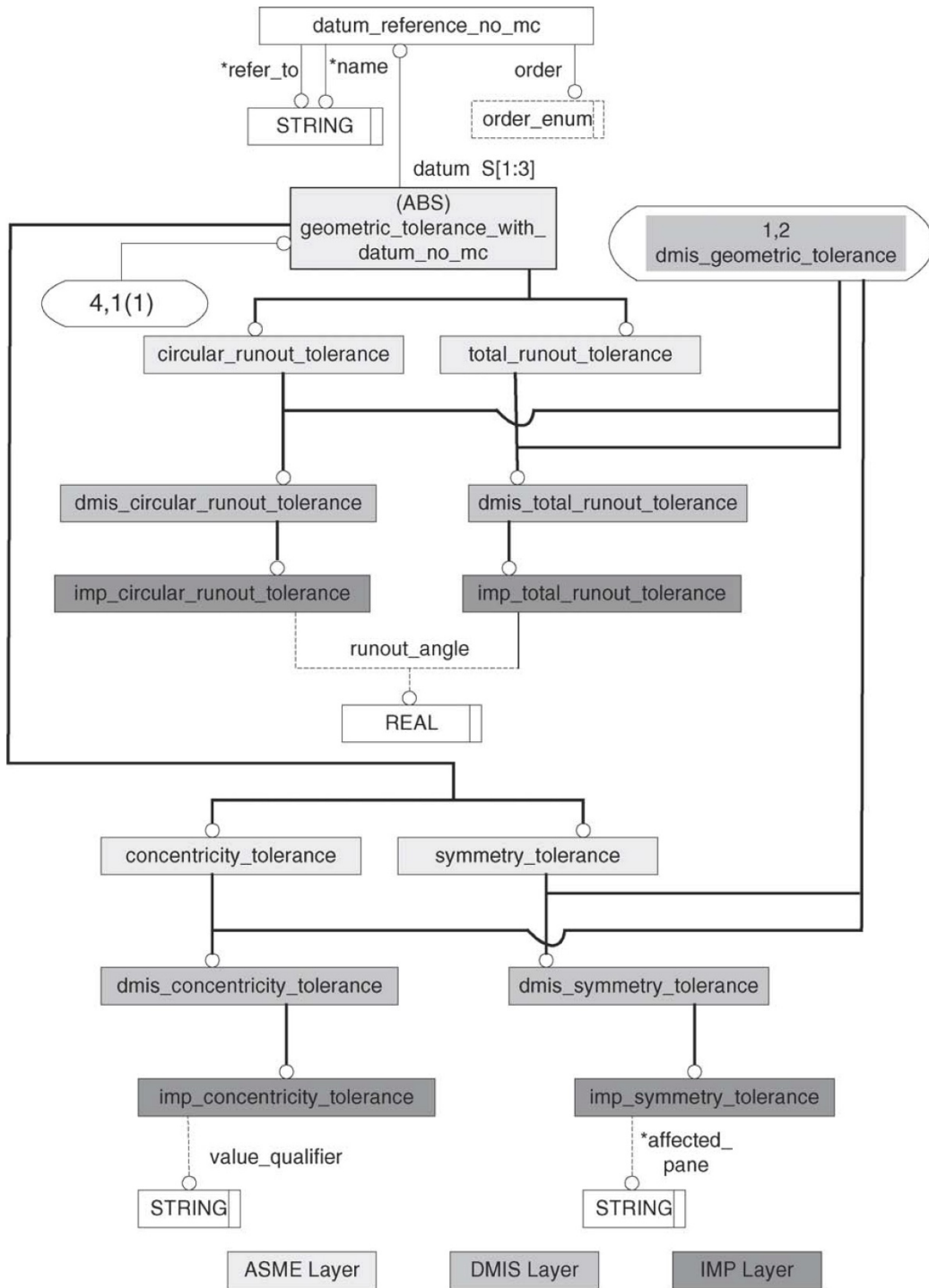


Figure 4. Layered conformance level of geometric tolerances model in IMP (3 of 4)



