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Geometric Dimensioning and Tolerancing (GD&T) Integration throughout a Manufacturing Engineering Curriculum

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Geometric Dimensioning and Tolerancing (GD&T) Integration throughout a Manufacturing Engineering Curriculum

"Both industry and education still have a long way to go on Y14.5. Many of those who use the symbology in professional practice do not understand what they are doing." – John Larson, 30-year veteran mechanical designer and educator from Lawrence Livermore National Laboratory, on the use of the ASME standard for GD&T

Abstract

The Geometric Dimensioning and Tolerancing (GD&T) ASME Y14.5 standard[1] for specifying engineering requirements on drawings and related documentation was initially accepted in 1994 and has been formally modified as recently as 2009. Despite many advantages for clarifying and simplifying design requirements as well as implications for reducing manufacturing costs and streamlining manufacturing activities, the various aspects of the standard have seen inconsistent adoption throughout the manufacturing industries across the US. A recent increase in employer expectations when hiring undergraduates at one institution has prompted an ambitious effort to increase student learning of GD&T standards and of the numerous practical ways to utilize it to achieve high quality, low cost manufacturing. The effort involves integrating different aspects of the standard across a broad spectrum of the curriculum for both an undergraduate major program in manufacturing engineering and for a manufacturing engineering concentration in a mechanical engineering program. Lecture content, assignments, lab exercises, and projects have been developed across eight different courses to increase understanding of GD&T from various perspectives such as documentation, mechanical design, design for assembly, design for manufacture, fixture design, machining, and inspection. Altogether, the content covers most of the key GD&T concepts and provides a consistent, coherent approach to graduating GD&T-savvy manufacturing and mechanical engineers. A comprehensive exam has been compiled to track student learning and to monitor the effectiveness of new efforts in this key area.

Introduction

Geometric Dimensioning and Tolerancing (GD&T) is a symbolic and rule-based language for specifying geometric requirements (size, shape, form, orientation, and location) on engineering drawings and CAD model representations of designed parts[2]. Compared to conventional "coordinate" dimensioning and tolerancing (which has been around since the 1800s), GD&T changes the shape of acceptable tolerance zones, removes the need for drawing notes to control form and orientation, and more clearly communicates design intent in terms of functional part features, relations between features, and feature boundaries that enable interchangeable assembly of components. The precepts of GD&T are designed to remove ambiguity in interpreting engineering drawings and give designers the tools to achieve part functionality while allowing manufacturing to operate with the widest (and hence least costly) possible tolerances. The most widely accepted document that spells out the rules and interpretations of GD&T symbols is ASME Y14.5 – 2009[1], although a commonly used and similar ISO standard (ISO 1101:2004) is also in service.

Conventional dimensioning and tolerancing schemes have been used to satisfactorily identify the size of designed features even to this day, along with the acceptable variations in size. These schemes are poor, however, in specifying the location of part features in relation to other features, and they generally cannot be used to specify allowable deviations in form (e.g., flatness) and orientation (e.g., parallelism) without excessive and often confusing notes on drawings. The GD&T standard enables unambiguous communication of the following aspects of a part design:

- The identification of datum features (e.g., surfaces or axes) that are referenced with respect to the position and orientation of other features and that serve as positive contact points during assembly, fixturing, machining, or inspection.
- Bounding envelopes or zones for features based on a maximum (or minimum) allowable material of each feature, thus guaranteeing assembly and interchangeability of components.
- Well-defined geometric zones of allowable deviation for produced features, including the form, orientation, and location of feature surfaces and axes.

Advantages of GD&T over conventional methods include[2,3]:

