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# STEP-based Conceptual Framework for Measurement Planning Integration

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**Abstract**

Measurement aims to check the product conformance or to control the manufacturing processes' parameters. It needs to be planned in an integrated and interoperable manner with other manufacturing activities. Integration of measurement planning is based on the information provided by the design phase. This paper aims to assist the interoperability of the measurement plans through introducing the resource-independent measurement specifications (RIMS) concept. The paper presents a conceptual framework for representing a STEP-based measurement features from the coordinate metrology perspective. The proposed framework supports the direct formulation of the measurement process specifications in an operation-based manner and the realization the process control functionality of the measurement processes.

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*Keywords:* Measurement Planning; Measurement Integration; STEP

## 1. Introduction

Integration of manufacturing systems is essential for capitalizing the benefits of flexible manufacturing resources and to cope with the increased demands for customized products. Communications between the manufacturing system's phases, have been improved through digitalization [1]. Computerized data models of the manufacturing products and processes are essential enablers for the digital manufacturing revolution [2].

Coordinate metrology is one component of manufacturing; its main function is to check the product conformance to the designer's specifications. In addition, as being a tool for gaining knowledge, the measurement process assists in controlling the various manufacturing processes [3]. Measurement still lacks the interoperable integration with other manufacturing activities [4], which increases cost and time demands.

Recently, standard organizations and the academic community raised awareness of the importance of the measurement processes' interoperable integration. This was a result of the understanding and the quantification of its economic potential in manufacturing [5, 6]. The consistency and the value of the gained measurement knowledge is heavily influenced by the measurement planning stage.

Measurement planning integrity is challenged by the included operator-dependent decisions and the different applied measurement procedures or technologies. Moreover, it is influenced by its data communication interface to the product design phase. Geometric and dimensional tolerancing (GD&T) data models, that support the measurement planning tasks in a uniform and explicit manner, are necessary. There is a need for re-evaluating the connecting data interfaces of the design specification frameworks from the measurement process viewpoint.

This work contributes to the model-based engineering (MBE) efforts and is within the digital manufacturing scope. The paper introduces the concept of a resource-independent measurement specifications (RIMS) for enabling the measurement planning integration and interoperability. It then proposes a conceptual framework for representing the measurement features from the coordinate metrology viewpoint. The proposed framework introduces new relations that assist the modern processes control functionalities of the coordinate metrology. The paper continues in section 2 by reviewing the recent advances in the GD&T modelling and the state of the art standardization developments in this area. Later, section 3 presents the RIMS concept followed by discussing the proposed framework. The paper then ends with work conclusions in section 4.

## 2. Background survey on the GD&T modelling

Measurement plans are based mainly on the amount and the quality of the information provided from the product definition phase in the form of a drawing sheet or a solid model, the latter is the more commonly used source in the digital era. Solid models were initially developed using the constructive solid geometry (CSG) representation or the boundary representation (B-rep). Today's computer aided design (CAD) environments use the B-rep with a history tree, which allows model modifications by rolling back through the modelled data [7]. CAD databases include all the geometrical and topological data necessary for representing the nominal product boundaries.

The designers must specify the permitted variations of the nominal part boundary and of the geometric constraints between its geometric entities. This is to accommodate the manufacturing and measurement errors while not sacrificing the targeted functional performance. ISO 1101:2013 [8] and ASME Y14.5:2009 [9] are the latest applied standardized practice for applying the design specifications' syntax. The derived semantics are defined through the GD&T rules represented by different documented examples and figures, which is a human understandable format rather than being computer interpretable.

Tolerance modelling has been a topic of research for many years, but the majority of GD&Ts representations are oriented to the tolerance analysis applications [7]. These frameworks aimed to provide the designer with the necessary computerized tools to assist the tolerance synthesis and validation tasks, in what is known as computer aided tolerancing (CAT) applications. Tolerance allowances were first represented by the offsetting operations and the variational class theory [10].

