Use of Model-Based Definition to Support Learning of GD&T in a Manufacturing Engineering Curriculum

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Abstract

Model-based definition (MBD) has been attracting significant attention in industry as a means for consolidating access to critical engineering information using the CAD model as a portal. One of its goals is to improve engineering efficiency and reduce the time taken to develop a product throughout its design, manufacturing and marketing phases, by integrating engineering annotations with the 3D CAD model. This contrasts with the traditional approach of providing access to this information utilizing a 2D drawing, either in paper or electronic form. Case studies have shown that MBD has the potential to significantly reduce the development time with reductions in cost. At the same time there is resistance to embracing this methodology due to the continued preference for the traditional engineering drawing as a means to communicate non-geometric information on the production floor.

As industry pursues greater adoption of MBD, it is also important to consider its use in engineering design and manufacturing curricula to promote better learning of product function, and how this can be captured through the specification of Geometric Dimensioning and Tolerancing (GD&T). As engineering design and graphics instruction has embraced 3D modeling, there is an argument to be made that there is an overemphasis on developing 3D parametric modeling skills. The integration of appropriate engineering annotation such as dimensions and specification of GD&T, which require greater insight into product function than just size and shape, are often relegated to an afterthought when a drawing is generated from the 3D model. This paper presents the experiences and challenges of using MBD technology in an undergraduate manufacturing engineering curriculum for capturing design function and manufacturing requirements through GD&T. It reviews a junior level Design for Manufacture course, where advanced concepts in GD&T are introduced, and where students are required to demonstrate their grasp of these concepts by utilizing MBD. To facilitate this methodology, students receive instruction in the use of CATIA's Functional Tolerancing and Annotation (FTA) workbench which they are required to use in their assignments and project work. In addition to allowing the integration of annotation with the 3D model, the FTA workbench provides a *Tolerance Advisor* that forces conformance with the ASME Y14.5-2009 standard. This tool guides students in making appropriate choices in their selection of datums, material conditions and geometry depending on the form controls applied. Finally, students are evaluated in their ability to independently apply this knowledge in a senior level Design of Tooling class. This paper will show examples of how learning is accomplished in the junior and senior classes and summarize how the use of MBD is leading to final 3D models and drawings that more fully capture the functional and manufacturing requirements of a design through appropriate use of GD&T.

Introduction

The development of CAD and Product Lifecycle Management (PLM) has followed parallel though converging tracks. Today, the CAD model is now capable of capturing a broad range of

geometric, feature-based and parametric data that facilitates the construction and interactive manipulation of a design. The ability to associate geometry in a persistent way further supports the data requirements for assembly modeling. In integrated CAD/CAM/CAE systems this associativity is also the key to supporting efficient design changes as the product evolves. On the PLM side, traditional Product Data Management (PDM) systems have evolved to support the management of data and engineering processes involved in the creation of products, manufacturing processes and use of resources over the entire product development cycle. These systems support version control, authorship and ownership, and workflow processes which are needed to align and integrate the product data with the engineering processes a company follows in product development. CAD and PLM are converging in the emerging field of Model-Based Definition (MBD). This utilizes the CAD model as the core around which all lifecycle data is organized, and through which it can be accessed.

What is Model-Based Definition (MBD)?

Model-Based Definition is an emerging methodology for creating and managing data generated during product development, by utilizing the 3D CAD model as the primary source to which all this data is linked. This provides associativity between data that would normally be stored separately in a PDM system and the geometric structure of the product. Thus, the CAD model becomes the doorway to the data that is needed to support design, manufacturing and production activities. Some of this data may be stored as part of this model, while other sets can be accessed through links. Alemanni et al. [2] highlight an evolution in MBD as deployed by industry following three stages. The first just limited changes to drawings using only modifications to the geometry of the 3D model from which it is generated. The second is the integration of Functional Tolerancing and Annotation (FTA) with the 3D model. The third extends to including embedding or materials, technology, processing and overall lifecycle data in the 3D model.