- The elimination of unnatural rectangular and wedge-shaped tolerance zones for the location of features. For example, the axis of a cylindrical feature that is dimensioned and toleranced from two orthogonal sides (or from the center of a circle) on a part has a rectangular (or wedge-shaped) tolerance zone for which the axis is allowed to deviate in some directions more or less than others. The GD&T standard specifies cylindrical tolerance zones for such axes so that deviation in any direction is considered equal. This provides a more functional requirement for mating components (e.g., a shaft in a hole) in an assembly.
- The elimination of unintended and unnatural tolerance accumulation in sequentially (chained or patterned) dimensioned features. With a conventional approach, if a pattern of holes is toleranced with the first hole to one side of the part and with each subsequent distance between holes, the overall allowance from the last hole to the side of the part is the accumulation of the all previous tolerances. With GD&T, patterns can be dimensioned as a group, with consistent allowance for each feature, and with the ability to give different allowances for locating the pattern as a whole than for the within-pattern (feature-to-feature) location. This more naturally matches the function and assembly of mating components and it simplifies part inspection.
- The ability to specify feature relationships based on maximum (or minimum) material condition. Using conventional methods, the allowable location of a hole is a fixed region regardless of the size of the hole. But in GD&T, the position of the hole axis may be allowed more tolerance if the hole is of larger diameter since it will more easily fit a mating component. This ability can greatly simplify fixturing, processing, and inspection methods while still ensuring adequate functional performance of the part.
- All functional relationships between features are explicitly identified by labeling datum features on the part, thus simplifying and removing ambiguity in fixturing, processing and inspection. As well, GD&T allows up to six degrees of freedom of reference from these datums (including an order of precedence) for each three-dimensional zone of tolerance rather than relying only on two degrees of freedom from a two-dimensional drawing.

- Clearer communication of design intent and functional relationships on drawings and CAD models without excessive and confusing notations and without the need to make assumptions about features and relationships.
- Overall reduction in manufacturing costs by removing ambiguity, providing maximum tolerance where allowable, easing assembly, and simplifying fixture and gage design.

Much technical research has been undertaken in recent years on applying the GD&T standard and integrating new technologies towards a simpler and more automated application of the standard[4]. Various researchers[5,6] have studies methods for using computational intelligence for automatically assigning component tolerances when given an overall assembly tolerance using GD&T concepts. Typically, the effect of the tolerance value on processing cost is modeled as part of the optimization algorithm. Lemu[7] has investigated how modern CAD modeling software and other graphical data exchange standards represent and store GD&T information and how that information is transferred downstream to associated software programs such as those for computer-aided manufacturing (CAM), tolerancing (CAT), analysis (CAE), and inspection (CAI). Both Quintana[8] and Srinivasan[9] have examined how GD&T requirements fit in with the trend of a paperless, model-based digital manufacturing environment.

Less research can be found in the literature on the impact of GD&T concepts on educational programs in engineering. Wang[10] studied the research concept described above in terms of representing GD&T concepts and symbols within a model-based system of product communication (i.e., a 3-D model rather than 2-D drawings) and made some recommendations for engineering graphics education, though not in the realms of engineering design and manufacturing. Ziemian[11] focused on the integrated nature of design and manufacturing in attempting to introduce more hands-on manufacturing experiences to the mechanical designers and reached the conclusion that GD&T concepts were a critical ingredient that needed to be integrated more fully throughout the ME/Mfg curriculum. Mott[12] has made the case for how manufacturing education is indispensable for mechanical engineers and how it fits in both with the direct mandate of the ASME Vision 2030 philosophy[13] as well as the fundamentals of SME's Four Pillars of Manufacturing Education[14]. Although GD&T is not always considered[15] an essential part of early manufacturing education for engineers, it is increasingly thought of that way[16].

Unfortunately, GD&T is often considered more a part of on-the-job or technical training than a key aspect of engineering education. For example, Grand Rapids Community College offers a "Workforce Training" series including the course *Tolerancing Strategies for GD&T*, [17] with the opening description line claiming that "Tolerancing strategies are rarely taught in engineering programs. Designers and engineers are left to fend for themselves, frequently pulling past design practices forward, whether there is a rational basis to do so or not." Indeed, accredited engineering programs in the U.S. would not have such a course, but an internet search on GD&T training reveals countless consultant and university "technical and professional training" opportunities like the one in Grand Rapids. Nevertheless, the idea of integrating GD&T throughout an engineering curriculum has found some traction. In a recent article[18] published out of the University of Illinois at Urbana-Champaign (UIUC), researchers partnered with industry (mainly Caterpillar) to establish innovative, hands-on approaches to teaching GD&T throughout several activities as part of a freshman engineering course on design and graphics. Although

GD&T was originally considered "difficult to teach and learn," the new activities focused on manufacturing and inspection, in addition to form, fit, and function of design. The new efforts were not assessed, but the authors do conclude that GD&T is a fundamental engineering tool that has continued to gain emphasis in industry and suggest that engineering programs consider its importance and avoid excluding it in their curricula. The Mechanical Engineering curriculum[19] at UIUC currently shows at least three courses describing GD&T concepts as key course topics.