Note : * means a uniqueness constraint is applied

Figure 5. Layered conformance level of geometric tolerances model in IMP (4 of 4)

Since some geometric tolerances cannot have data, such as flatness, straightness, circularity, and cylindricity; some can have optional data, such as profile of a line, profile of a surface and position; some must have data, such as angularity, perpendicularity, and parallelism; some must have data, but the data cannot have material condition, such as concentricity, symmetry, circular runout and total runout, we further create three entities *geometric_tolerance_with_optional_datum*, *geometric_tolerance_with_datum*, and *geometric_tolerance_with_datum_no_mc* to model these three categories. All of them extend from *geometric_tolerance* entity and have an attribute *datum* to describe the datum information but have different lower limit and datum material condition. The definition of other attributes can be traced back to relate standards.

5. Layered conformance level data representation

After we model geometric tolerances with EXPRESS-G as shown in Figures 2–5, it is straightforward to create the representation with XML Schema that can be used to instantiate XML file. Since XML Schema does not support multiple inheritances, the information from DMIS is embedded in the lower level entities. Here, we illustrate only how to represent one typical tolerance in EXPRESS_G diagram—angularity with XML Schema. Interested readers can find all types of geometric tolerances representation with XML Schema from [36].

In XML Schema, related elements and datatypes can be grouped together and put in a separate target namespace. These elements and datatypes can be further referred by other target namespaces. By organizing information in this way, it can be easily extended in a hierarchical way. So, before we define the XML Schema file for angularity tolerance, we create a target namespace such as:

```
<xsd:schema targetNamespace=http://www.coe.uncc.edu/~rgwilhel/geometric_tolerance
xmlns="http://www.coe.uncc.edu/~rgwilhel/geometric_tolerance"
xmlns:xsd="http://www.w3.org/2001/XMLSchema" element FormDefault="qualified"
attributeFormDefault="unqualified" version="1.0">
```

After defining some basic datatypes, we define ASME Y14.5-1994 conformance layer (foundation layer) angularity tolerance datatype based on Figure 2:

```
<xsd:complexType name="angularity_tolerance">
  <xsd:complexContent>
    <xsd:extension base="geometric_tolerance_with_datum">
      <xsd:sequence>
        <xsd:element name="feature_modifier" type="material_condition" nillable="true"/>
        <xsd:element name="is_tangent" type="xsd:boolean" nillable="true"/>
        <xsd:element name="project_to" type="xsd:string" nillable="true"/>
        <xsd:element name="max_value" type="positive_double" nillable="true"/>
      </xsd:sequence>
    </xsd:extension>
  </xsd:complexContent>
</xsd:complexType>
```

An angularity tolerance conforms to DMIS layer can be defined like:

```
<xsd:complexType name="dmis_angularity_tolerance">
  <xsd:complexContent>
    <xsd:extension base="angularity_tolerance">
      <xsd:sequence>
        <xsd:element name="result_indicator" type="in_out_tolerance" minOccurs="0"/>
        <xsd:element name="is_parallel" type="xsd:boolean" nillable="true"/>
        <xsd:element name="nominal_angle" type="xsd:double" nillable="true"/>
        <xsd:element name="lim" type="positive_double" minOccurs="0"/>
      </xsd:sequence>
      <xsd:attribute name="category" type="nominal_actual" use="required"/>
    </xsd:extension>
  </xsd:complexContent>
</xsd:complexType>
```

Finally, we define the angularity tolerance that can be used in IMP, like:

```
<xsd:complexType name="imp_angularity_tolerance">
  <xsd:complexContent>
    <xsd:extension base="dmis_angularity_tolerance">
      <xsd:sequence>
        <xsd:element name="unit_size" type="xsd:string" nillable="true"/>
        <xsd:element name="unit_tolerance_value" type="positive_double" nillable="true"/>
        <xsd:element name="unit_tolerance_result" type="in_out_tolerance" minOccurs="0"/>
        <xsd:element name="unit_tol_significant_digits" type="xsd:nonNegativeInteger"
          nillable="true"/>
      </xsd:sequence>
    </xsd:extension>
  </xsd:complexContent>
</xsd:complexType>
```