Benefits of MBD in Industry

The goal of industry is increasingly the use of digital mockups (DMUs) to create and validate designs, tooling, equipment and processes throughout the lifecycle. The foundation of these DMUs are the 3D CAD models of the product design and all resources used in its manufacture. MBD aligns naturally with this trend. In addition to the DMUs being utilized in a broad spectrum of simulation and analysis activities, being MBD-enabled allows engineers to use links associated with these mockups to save results from these activities, and to be able to quickly retrieve these as they need to in the future. The following list summarizes some of the benefits of this strategy:

- Greater ability to access data using the same environment and computer tools where engineering takes place.
- Connection to the visualized models eliminates time consuming file name searches for product information in the PDM system.
- Reduced external associativity by reducing the number of disparate databases that store product data.

- Greater data consistency through organization of data around product and resource structures.
- Improved portability of engineering data across multi-functional teams.
- Enhanced support for concurrent engineering.
- Single data source for all product development activities.
- Reduced Manual Re-Input.

Functional Tolerancing and Annotation (FTA)

One key function associated with MBD is the integration of tolerancing and annotations with the 3D CAD model. The traditional parametric 3D model is created assuming an exact geometric shape. However, Design for Manufacture (DFM) requires that all dimensions be subject to manufacturing variability. These need to be specified using appropriate tolerances. DFM also drives the trade-offs that must occur between design and manufacturing when negotiating the best compromise between meeting functional requirements and minimizing fabrication costs. The CAD-based approach to specifying tolerances and annotations is during the drafting phase, after the 3D model has been created. Associativity is made to drawing elements that are parts of views generated from the 3D model. However, this associativity is largely non-semantic i.e. it's purely for visualization purposes on the 2D drawing and does not typically capture the underlying relationships between the part features that convey the true meaning of the tolerance and how it relates to associated dimensions and datums.

CATIA FTA Workbench

Functional Tolerancing and Annotation (FTA) is a term coined by Dassault Systemes [4] for the technology used within CATIA for attaching GD&T and other annotations to the 3D model. The FTA workbench in CATIA provides two mechanisms for attaching GD&T. The first is the 3D analog to what is done on the 2D drawing. The designer simply tags surfaces with the ends of basic dimensions, datums or feature control frames to convey the form and dimensional controls that are desired. In this scenario, the designer is free to specify tolerances regardless of conformance to standards, and so can do so in ways that are noncompliant. The second approach generates “semantic” tolerances using a “Tolerance Advisor”. This advisor forces the GD&T applied to conform to a standard that must be set by the designer for the model, typically ASME 14.5-2009. It does this in an assistive manner by limiting the choices available based on the geometry selections made. For example, selecting a single plane would provide the user with the options to specify a datum or a flatness control. Selection of two parallel planes would limit specifications to parallelism or angularity tolerance.

Benefits of Use of FTA in Education

One of the desired learning outcomes in Manufacturing Engineering curricula is to develop the ability of students to design products that are first feasibly fabricated, and that second can be done so cost effectively. A key part of meeting the latter part of this challenge is developing the students' knowledge of the tolerances and surface finishes that are attainable using different processes. Other outcomes related to the design of tooling require the ability to select appropriate

datums and to define the location, orientation and form of key features (e.g. locators on a fixture) with respect to these datums. It is difficult to meet these outcomes if students do not possess knowledge about how GDT is specified in practice.

GD&T Instruction

Instruction in GD&T has aspects that lend themselves well to both academic learning and also professional development. As mentioned previously, in a Manufacturing Engineering curriculum the ability to select processes and parameters for fabrication is not possible without knowledge of how these processes impact the tolerances that are attainable. Design of tooling and fixtures, and inspection requires the ability to choose appropriate datums and to base dimensioning schemes off these. Variability in size of both features on a part and components in an assembly require the ability to identify and evaluate how dimensions stack across dimension chains. GD&T must be interpreted and accounted for when setting up tolerance stacks. Examples of pedagogical experiences in teaching GD&T are present as published work [7], [8], [9]. Finally, study of GD&T can also delve into the subject from a geometric modeling perspective that studies how tolerance zones can be mathematically represented and visualized, and how interpretation can be automated as part of the technologies that assist in design interpretation for process planning [10]. The latter area of academic interest is typically the topic of technical electives or graduate courses.