Although there is evidence that knowledge of GD&T concepts is lacking and in need in industry, there is some growing consensus that industry now recognizes the strategic importance of design and manufacturing activities that capitalize on consistent application of the rules of ASME Y14.5 2009. Maropoulos[20] describes the current adoption of the GD&T standard as "widespread" in industry but still concedes that problems and misunderstandings are common. Campbell and Roth[21] have developed an entire textbook dedicated to teaching and learning GD&T in a manner that is integrated throughout the steps of any mechanical design process and cite many examples of common misunderstandings in industry. In Srinivasan's summary[22] of research and trends in the digital communication of product geometry, adoption of the GD&T standard is found to be widespread in industry but education is lagging. Perhaps one of the best indicators of industry expectations around GD&T can be found in current advertisements for employment of both mechanical designers and manufacturing engineers. A quick internet search by the authors has come up with numerous current ads, including: one for a Product Design Engineer that requires someone with a BSME who is "fluent in GD&T;" one for a Senior Product Development Engineer (also with BSME) who is "capable of correctly applying and interpreting GD&T principles;" one for a designer (BSME or MSME) with "experience in statistical analysis, RSS (statistical tolerancing), GD&T, and manufacturing;" and one for a designer (BSME) with "demonstrated understanding of … proper tolerance, drafting standards, and GD&T." Perhaps the best publication on the topic is from Watts[23] who specifically analyzed the "GD&T Knowledge Gap" in industry. The paper claims that typical industry designs attempt to incorporate GD&T concepts but generally fail to capture the elements that would unambiguously communicate part function as well as those that would provide a competitive advantage by minimizing manufacturing costs. The paper concludes that the subject is "an important element of a design focused mechanical engineering education" and recommends at least two quarters of related instruction.

The goal of the current study is to improve student comprehension of the GD&T standard at the authors' institution and develop an understanding of how consistent application of its rules can result in better product designs that can be and are manufactured with higher quality and lower costs. The students involved are primarily undergraduate majors in mechanical engineering who have chosen to concentrate in manufacturing engineering as well as majors in manufacturing engineering itself. Each of these programs are ABET accredited and so have the following relevant educational objectives:

- Students will attain *an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic or manufacturability*
- Students will attain *an ability to communicate effectively*
- Students will attain *a knowledge of contemporary issues*
- Students will attain *an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice*

Though similar, the mechanical engineering concentration in manufacturing engineering (ME/Mfg) has a slightly different set of specific learning outcomes than the manufacturing engineering program (MfgE). The relevant outcomes for the ME/Mfg program include:

- Students will gain knowledge of manufacturing processes and will be able to incorporate manufacturability concerns into component design decisions.
- Students will be able to estimate cost and specify an efficient sequence of operations for the manufacture of components or products.
- Students will be able to inspect and test manufactured product, analyze results, and consider quality and reliability criteria during product and system design.

In the MfgE program, the specific outcomes (from the ABET program-specific criteria) are stated as:

- Students will attain proficiency in process, assembly and product engineering, the ability to design products and the equipment, tooling, and environment necessary for their manufacture
- Students will attain proficiency in manufacturing processes, the ability to design manufacturing processes that result in products that meet specific material and other requirements;
- Students will attain proficiency in manufacturing competitiveness, the ability to create competitive advantage through manufacturing planning, strategy, quality, and control.

With these learning outcomes in mind, the objectives of the current study are to

- Develop a consistent approach to teaching GD&T across the design and manufacturing activities throughout the ME/MFG and MfgE curricula.
- Ensure program graduates can effectively use the tools of the GD&T standard to communicate the functional aspects of a product design through geometric requirements.
- Ensure program graduates can assess the impact of their design decisions concerning the use (or lack) of GD&T requirements in terms of the costs and activities of manufacturing and inspection.
- Ensure program graduates can design processes and systems for manufacturing and inspection that take advantage of the opportunities awarded by a product defined using GD&T principles.

The approach taken is to integrate different aspects and levels of proficiency of the GD&T standard into different existing courses in a way that builds each student's knowledge throughout the program. Bloom's Taxonomy[24] is the basis for categorizing activities and formative assessments for each course as students progress from introductory freshman design to senior design projects. Collaboration and communication across instructors and even departments is a key requirement for consistency of the approach. The proper selection and matching of course content to GD&T topic is important in order to ensure that function product design, design for manufacture and assembly, and manufacturing process design are all a part of the solution strategy for effective product development that gets instilled in program graduates. An assessment strategy is developed to test proficiency at different levels.