Tolerances were implemented based on this theory as attributes of a variational graph linked to a CSG solid modelling system [11]. This is a limited representation, for example, it is not suitable for representing the floating tolerance zones. Johnson [12] stored the tolerance data with the B-rep solid models, while Roy and Liu [13] and Wang and Ozsoy [14] attached it with the hybrid CSG/B-rep representations. Later, the tolerance data has been represented in an explicit manner as constraint nodes attached to the model faces [13]. Early tolerance models aimed to store the tolerance information within the model database for later basic modification or retrieval requirements.

For supporting the tolerance synthesis and validation tasks, Wu et al. [15] developed a directed attributed constraint graph representation by applying tolerances as constraints on the metric relationships between different entities. It's worth noting that these attributed tolerance representations are not suitable for automating the tolerance analysis applications [7]. As a consequence, Shah et al. [16] used the dimensional graph structure to represent the GD&T data. This model was based on the relative degrees of freedom (DOF) among the different geometric primitives. Based on the same concepts, Shen et al. [7] used separate super-constraint-tolerance-feature-graph-based model for automating the tolerance analysis process. These efforts were based mainly on ASME Y14.5 early versions and held sufficient data for the subsequent machining and assembly demands.

On the contrary, the current CAD systems and GD&T models are unable to effectively support the computer aided inspection (CAI) integration [17], which is required for the digital manufacturing environment [18]. Tolerance models still need to be evaluated and updated with necessary data requirements for the proper and uniform consumption by the coordinate metrology applications. In parallel to the academic research, standard data models have been developed, such as ISO 10303:1994, known as the standard for the exchange of product model data (STEP) [19]. ISO 10303 enables the exchange of product data and attains a unified integration mechanism throughout the product life cycle.

As it is an open-standard, it supports the interoperability and applicability for the process planning decision making dilemma. Within the STEP standard, there are various resource constructs (RCs) and application protocols (APs) to cover the data exchange needs of various specific application domains. For example, the STEP AP203:2011 [20] is a common design data exchange standard protocol that is exported from the CAD applications. The AP203 is designed to represent the product information such as the geometric and topological data. The published STEP APs also suffered for many years from the absence of a mean to communicate the GD&T data.

In STEP generic resources, part 47 [21] contained the early formal definitions of these standard RCs needed for building a GD&T data representation. The later notable shift was when the STEP AP 214:2010 [22] was defined; it extended the STEP AP203 by including additional information about the colors, layers and GD&Ts. Following and during 2011, STEP AP203 part 2 was also augmented by adding GD&T information. This raises a logical request for harmonizing both of the standardized product definition versions. Today, the STEP AP242:2014 [23] was developed by merging and harmonizing both AP203 and AP214 data structures [2]. This development added the representation context to the presentation rules defined in the ISO/DIS 16792:2012 [24] and ASME Y14.41:2012 [25] digital product definition standards.

AP242 is targeting the management of the 3D MBE perspective, so its scope is wider than just representing product manufacturing information (PMI). One industrial limitation of its first edition is the lack of coverage and support of its framework for the machining features [26], which is critical requirements for the measurement functionality as a process control enabler. In addition, during an exploration of the STEP AP242 standard status, Feeney et al. [1] and Qin et al. [27] agreed that the exchange of the PMI semantics still a current limitation of the tolerance standard models. In this context, Sarigecili et al. [28] interpreted the STEP-based GD&T specifications for tolerance analysis by using the OntoSTEP product model to add the necessary semantic definitions.

CAx implementation forum (CAx-IF), a software developers' group, developed recommended practice specifications to implement the STEP-AP242 within CAD systems [29]. These data specifications were documented only in a human understandable format [2]. Recently, the national institute of standards and technology (NIST) research groups focused on the conformance testing of the published neutral data formats from the CAD software with respect to the formal tolerancing standards [2, 30].