From a professional development perspective, training courses in GD&T are offered in a broad range of formats. Some of these are provided by professional organizations such as SME and ASME [11]. Others are provided by consultants in the field.

The availability of this professional training underscores a number of challenges that academic treatment of this subject matter faces.

- First, as mentioned previously, this is a broad and deep subject that busy curricula can find difficult to incorporate. This together with lack of a universal requirement that GD&T be taught in mechanical and manufacturing engineering to the same extent as other subject matter, leads to significant differences in the knowledge of graduates in the subject matter when they enter the work force. Professional training helps to level out these differences.
- Second, and probably more importantly is that companies that utilize the AMSE Y14.5-2009 have considerable flexibility in how they implement and enforce consistency in the manner in which the GD&T they use is interpreted. This is particularly true in how design and manufacturing work together to ensure that components are toleranced in ways that are consistent with the fabrication capabilities that are available. As one example, since the manner in which material modifiers are used can impact the ability to do trade-offs between size and location tolerances of features, manufacturing would like to be given the greatest flexibility through what is specified to drive fabrication costs down. At the same time designers need to be aware of what trade-offs they are permitting and whether or not this may impact function. These trade-offs vary significantly based on the function, sizes, materials and processes available, which varies from company to company. It's impossible within an academic setting to study all the ways that GD&T use can be customized to meet the

requirements of specific industries such as aerospace or automotive. It is role of professional training delivered from a consultancy perspective to bridge this gap.

Teaching GDT in a DFM Context

One of the challenges in teaching GD&T within a MFGE curriculum is determining appropriate contexts in which to do so. The breadth and depth of the subject is such that it could easily occupy the time of multiple courses. A technical elective is then obviously one option. However, electives are often taken towards the end of a program, and not by all majors thus allowing some students to miss out on the subject. It can also be introduced as modules within other courses. Those best suited are machine design, design for manufacture, or tooling design. For the curriculum in question, the bulk of this material is covered within the context of a DFM class, MFGE 333. A follow-on class on Design of Tooling, MFGE 463 is used to further develop and hone these skills. Both are required courses in the curriculum.

Figure 1 shows the content of this DFM class arranged pictorially and highlights the GD&T topics. The strategy adopted spreads these topics out over the duration of the term so that they are presented concurrently with other DFM concepts. The course starts off with an introduction to DFA which motivates topics such as mechanical fits and finishes. Fits in turn bring out the connection between function and the importance of applying appropriate tolerances. GD&T and the capabilities of different manufacturing processes in achieving specified tolerances are built upon these concepts.

Figure 1. High-Level Concepts Covered in MFGE 333 with GD&T with Text for Instruction [6]

As will be discussed in more detail later in this paper, assignments related to developing skill at using CATIA's FTA workbench are part of MFGE 333. These are taught using a flipped-classroom approach. Students already familiar with CATIA's parametric modeling and drafting capabilities utilize a training manual to complete homework assignments on how to use this workbench. The instructor verifies completion of these exercises in class and further leads the class in completing integrative type demonstrations that reinforce the proper thought process behind application of the technology.

While this in-depth treatment of GD&T occurs during the junior year of the program, it is not the first exposure students receive to the subject. During the sophomore year, they are introduced to the basic meaning of datums and feature control frames as annotations that are added to drawings during drafting. This takes place within the context of an introduction to CAD class, MFGE 261. Drawings are created from 3D parametric models and views must be appropriately dimensioned and annotated. The outcomes of this activity are largely raising the awareness of students to the need to include GD&T and annotations in creating a complete drawing, and in developing their skill in use of the drafting system. Students then reinforce an understanding of datums and dimensional tolerancing in the Introduction to Manufacturing Processes class (MFGE 231) where they learn about the manufacturing cycle and also spend 10 lab session fabricating parts from drawings using multiple metal manufacturing methods.