It should be noted that the implementation represents a balance of somewhat competing instincts within the strategy of teaching GD&T in design and manufacturing. In teaching design and drafting, it is natural to start with the simplest GD&T concepts (e.g., basic dimensions, datums, flatness or perpendicularity callouts) and progress through to the more complex (surface profiles, true position, runout, virtual condition, and composite datum reference frames). Most textbooks[1,25] on dimensioning and tolerancing in design follow this approach, including frequently presenting traditional plus/minus "coordinate" location tolerancing[26,27] even though the practice is specifically discouraged in the GD&T standard[1]. From a manufacturing and inspection perspective, it is precisely the more complex aspects of the GD&T standard that simplify, clarify, and reduce costs the most, and for which the intention of the GD&T standard is to use these the most often in a design. And so getting students comfortable from an early stage in using these tools is quite important[21]. In contrast, some of the simplest GD&T tools to specify (e.g., flatness, straightness) are some of the most difficult to ensure during manufacturing and the hardest to inspect. Consequently, these tools should be used quite sparingly and judiciously and may seem an advanced topic during design.

Curriculum and Course Design

The Mechanical Engineering Program with a concentration in Manufacturing Engineering (ME/Mfg) at the authors' institution includes the following courses that address GD&T:

- ME 130 Introduction to Mechanical Engineering III – covers basic design dimensioning and tolerancing including assembly fits, datums, and geometric tolerances
- IME 143 Manufacturing Processes: Material Removal – covers basic drawing interpretation for setup, planning, and inspection of machining processes
- ME 251 Introduction to Detailed Design with Solid Modeling – covers solid modeling of parts, drawings, and assemblies, including assembly fits and location tolerancing
- IME 330 Fundamentals of Manufacturing Engineering – covers design for assembly and interchangeability of parts, design for manufacture, cost estimation and the effects of tolerancing decisions
- IME 335 Computer-Aided Manufacturing I (elective) – covers specification and interpretation of datums for machining fixturing, creation of part drawings that include GD&T, inspection of machined parts to GD&T tolerances
- IME 450 Manufacturing Process and Tool Engineering – covers drawing interpretation for manufacturing fixture design and corresponding impacts of design decisions
- IME 428 Engineering Metrology (elective) – covers specification and interpretation of design dimensions and tolerances of all types and the design of inspection tooling and procedures

The Manufacturing Engineering Program (MfgE) includes the following courses with GD&T content:

- IME 140 Graphics Communication and Modeling – covers basic geometric design, dimensioning and tolerancing, and introductory solid modeling of parts and drawings

- IME 144 Introduction to Design and Manufacturing – covers solid modeling of parts, drawings, and assemblies as well as drawing interpretation and machining as in IME 143
- IME 330 Fundamentals of Manufacturing Engineering – covers design for assembly and interchangeability of parts, design for manufacture, cost estimation and the effects of tolerancing decisions
- IME 335 Computer-Aided Manufacturing I – covers specification and interpretation of datums for machining fixturing, creation of part drawings that include GD&T, inspection of machined parts to GD&T tolerances
- IME 450 Manufacturing Process and Tool Engineering – covers drawing interpretation for manufacturing fixture design and corresponding impacts of design decisions
- IME 428 Engineering Metrology (elective) – covers specification and interpretation of design dimensions and tolerances of all types and the design of inspection tooling and procedures

Typical examples of practice assignments are available by request from the authors and are posted online[28].