It is worth noting that few researchers were concerned with tolerance modelling from the measurement integration perspective. For example, Zhao et al. [31] merged the already existing tolerance models defined in ASME Y14.5-1994, STEP and the dimensional measurement interface (DMIS) standards. The merged framework designed in a layered structure without modifying the included data definitions or requirements. Recently, the dimensional measurement standards consortium (DMSC) published, the quality information framework (QIF) ANSI standard [32].

QIF aimed to enable quality data interoperable exchange. One drawback of the QIF approach is that it is based on its own designed model based definition (MBD) and tolerances data structures for conveying the part geometry, features and tolerances data [33, 34]. This requires translation processes from both the design and the measurement computerized applications to the QIF formats. The contradicting proposed strategy is to build the quality information exchange based on the currently applied MBD neutral standards such as STEP AP242. These are the natural output of the design stage and should lead to the seamless data consumption by the downstream applications, which matches the normal data flow within the product life chain. This strategy supports the overall manufacturing system interoperability and direct applicability.

In summary, the explored literature clarifies that the measurement process integration has not yet been evaluated against the developed neutral GD&T standard models. This evaluation process endeavors to identify and define any necessary new data entities, requirements or relations from the measurement process perspective. The MBD neutral standards need to be extended to enable the seamless and explicit integration of the measurement operations. Section 3 illustrates the conceptual argument of the proposed framework. The designed framework allows the direct construction of the measurement plans based on the published design data.

## 3. Conceptual argument and the proposed framework

### 3.1. Resource-Independent measurement specifications

Coordinate metrology systems consist of four main components and 3 connecting interfaces. The components are the product definition, measurement planning, measurement execution and measurement results' analysis [35]. This paper is concerned only with the first interface connecting the design and the measurement planning phases.

Measurement planning phase identifies what to measure and how, based on the specified characteristics or the manual operator selections, even done through computerized interfaces. Besides, modern coordinate metrology approach requires to add the decisions necessary for the applied evaluation methods of the extracted data from the physical part. These data analysis decisions result in the actual controlled parameters to be compared with the design specifications or to be used for further control of a manufacturing process.

Measurement plan globally includes a list of defined working steps that are mostly consisting of the various inspection operation types. These inspection operations are defined to extract, process or evaluate different geometric entity types according to the planned strategy. The evaluation here includes any necessary measurement analysis' actions such as filtering, fitting or constructing operations. This operation-based structure of a measurement plan aligns with the feature operations concept introduced in ISO 17450, the next generation of geometric product specifications (GPS) standard [36].

Formulating a resource-independent measurement plan is necessary to attain the interoperability objective, which enhances the flexibility of the measurement scheduling activities. This could be achieved through specifying what is to be measured and then how it is to be evaluated. The decisions regarding how to measure, could be only specified in a technology based manner rather than resource dependent manner. This research introduces the "resource-Independent measurement specifications (RIMS)" term, to reflect this concept more precisely than the "measurement planning" term. RIMS stresses on formulating the measurement plans in a technology dependent, but in a resource independent way. It enables the exclusion of the implicitly contained programming tasks within the measurement planning activity, as the measurement programming phase is strictly linked to a specific measurement resource.

### 3.2. Feature technology as an integration enabler

Feature technology is the principle upon which the integration between different computer aided for x (CAx) applications has been realized. However, different applications involved different feature definitions. For example, design features are not the same as manufacturing features [35]. Design features are used in CAD systems during the product conceptualization phase by being added or removed to alter the final shape of the product boundary. Conversely, manufacturing features are used in the computer aided manufacturing (CAM) systems to identify the volumes to be removed from an initially defined raw material, through a set of machining operations, to reach the product final boundary.