This approach for instruction and assessment of this subject, mirrors the program's mechanism for assessment of ABET a-k outcomes. These are evaluated at three different points in the program corresponding to Introductory (I), Reinforcement (R), and Mastery (M). For GD&T students are introduced to the subject in MFGE 261 (I), receive detailed instruction in MFGE 333 (R), and demonstrate their grasp of the concepts in MFGE 463 (M).

Use of FTA in GDT Instruction

The use of the Functional Tolerancing and Annotation workbench in the CATIA CAD system is used to assist students in their learning of how to properly apply and interpret GD&T. It does this in the following ways:

1. By providing a 3D model to which this information is attached, it helps in visualizing the geometry that is impacted by the relationships that exist between dimensions, tolerances and datums.
2. It helps to clarify interpretations that are difficult to see from 2D views on a drawing. One example of this is shown in Figure 2. It is not immediately clear without synthesizing information from multiple 2D drawing views whether the datum specifications are referring to a datum axis or datum center plane. As can be seen from the accompanying 3D figure, the meaning is obvious when the call out is associated with the 3D model.

Figure 2. Example of Improved Clarity of the Meaning of Controls by Using the 3D Model

3. It allows students to practice and develop dimensioning and tolerancing skills without the additional requirement of having to create a 2D drawing. At the same time they are actually generating the annotation components that will appear on a final 2D drawing. Since the technology is based on inserting annotations on planar views in the 3D model, drawings use this information when 2D views are generated. This can be viewed as an extension of the projection of the geometry of the 3D parametric model onto a view plane to create the edges that appear in a view.
4. As mentioned previously, the FTA workbench includes a mechanism for inserting what is referred to as “Sematic Tolerances” that conform to a selected GD&T standard for the model. This is typically ASME Y14.5-2009. It does this through use of a “Tolerance Advisor”. This can be viewed as a wizard-type tool that assists the user in making correct use of the standard. By following the guidance students can in real-time get feedback on whether they are applying the standard correctly. They can make corrections and iterate until they are in conformance, or know when they need to seek clarification on a concept they may not be grasping. The following section will discuss the methodology and some of the features of the Tolerance Advisor that make this possible.

GDT Concepts Promoted Using the Tolerance Advisor

The process of inserting annotations using the FTA workbench promotes learning of the following concepts:

- Selection of appropriate views that will best communicate annotations on a 2D drawing.
- Identification of the datums needed to impose adequate control of the geometry.
- The creation of datum reference frames (DRFs) using appropriate combinations of datums.
- For a desired feature control (position, angularity, parallelism etc.) the combination of DRF and feature geometry that is appropriate.

- [illegible]

To understand this, it is necessary to review the process by which the FTA workbook creates these annotations. Figure 3 shows an example sheet metal bracket used during an in-class activity by the students to develop their knowledge of and ability to use this tool. The steps followed are captured in the specification tree shown to the left. First, views are created to define planes on which annotations are to be displayed. These view planes will eventually correspond with 2D drawing views. This gets students thinking about how this information will be effectively communicated using a 2D drawing. The second step is the definition of datums. Though datums can be continually added throughout the annotation process, students are encouraged to develop a datum scheme that will fully cover specifications at this stage. Though changes can be made to these after they are referenced by other elements, novices typically have difficulty or lack the patience to do this, and resort to deletion and reinsertion (similar to making modifications to geometric features that “break” the CAD model). The third step is combining individual datums into datum reference frames (DRFs). The most common of these being the A|B|C orthogonal planar structure, though all feasible combinations based on the selected standard can be defined. Datum target points, lines and areas can also be selected in lieu of planes, as the geometry defining the datum. These reference frames must be created prior to the insertion of any geometric tolerances or basic dimensions that utilize them (steps 4 and 5). It’s been observed that when students are early in their GD&T education they will often attempt to insert a geometric tolerance and find that they have not adequately defined an appropriate DRF to be able to complete the tolerance frame. As students become better at planning their dimensioning and tolerancing scheme, the frequency of this occurrence drops significantly.