The proposed learning taxonomy for GD&T based on Bloom's Taxonomy[24] develops mastery of basic GD&T concepts by integrating increasingly more complex learning outcomes with the progression of courses in the programs. Assignment of outcomes to courses is as follows:

Knowledge

- Recognize and recall basic GD&T symbols (IME 140, ME 130)
- Define maximum material condition (IME 140, ME 130)
- Recognize MMC symbol where specified (IME 143/144, ME 251, IME 335)
- State Rule #1 for Features of size (IME 143/144, ME 130)
- Recognize situations when Rule #1 does not apply (IME 428)
- Locate datums where specified on a drawing (IME 140, ME 130, IME 335, IME 450)

Comprehension

- Classify form, orientation, and location tolerances (IME 140, ME 130, IME 335)
- Explain or describe allowable form and orientation errors inherent in size tolerances (IME 140, ME 130, IME 335)
- Explain the concept of a tolerance zone (IME 140, ME 130)
- Explain the concept of bonus tolerance (IME 143/144, ME 251)
- Explain or describe the allowable location errors inherent in traditional coordinate location tolerancing (IME 140, ME 251)
- Describe the "stack-up" of locational tolerance produced by traditional dimensioning strategies (i.e., chaining, origin dimensioning, pattern dimensioning) (IME140, ME 130, ME 251)
- Relate datums to part features (IME 140, ME 130, IME 335)
- Relate tolerances to features (IME 140, ME 130)
- Interpret and explain Rule #1 for Features of Size (IME 143/144)

Application

- Construct drawings with size and location dimensions for all features (IME 140, ME 130)
- Link tolerance block information to appropriate drawing dimensions (IME 140, ME 130)
- Apply drawing tolerances to feature sizes and to locate features of size and non-features of size (IME 140, IME 144, ME 251)
- Apply Rule #1 to determine inspection procedures of features of size (IME 143/144)
- Apply form or orientation tolerances to part designs to refine geometric requirements without affecting size tolerances (IME 140, ME 130, IME 335)
- Apply location tolerances to part designs to establish appropriate tolerance zone shapes and orientations (IME 140, IME 144, ME 251)
- Apply location tolerances to patterns of features to establish appropriate tolerance zone size/orientation (ME 251), including the use of composite reference frames (IME 330)
- Associate basic dimensions with corresponding geometric tolerances (IME 140, ME 130)
- Apply bonus tolerances to determine sizes of tolerance zones (IME 330, IME 450)
- Interpret feature control reference frames for tolerance zones (IME 140, ME 130. ME 251, IME 450)
- Practice MMC and bonus tolerance calculations (IME 140, IME 143/144, IME 450)
- Show tolerance zones on drawings (IME 140, ME 130 w/o bonus tol., IME 428)
- Associate product functional requirements with the assignment of datums on drawings (IME 450, ME 251)
- Apply fixed and floating fastener formulas for location tolerances (IME 330, ME 251)

Analysis

- Question the inappropriate use of datums in form tolerances (IME 428, IME 450)
- Question inappropriate use of max material condition for non-features of size (IME 143/144)
- Question the use of key tolerances that are difficult to ensure or inspect, such as straightness of an axis (RFS), flatness of a midplane (RFS), concentricity, etc. (IME 428)
- Distinguish between features of size and non-features of size (IME 140, ME 130)
- Distinguish between bonus tolerance and datum shift (IME 450)
- Distinguish between regular datums and datum features of size (IME 330, ME 251)
- Distinguish between simulated datums and datum features (IME 140, IME 450, IME 428)
- Distinguish between individual datums and datum reference frames (IME 428)
- Order the basic steps of design using GD&T principles (size and location dimensions, then size tolerances, then datums, then datum refinements, then location tolerances, then orientation tolerances, then form tolerances) (IME 330, IME 428)
- Distinguish between regular pattern positional tolerance and within-pattern positional tolerance (i.e., composite tolerance) (IME 330, IME 450, IME 428)
- Find features that can be inspected with full-form (functional) gages (IME 428)
- Infer part functionality from drawing datums and geometric tolerances (IME 450)
- Infer part rotational functionality from axis-to-axis tolerance control (IME 450, IME 428)
- Relate geometric tolerances to datums and datum frames (IME 130, IME 143/144, ME 251, IME 335, IME 450, IME 428)
- Differentiate between methods for specifying axis-to-axis feature controls (position, profile, runout, concentricity) (IME 450, IME 428, ME 251)

Synthesis

- Plan and construct a solid CAD model and a part drawing with datums, datum refinements, and location tolerances (IME 144, ME 251)
- Formulate a strategy for location tolerancing to ensure interchangeability of parts (ME 251, IME 144, IME 330)
- Visualize the size, shape, location, and orientation of tolerance zones (IME 428)
- Simplify fixturing and inspection procedures for features by considering use of an MMC modifier during design (IME 143/144)
- Simplify fixturing or inspection procedures by considering specifications that override Rule #1 (Straightness of an axis at MMC or flatness of a midplane at MMC) (IME 450, IME 428)
- Improve a design to make it easier to fixture, produce, or inspect (IME 450, IME 428)
- Create fully compliant part drawings to the ASME Y14.5 standard (IME 144, ME 251)
- Design a production fixture for an operation based on part drawing (IME 335, IME 450)
- Design an inspection process for a part based on part drawing (IME 335, IME 428)