6. Case study

After we define these geometric tolerance datatypes in a single XML Schema file, later users can write their own XML Schema file to specify their part's geometric tolerances information by including or importing this file. Finally, they can instantiate an XML file based on their own XML Schema file. This section illustrates this process with a simple example part as shown in Figure 6. This part has a partial unilateral surface profile tolerance applied to the arc, position tolerance for a four-hole pattern, and flatness tolerance applied to the bottom plane. Due to the powerful control ability of surface profile tolerance and its wide application in the auto industry, we use that as an example. The corresponding complete XML Schema file and XML file are available from [36].

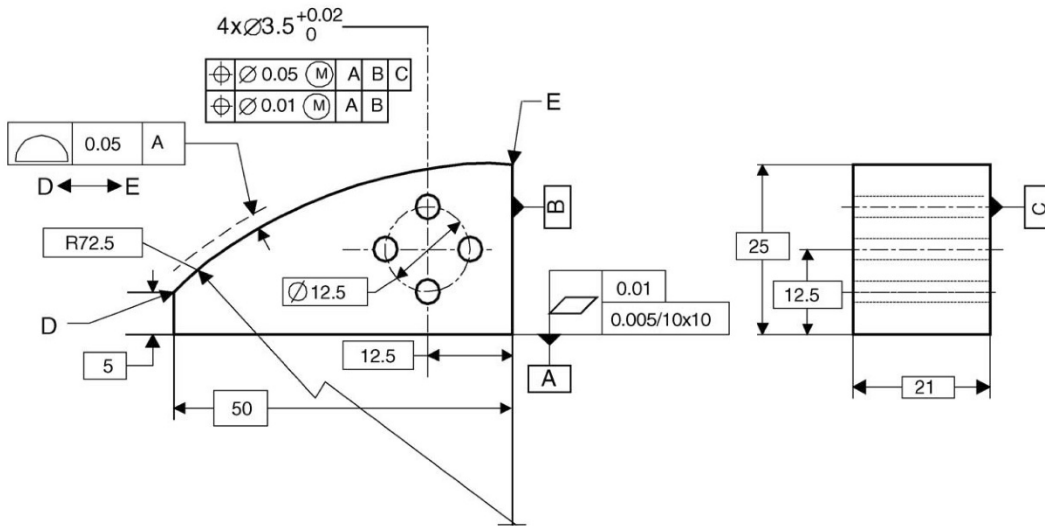


Figure 6. Example part

6.1. XML Schema file construction

Here, we use the same target namespace as the *geometry_tolerance.xsd*. So, it should include predefined *geometry_tolerance.xsd*.

After defining some auxiliary information, we define the element and datatype for our example part as below:

```
<xsd:complexType name="example_part">
  <xsd:sequence>
    <xsd:element name="auxiliary_info" type="auxiliary_info"/>
    <xsd:element name="arc_tolerance_design" type="surface_profile_tolerance"/>
    <xsd:element name="arc_tolerance_imp" type="imp_surface_profile_tolerance"/>
    <xsd:element name="pattern_pos_design_1" type="position_tolerance"/>
    <xsd:element name="pattern_pos_design_2" type="position_tolerance"/>
  </xsd:sequence>
</xsd:complexType>
<xsd:element name="example_part" type="example_part"/>
```

6.2. XML file instantiation

Based on the XML Schema file illustrated above, we can construct an XML instance file. In the XML instance file, for its validation, we need to specify the XML Schema file location.