Figure 4 shows the sequence followed using the FTA dialog windows in specifying DRFs, geometric tolerances and dimensions. Step 1 in dialog A shows the creation of reference frames from individual datums. Step 2 in dialog B shows the selection of a DRF from the list of those created. At this step, in addition to selecting the DRF, the user selects the geometry from the model that the control or dimension will be attached to. In this example, the cylindrical surface of the large hole in the sheet metal bracket from Figure 3 was selected. Depending on the DRF and the geometry selected, buttons appropriate to the applicable controls appear in *Commands* pane of the advisor. For this example, control of the angularity of the hole axis, its location or profile of a line or surface are the options that are valid. Had other combinations of DRF and feature geometry been selected, the advisor would have filtered to the applicable controls. This is a useful learning mechanism to engage students in GD&T learning, as they must correctly setup and choose the DRF/feature geometry combination to get access to the controls they wish to apply. If they do not appear, then they must backtrack and trouble shoot what in their thinking is incorrect. Upon selection of the appropriate control (position in the case), a dialog appears (C) that allows input of the information that will appear in the feature control frame. This includes important details such as material modifiers for the tolerance zone. More complex dialogs appear when composite feature control frames are required, such as that used to control the hole pattern around the large hole in the example sheet metal part.

Figure 4. Process of Using the Tolerance Advisor in CATIA FTA Workbench

Examples of Assignments and Student Work Using MBD

Several learning modes are utilized to develop a student's knowledge of GD&T that integrate in the use of CATIA's FTA Workbench. These are as follows:

- Use of a training manual [5] using a flipped classroom approach.

This is provided in e-Book format. It is structured chapter-by-chapter using a description of the capabilities of the different features of the workbench, each culminating in a series of exercises that lead students through the mechanics of executing each feature. Project type exercises are available at the end of the manual. Students are assigned reading and exercises

to be completed prior to class time during the first part of the term. These are checked in class by the instructor, along with resolution of any difficulties encountered.

- Instructor led demonstrations correlated with GD&T lectures.

Instruction in GD&T utilizes reference [6]. As different controls are presented, students are led through the insertion of these using the Tolerance Advisor within the FTA workbench. Figure 5 shows examples of demonstration models that are used in class. The model on the left shows students the use of different form and orientation controls, while the one of the right is used to demonstrate the application of position control, basic dimensions and composite tolerances. Other models are used to demonstrate runout control. In contrast to the use of the training manual, the instructor can assist students in real-time with problems they are encountering in the lab where the class is held. The results are likewise checked off to ensure student participation.

Figure 5. Examples of Instructor Led Demonstrations on Using FTA for Specifying GD&T

- In-class activities

To begin the process of cutting the tether to the manual and the instructor's guidance, students are given in-class exercises to fully annotated drawings of simple components that they are to duplicate on the 3D model. The sheet metal bracket discussed earlier is one example of this. Though the instructor is available for assistance, the students are encouraged to discuss and get help from their peers when they encounter difficulties.

- Design for Manufacture Communication Requirement (CR)

As a capstone requirement for the DFM class, students are required to demonstrate their ability to effectively communicate on a drawing the specifications of a part with GD&T. Drawings must be generated using only the annotations input on the 3D model. This requirement ties into their final project where teams of three to four students must design a part that is to be fabricated using different manufacturing strategies (one per team member

- Deliverable CR 1: Duplication of annotations from an existing drawing. This is similar to the in-class activities described earlier (sheet metal bracket exercise) though with a more complicated part and a broader range of specifications. Students must also work independently and create a properly formatted drawing (adherence to layout rules, frame and title-blocks etc.). An example of the type of part used along with the annotations from the top view of a final drawing are shown in Figure 6.