The designed product is generally composed of a number of 3D features. During the design phase, the nominal form, size, location and orientation of those 3D features are geometrically and dimensionally characterized. The example shown in Fig. 1 clarifies that the design specifications control 2D geometric entities, although being specified from the design perspective, to control the variation of the 3D features' parameters. The actual 2D entities, related to the nominally defined ones, can be obtained through two methods. The first is by the direct measurement of the actual specified entity if it is an integral part of the actual product boundary. If it is not, then it is derived from other directly measured boundary entities.

To illustrate, the flatness tolerance in Fig. 1 controls the planar face feature which is directly measurable, while the position tolerances control the axis of the hole feature and the slot feature central-plane; they are both constructed using other directly measurable integral features. These classifications of the 2D entity matches the characterized and verification features concepts defined in GPS ISO 22432:2011 [37].

The presented variation in features' dimensionality is important when dealing with RIMS. Operation-based RIMS is
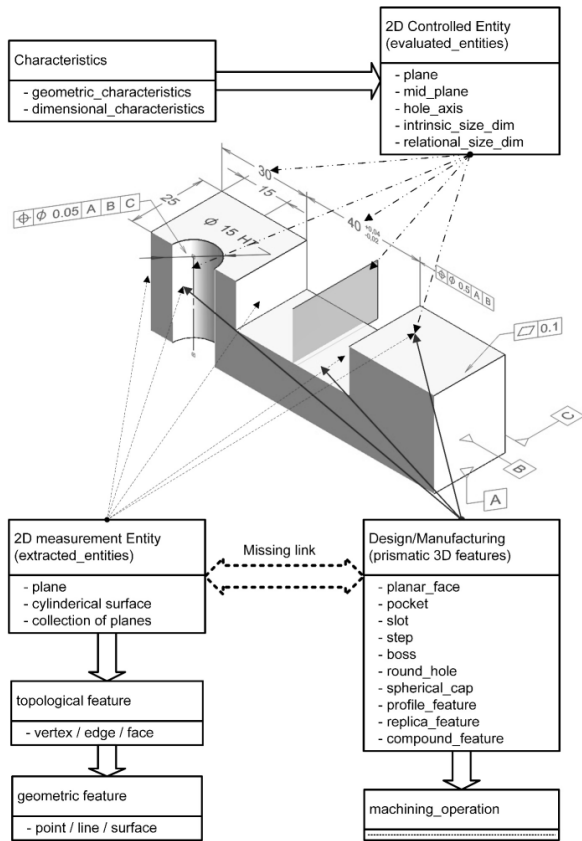
Fig. 1. Illustrative example for representing different feature views.



Fig. 2. Conceptual model for illustrating the RIMS concept.

directly linked and derived from the design specifications through the clear definition of the controlled and measured 2D entities and their related inspection operations. Fig. 2 presents a conceptual UML model to illustrate the direct formulation of the operation-based RIMS based on the explicit identification and definition of the included 2D entities.

In subsection 3.3 a proposed data structure of the measurement 2D entities will be discussed, while section 3.4 proposes the necessary measurement feature's relationships from the measurement process viewpoint.

### 3.3. Measurement feature representation

What is actually measured is the product final boundary represented by various 2D geometric entities, which are unique [35]. This can be clarified by considering that the same manufacturing feature may require different measurement entities and procedures based on different control specifications. A conceptual data model is proposed for representing the measurement entities. The aim is to assist the direct formulation of the RIMS and to allow the integration of the gained measurement knowledge with other manufacturing operations. Fig. 3 presents the proposed framework in the form of an Express-G diagram. In the proposed framework, three mutually exclusive classifications can be set for a single measurement entity.