After some dummy features and data are defined, a nominal surface profile tolerance with one datum can be defined at the part design phase like:

```
<arc_tolerance_design applied_feature="surface_feature_001" label="nominal_sur-
face_profile_001" category="nominal">
  <name>surface_profile_tolerance</name>
  <zone_type>3d_uniform_boundary</zone_type>
```



```

<value>0.05</value>
<unit>mm</unit>
<is_free_state>>true</is_free_state>
<is_statistical_tolerance>>false</is_statistical_tolerance>
<significant_digits>2</significant_digits>
<description>nominal surface profile tolerance</description>
<datum>
  <name>A</name>
  <refer_to>plane_feature_001</refer_to>
  <order>primary</order>
</datum>
<is_all_around>>false</is_all_around>
<from>line_D</from>
<to>line_E</to>
<rotation>clockwise</rotation>
<is_separate>>true</is_separate>
<up_tolerance_value>0.05</up_tolerance_value>
<low_tolerance_value>0</low_tolerance_value>
</arc_tolerance_design>

```

The corresponding actual surface profile tolerance to show inspection result at IMP layer can be instantiated like:

```

<arc_tolerance_imp applied_feature="surface_feature_001" label="actual_surface_profile_001" category="actual">
  <name>surface_profile_tolerance</name>
  <zone_type>3d_uniform_boundary</zone_type>
  <value>0.043</value>
  <unit>mm</unit>
  <is_free_state>>true</is_free_state>
  <is_statistical_tolerance>>false</is_statistical_tolerance>
  <significant_digits>3</significant_digits>
  <description> actual surface profile tolerance </description>
  <datum>
    <name>A</name>
    <refer_to>plane_feature_001</refer_to>
    <order>primary</order>
  </datum>
  <is_all_around>>false</is_all_around>
  <from>line_D</from>
  <to>line_E</to>
  <rotation>clockwise</rotation>
  <is_separate>>true</is_separate>
  <up_tolerance_value>0.045</up_tolerance_value>

```

```

<low_tolerance_value>0.002</low_tolerance_value>
<result_indicator>INTOL</result_indicator>
<is_avgdev>>false</is_avgdev>
</arc_tolerance_imp>

```

7. Conclusion

The requirements of a representation scheme that act as an adapter for the communication of geometric tolerances information is presented. Such a representation is required to meet the needs of the modern manufacturing enterprise for unambiguous communication via the Internet among different application domains. We refer to this communication of geometric tolerances information on a need-to-know basis as Integrated Measurement Processes.

To develop IMP, we present a new layered conformance level data model. This data model has a solid foundation layer by abstracting most geometric tolerances information that appear in the feature control frame and notes from ASME Y14.5-1994 standard. This data model is further extended to form a DMIS layer by incorporating geometric tolerances information from DMIS 04.0 standard and an IMP layer by incorporating geometric tolerances information from STEP standard. Thus, different application domains can take different layer's information to meet their requirements.

XML Schema is chosen to represent our layered conformance level data model since a robust XML instance file needs to have a schema file as its skeleton and XML is a preferred data exchange medium throughout the Internet. Such an XML file is web-applicable, computer-interpretable, and human-understandable. Finally, an example is presented to illustrate the geometric tolerances modeling and representation process of our approach. Additionally, the example provides a brief explanation of the XML Schema and XML instance file construction.

The current development focus of XML and XML Schema at W3C provides data representation and data structure, respectively, to meet data integration requirement, with limited constraints that can be applied to primitives. Thus, they are not appropriate to be used for reasoning and deduction. Neither do they support ontology representation. A separate application is usually required to meet those requirements after parsing data from XML instance file. If W3C supports these functionalities in the future, the XML schema developed here can be extended.

This work provides a near complete model. However, certain informal information that designers tend to use as notes is not addressed. This model does not attempt to interpret design intent and, similar to the case with actual drawings, interpretation deviations can occur.

Acknowledgments – This work was supported by DaimlerChrysler through the Challenge Fund project entitled “Software Frameworks for Integrated Measurement Processes.” We particularly thank Mr. Robert Waite of DaimlerChrysler for his leadership and support. Also, the authors are grateful to ISO 10303-AP 219 and DML committee members for their materials and ideas.

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