- Deliverable CR 2: Specification of GD&T given a functional textual description of features in a 3D model. This requires students to themselves select the appropriate datums and controls that are needed to meet their understanding of the functional description provided. This is designed to assess whether or not students are developing the ability to reason by themselves on how function drives the selection of GD&T.

- Deliverable CR 3: Specification of GD&T on a newly designed part. This is the tie into their DFM project, and represents the highest level of ability in the use of GD&T. In contrast to the previous deliverable, students must on their own first infer the functional requirements of their design and then translate these into the appropriate specifications. Other material covered in the DFM class on topics such as fits, finishes and the capabilities of different manufacturing processes and operations comes into play. Figure 7 shows an example of a machined pedal design and some of the accompanying annotations created by a student on a team evaluating different strategies for manufacturing mountain bike pedals.
- Tooling Design Project (MFGE 463)
To further reinforce a Manufacturing Engineering student's knowledge of GD&T, concepts covered in MFGE 333 (DFM) are being reinforced by assignments and project work in a follow-on class MFGE 463 Design of Tooling. These classes are taught sequentially, though with the summer in-between for most students. So, MFGE 463 starts with a homework assignment that includes two exercises (Review 1 and Review 2) that are designed to assist students review their knowledge of GD&T, and their ability to use the FTA methodology. Later in the term, as part of a group project to design a multi-cavity injection mold, GDT must be used in specifying feature locations on the B-side plate of the mold. Figure 8 shows the part used in this project, an example of a mold design and a view from the final drawing showing the annotations that were specified.

Figure 8. Use of GD&T and FTA in Injection Mold Design

Observations on Student Performance and Learning

Table 1 shows the scores on GD&T and FTA related assignments, from a cohort of 18 manufacturing engineering majors who first took MFGE 333 in the Spring term, followed by

MFGE 463 in the Fall term of their senior year. These assignments have been described above. It can be seen that not surprisingly, students perform significantly better on those assignments where they are translating specifications given to them on a drawing into annotations on the 3D model (CR 1). They also demonstrate good retention in their ability to interpret GD&T information on a drawing between classes that include the summer break in-between (Review 1). However, there is a significant drop off when they are asked to start exercising their independent judgement on the correct selection and insertion of specifications onto the 3D model (CR2 and Review 2), and further still when they must first start by inferring functional requirements of a design (CR3 and Mold). The larger drop-off in Review 2 over CR2 is partly due to some students not retaining the ability to efficiently use the FTA workbench due to lack of practice over the summer. This is particularly true for students who may not be strong in their CAD abilities.

	MFGE 333 Design for Manufacture			MFGE 463 Design of Tooling		
Student↓	CR1	CR2	CR3	Review 1	Review 2	Mold*
Marks →	40	40	30	25	25	15
1	40	36	28	23	18	13
2	31	27	20	-	-	13
3	40	39	27	23	20	13
4	36	32	29	25	20	11
5	40	39	30	25	23	11
6	39	35	25	23	22	11
7	36	37	26	23	18	13
8	40	36	24	25	24	13
9	39	29	24	23	18	13
10	39	38	27	22	18	12
11	39	36	27	23	23	12
12	37	36	27	25	23	12
13	37	34	22	22	21	-
14	39	37	28	24	20	-
15	39	37	27	23	20	14
16	39	38	27	23	23	14
17	39	37	27	25	25	14
18	37	33	21	23	17	14
Averg.	38.1	35.3	25.9	23.5	20.8	12.7
Mean	39	36	27	23	20	13
Stdev	2.16	3.18	2.64	1.04	2.39	1.04
Percent.	95.3%	88.3%	86.3%	94.1%	83.1%	84.6%