Evaluation

- Evaluate the need for refinements of orientation or form in part designs (IME 335, IME 428)
- Evaluate the impacts of specifying geometric tolerances both with or without the maximum material condition modifier (IME 450, IME 428, ME 251)
- Assess the impact of specifying zero geometric tolerance value at MMC (IME 330)
- Convince a part designer to use geometric tolerances that make fixturing, production, and inspection easier and less expensive
- Consider the use of least material condition modifier
- Compare production costs for two similar designs with differing tolerancing schemes (IME 330)
- Compare fixturing and inspection alternatives for features or datums that are referenced at MMC (IME 450, IME 428)
- Defend design decisions in terms of part functionality and production costs

It should be noted that although a general trend is clear, the progression of GD&T topics along the trajectory of increasing complexity does not always follow with the simple progression of courses from freshman (100-level) to senior (400-level). Occasionally, more advanced learning is covered in earlier courses or basic concepts are covered in later courses. Some aspects of the GD&T standard are covered in their entirety within courses, from Knowledge level to Evaluation, as in the coverage of process fixturing in IME 450 or dimensional inspection methods in IME 428. A small number of the more advanced concepts are not covered at all in the curriculum and represent an opportunity for improvement with the current method.

Another interesting result from analyzing the GD&T content across the curriculum is a confirmation of the concern described earlier with regards to the somewhat conflicting strategies that have evolved for covering the content in the ME courses as opposed to the MfgE (IME) courses. In mechanical engineering instruction, after size dimensioning and plus-minus tolerancing are taught, GD&T concepts are introduced from the simplest to the most complex in terms of the ASME standard. First, form tolerances (e.g., flatness, straightness, circularity) are introduced as a refinement of simple size tolerances for individual features. Then, orientation tolerances (e.g., parallelism, perpendicularity, angularity) are applied to introduce the ideas of relationships between features, datums, and basic dimensions. Lastly, locational tolerances (e.g., position, profile, runout) are covered to introduce the ideas of multiple datums, material condition modifiers, datum features of size, etc. In terms of understanding the concepts and language of the standard this sequence adds topics and complexity in a natural progression for learning. However, from a manufacturing perspective, when setting up processes, designing and using fixtures, and planning inspection, the simplest and easiest designs to interpret are precisely those with multiple datums (to indicate 3-2-1 part location and x-y-z part setup) and use of material condition modifiers (particularly maximum material condition) that allow fixed-form fixture/locator elements and simple, functional gaging. The "simpler" GD&T tolerances such as flatness and straightness are actually the most complex and difficult to assess and measure during fabrication. The MfgE courses have thus tended to stress plentiful and practiced use of datums and true position (with MMC modifier), profile, and runout during design, with progressively sparing use of orientation and form tolerances.

Each of the courses described above includes written exams that evaluate student mastery of the relevant GD&T concepts addressed in the class. Though administered separately, the exam questions can be combined to create a single comprehensive exam that assesses overall competency with the GD&T standard. Or alternatively, the exam could be broken into parts that assess regular progress towards mastery (e.g., yearly in a four-year engineering program).

Just such a comprehensive exam has been compiled at the authors' institution and is available by request to faculty teaching similar programs.

Results and Discussion

Results from student exam scores in the various classes have been tracked in recent years to monitor the newly added GD&T content. Data is shown below:

Course Number	**Quarter Midterm Final**	**Number of Students**	**Exam Score Average %**
IME 140	Fall 15 (Final)	95	81.1
IME 330	Fall 13 (Midterm)	41	51.2
	Fall 14 (Midterm)	24	52.1
	Fall 13 (Final)	40	49.3
	Fall 14 (Final)	24	74.5
IME 450	Spring 14 (Final)	30	65.8
	Winter 15 (Final)	29	65.5
IME 428	Fall 15 (Midterm)	15	41.7
	Winter 14 (Final)	15	77.0
	Fall 14 (Final)	19	66.7
	Fall 15 (Final)	15	69.8