The first classification is based on the shape of its geometric primitive. Three basic geometries exit, they are point, curve and
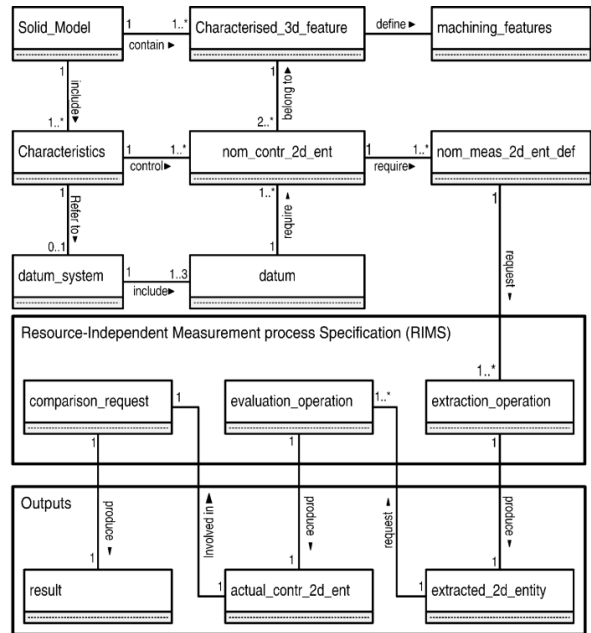
surface. They are derivable through the overlaying topological entities which are vertex, edge and face. These topological entities are referenced from the STEP geometry schema. The second classification is that a measurement entity could be an integral or a derived part from the product boundary. The integral element is directly measured while the derived element requires a relation to other direct measured integral elements and defined evaluation operations of the extracted elements.

The last classification is that a geometric entity could exist from measurement viewpoint in two main statuses which are nominally defined or actually measured. The nominally defined entities are those linked to the specified characteristics in the current STEP GD&T data models. On the other hand, the actual measured entities are defined to represent the extracted point clouds from the extraction measurement operations.
The actual entities also represent the evaluated entities that result from the other evaluation operations. There are three main types of evaluation operations and their associated measurement feature types. They are the filtration, association and construction operations, according to the coordinate metrology principles and the GPS concepts.
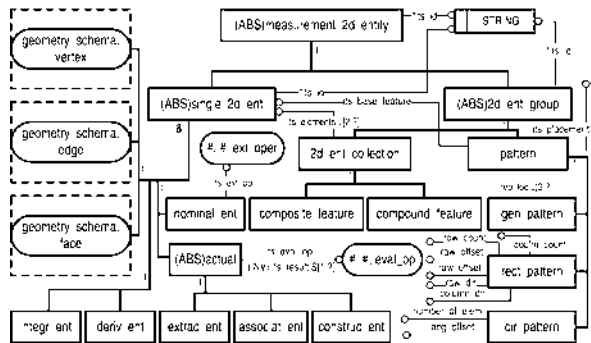


Fig. 3. Express-G representation of the 2D measurement entity.

By referring to Fig. 2, it is worth noting that the relations between the nominal measurement feature and the related extracted features data is established through the extraction operation definitions. This also applies to the relationship established between the extracted and the related evaluated measurement entities through the evaluation operation definitions. One nominal entity is allowed to reference many extraction operation definitions, and one extracted entity can reference many evaluation operation definitions.

A measurement entity could be defined as a single group that consists of a number of different single entities. In Fig. 3, the 2d_ent_group entity is defined to handle these different common situations. This entity and its subtypes are crucial, for example, when a pattern is used as a single controlled entity or as a single datum feature. In addition, they are useful when any number of different feature types need to be referenced as a collection as when a set of targets are used to define a datum feature, or as for features referenced by the in-between or all-around tolerance qualifiers. The compound_feature entity is defined to accommodate for example a common axis element that references different hole features with different diameters.