*Group Assignment; - Student did not receive a grade (e.g. late, not completed)

Table 1. Performance of Student Cohort on Key GD&T and FTA Assignments

One of the most common problems encountered in the R2 review was proper dimensioning to datums and the correct use of basic dimensions over conventional dimensions particularly for

locational tolerances. As previously mentioned, some of this maybe attributable to lack of recent practice with the FTA workbench, though there was evidence that some students had not fully grasped the concept on proper use of basic dimensions. This concept was reinforced in MFGE 463, and improvement was noted in the Mold project which required callouts on hole locations using basic dimensions as can be seen in Figure 8.

There are some caveats that must be pointed out regarding the conclusions that can be made using the data in Table 1. For CR3 in MFGE 333, students are allowed to select the part for their DFM project, and each member of a team creates a design suited to a different manufacturing process. This open-endedness meant that the GD&T requirement varied from student to student. This made evaluation of abilities by the instructor challenging. The mold project in MFGE 463 may provide a more level playing field in this regard. On the other hand, the broader set of requirements that students need to consider could adversely impact the attention they are able to give to satisfying this particular requirement.

Discussion and Recommendations

The use of the FTA workbench has as its primary objective, support for teaching concepts surrounding GD&T. This effort has led to the following observations and recommendations on the use of this technology:

- **Importance of Having a GD&T Focus**
As mentioned in the instruction, GD&T as a topic is expansive, and this makes it a challenging subject to deal with in an engineering curriculum. Having focused assignments helps to provide a foundation for the learning that can occur. Conversely, applying GD&T to open-ended design work is asking too much from novices as was evident in the C3 assignment for MFGE 333. The injection mold plate design assignment in MFGE 463 provided for a more manageable and focused experience, even though it was largely limited to locational feature control. While this may seem limiting, a sound knowledge of this type of control captures a significant breadth of fundamental GD&T concepts. In this regard, tool design applications (others include fixtures, jigs, Single-Minute Exchange of Die - SMED) provide a rich source of material to base projects and assignments off. In DFM, a more functionally constrained project could accomplish the same thing.
- **Building the Connection between Function and GD&T**
This follows from the previous point and reflects the challenge noted earlier that students experience the greatest difficulty when they are required to come up with the correct controls, and more so specific values of tolerance that will result in a desired function. In industry, this experiential knowledge has been acquired over time and is captured in standards and procedures for dimensioning and tolerancing the specific products that are designed and manufactured. Though it is difficult to reproduce this in an academic setting, tooling design again represents a good application area to support this connection. Significant generic knowledge on sizes, fits and tolerancing of components used in different types of tooling is available in handbooks, catalogs and on-line that reflect design knowledge driven by function. However, developing assignments and projects that truly tap into this in a manner that highlights this connection, requires significant effort on the part of the instructor.

- Impact of basic CAD skills

As a tool integrated within a CAD system, the skills developed in its effective use are predicated on a student's basic CAD skills to begin with. Experience has shown that CAD skill level can vary significantly within a particularly cohort of students. Students who struggle, take longer to complete work, become more frustrated and resort to short-cuts just to complete work rather than truly learning from working through the problems encountered. As CAD systems provide multiple paths to achieve the same goal, it is challenging for an instructor to always be aware of problems, and to be available to guide these students along the correct learning path, before they have invested time going down the wrong paths.

- Non-Semantic vs. Semantic Tolerances

Following from the previous point, the FTA workbench provides two paths to inserting GD&T. The first utilizes a *Tolerance Advisor* as described in this paper which forces compliance with the ASME standard (semantic tolerances). The second path allows the user to manually insert GD&T without conformance checking. Using this second approach short-circuits the learning process that following the steps prescribed by the advisor promotes. Students, particularly when pressed for time, default to using this approach to get assignments completed, rather than challenging their knowledge to work past the road blocks encountered when using the advisor. As with all CAD tools, this is largely a matter of experience and practice. In time an understanding of why the advisor allows what it does at each step becomes clear. Time available for students to practice with the tool prevents some from getting to this point, limiting their ability to use it effectively.

- Feedback from the Tolerance Advisor

Undoubtedly, in the hands of an expert, the advisor can efficiently and effectively be used. However, it was not designed to be used, as described in this paper, to assist in learning GD&T concepts. As such there is no the real-time feedback provided when problems and roadblocks are encountered. A report is provided that provides explanations for broken references and elements that become non-compliant with the standard due to changes in the model. But this can be difficult to interpret particularly for a novice. In addition, there are certain omissions that require significant backtracking to correct once the advisor is in use. Again, these are the type of omissions that someone new to the workbench is likely to make, less so an experienced user. Incorporating more feedback into the advisor would greatly enhance its education capabilities. It would be of great assistance to the designer if the advisor had a way to allow creation of needed DRF's without requiring backtracking.

- Learning Advanced Concepts

Some concepts in GD&T are beyond what can be studied using this particular technology. An example of this is developing an understanding of tolerance zones as they pertain to bonus tolerances, virtual conditions and composite tolerances. Weibe and Branoff [9] proposed the use of CAD to support teaching this concept by providing a mechanism for visualizing allowable variation in position. Our experiences confirm that this has promise, and by using the same CAD tool helps to compliment the capabilities of the FTA workbench. Figure 9 illustrates a simple hole pair pattern and a partially constrained sketch that restricts movement of the hole centers within each hole feature's position location control zone (small grey dashed circle), and this zone within the larger pattern location control zone (larger green

dashed circle). Though crude in its current form, students can drag the hole center and feature position location control zone as limited by the applied sketch constraints to help visualize what these controls allow. More work needs to be done to refine and expand this approach, possibly with the assistance of macro automation.

Figure 9. Use of CAD to Visualize Composite Tolerance Zones

- **Secondary Objectives**

Though not by itself reason to integrate this technology into the curriculum, it is worth going full circle back to the point made in the introduction, that MBD and its constituent technologies such as FTA are growing in prominence and acceptance for use within industry. There is a strong likelihood that with the growing using of portable electronic devices such as tablets, that this will supplant more and more uses of paper drawings (and by extension those drawings produced using what are now standard CAD-based drafting techniques) in a direction moving towards the production floor. Though it will continue to be debated how far paper elimination can progress in this direction, graduate engineers with exposure to this technology can promote themselves on their resumes in this area, and will likely be drivers for its further adoption. As a CAD embedded technology, its use in the curriculum also furthers familiarity and expertise in CAD.

Conclusion

This paper described the experiences of instructors in a Manufacturing Engineering program utilizing Model-Based Definition (MBD) technology in support of teaching Geometric Dimensioning and Tolerancing concepts and practice to students. The Functional Tolerancing

and Annotation (FTA) workbench in the CATIA CAD system facilitates the incorporation of GD&T on the 3D CAD model as opposed to the now common approach of adding these in a 2D drawing on views generated from the 3D model. The use of the 3D model improves visualization and interpretation of GD&T. In addition, the FTA technology includes a *Tolerance Advisor* that forces the creation of semantic tolerances that are compliant with GD&T standards such as ASME Y14.5-2009. Described are various assignments and projects spanning two courses in the curriculum requiring the use of this tool to help students deepen their knowledge of the concepts and correct application of GD&T. Performance in these assignments for the same cohort of students showed that they demonstrated strong capability in the mechanics of using the technology as evidenced in their ability to reproduce drawings. However, there was a significant drop-off when they were progressively asked to do more themselves in deciding what specifications should be used to attain requirements based on function. The refinement of project work to be more consistent in the functional requirements provided in the DFM course, and expanded use in the Tooling Design course where there is rich application material, will help in reducing this. Improvements in the feedback provided by the FTA tolerance advisor would greatly enhance the learning experience of novice users.

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