*3.4. The realization of the process control functionality of the measurement processes*

What is not yet clear is how to realize the measurement functionality as a process control enabler. In other word, how to integrate the gained knowledge through the measurement processes to be used to update the related machining operations. A parent-child relationship is proposed between the 3D features and their required evaluated 2D entities. Fig. 4 is a shortened figure from the STEP AP238 [38]. It clarifies that the manufacturing feature definition includes explicit relationships to both its related workpiece and its set of machining operations. This research is only concerned with finishing operations that solely alter the final product boundary and hence the measurement results.
Building upon the connections in Fig. 4, the proposed parent-child relationship, will support the measurement control functionality. Establishing this relationship is beneficial when a corrective action is requested based on the recorded measurement errors. This parent-child relationship is represented as illustrated in Fig. 5. It should be noted that the measurement_2d_entity in Fig. 5 is the same abstract supertype entity illustrated in Fig. 3.

The measurement process requirement analysis identified an additional crucial modification for the 3D feature definition itself. This modification requires the 3D feature to reference its
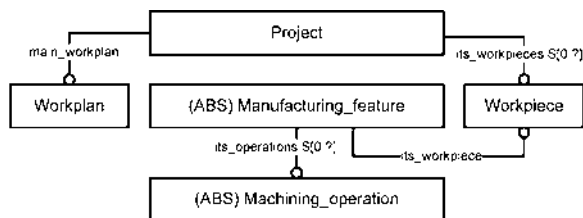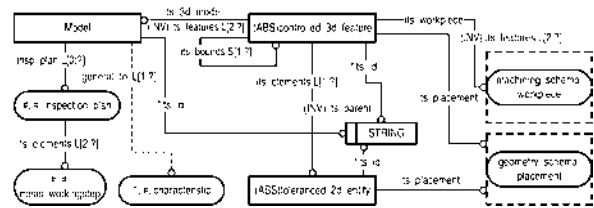


Fig. 5. 3D feature relationships with its related 2D measurement entities and bounding 3D features.

bounding 3D features. Machining operations of the bounding features may affect the size parameters of the bounded feature. Consequently, measurement errors may require the modification of the machining operations performed to one of the bounding features instead of the bounded feature's machining operations.

Simple rules can be built on the relation proposed in Fig. 3 to infer some related semantics of the dimensional characteristics. For instance, if the dimensionally characterized 2D entities, both belong to the same 3D feature, this implies that the dimensional characteristic is of an intrinsic type, i.e. a size parameter of a feature of size. On the other hand, if each of the dimensionally characterized 2D entities refers to different 3D features, the characteristic is known to be relational. The latter could be applied to locate a 3D feature with respect to another 3D feature, or it could result from the independent positioning of different 3D features as in a wall thickness case.

The suggested implementing approach for the proposed framework considers the nature of the data saved in the CAD databases and the recent GD&T standards representations developments. For defining the RIMS, the implementation is to be designed to retrieve those specified characteristics required to be checked from the CAD data. The explicit identification of the elements to be measured on the product boundary is then determined, using the relations between those characteristics and the 2D measurement entities as defined in Fig. 3. RIMS is then constructed directly by listing the specifications of the necessary measurement operations required for each measurement element. With regard to the measurement process results, if any errors are identified, the measured 2D entities could reference explicitly the related machining operation parameters that may need to be updated based on the relation introduced in Fig. 4 and Fig. 5.

**4. Conclusion**

This paper defined the resource independent measurement specifications concept, which excludes the measurement programming tasks, as a means for the direct formulation of interoperable measurement plans. A conceptual EXPRESS-G framework was discussed to represent the measurement 2D entities as a main pillar for deriving directly and explicitly the necessary measurement process specifications. Those defined entities are supposed to integrate seamlessly the measurement planning systems to the GD&T data models. In addition, new defined relationships are illustrated to realize the process control functionality of the modern coordinate metrology. Finally a suggested implementation scenario of the proposed



Fig. 4. The manufacturing feature relationship to its machining operations and parent workpiece.

conceptual framework has been discussed while its development will be the topic of a future work.

The concept and framework presented in this research contributes to achieving interoperable exchange of measurement process specifications. This enhances the overall measurement process integration within the digital manufacturing environment, which positively impacts manufacturing through potential cost-savings.

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