As can be seen, not every class has been tracked for the same duration, but a good baseline of data has been established and certain early trends and other observations can be made. Students have tended to do quite well in the early (Knowledge, Comprehension) stages of learning but seem to be more challenged as they get into the upper level classes (addressing Application, Analysis, etc). Students seem to be initially able to grasp the simpler concepts of geometric form (e.g., flatness, circularity) and orientation (parallelism, perpendicularity, angularity). They can list and recognize the symbols and can generally explain what they mean. Hands-on measuring exercises which are implemented in some classes most likely helps. Even the basic idea of maximum material condition is easily understood, whether for external or internal features. However, the subtler concepts of opposite-point measurement (i.e., for axes or centerplanes, Rule #1, position not at MMC, etc), true position at MMC, profile, and axis-to-axis control are much more difficult to retain in just one exposure. Since it is early in this integration effort, it is anticipated that the repeated exposures across multiple classes will improve the cognitive retention of these more difficult concepts.

Several specific projects and activities are being developed and implemented in the classes mentioned in order to give students a more hands-on experience with even the more advanced GD&T concepts. For example, even during freshman year, students will be exposed during their material removal class to fixed-form, functional gages and fixtures based on position and MMC callouts from a drawing. The students will use these fixtures to produce components that must assemble, and the students will be able to see how the gages mimic the mating components and achieve truly functional inspection in a way that simple measuring devices cannot. During their fixture design class (junior year), they will be expected to follow the recipe of a part drawing to actually design and fabricate these types of fixtures and gages as well. Once they become used to following the procedure demanded by the GD&T symbols, it is expected that the students will question any ambiguous design in which those symbols do not appear.

During metrology class (senior elective), students also get repeated hands-on experience with the benefits of the GD&T language. It is not until one has physically struggled with measuring flatness, straightness, or concentricity that one can truly comprehend what those requirements are demanding of the manufacturer as well as the inspector when they are added to a drawing. It is not until one has compared a time-consuming programming and inspection routine on a coordinate measuring machine to measure true position that one can truly appreciate the beauty and simplicity of functional gaging for assembled components and the relationship of these to the MMC symbol on a drawing. It is a lot easier to specify a surface profile tolerance than it is to determine how to achieve it and measure it. So the emphasis in this class is to help students learn how to evaluate products that have GD&T requirements but also to recognize the impact on the time and cost of manufacture (both positive and negative!) when the symbols are used. Again, as these efforts have only been in place for 1-2 years or less, the authors are anxious to see the effects on student scores from the related exam questions.

So far, students have performed consistently across different offerings of the same course, but occasionally significant changes in the exam are reflected in changing scores (see, for example, IME 330 final exam). The authors intend to continue using this assessment tool to track student progression towards GD&T mastery throughout the curriculum. The data can serve as an indicator of the effects of any system changes (instructor, course activity, prerequisite or sequence, etc.) as well as monitor general improvement or decline in performance.

Of course, exam questions are not the only way to assess the effectiveness of the new integrated effort. Some of the inspiration for the effort began in the job offerings, job descriptions, and job interviews that students and instructors have been seeing more of in recent years. Therefore, keeping track of what jobs students get and how successful they are in those jobs is another key measure of program success. Similarly, surveying recent alumni for feedback both on their experience while at school and their ability to apply their knowledge at work is also a valuable tool for assessing improvement efforts. Although recent anecdotal evidence has been positive, the authors intend to track alumni-survey responses and comments related to design, design for manufacture, and general tolerancing issues over the next two to four years to further gage the success of the effort.

Conclusion

In summary, an integrated effort has been made to address the knowledge gap of GD&T concepts as defined by the ASME standard Y14.5 R2009. That gap has been acknowledged in both academic programs and industrial practice. The effort described here involves a careful parsing of the many concepts of GD&T into categories that reflect the learning levels of Bloom's Taxonomy. Those separate concepts were then mapped onto a sequence of courses taken by manufacturing engineering majors as well as mechanical engineering majors who are concentrating on manufacturing engineering as part of their degree. Each course covers the GD&T standard from a different level and a different perspective, with the cumulative result being that all of the major considerations in the standard are covered throughout a four-year engineering program. A large number of course assignments, lab activities, and exam questions are employed in the classes to both teach the concepts and assess learning. While year-by-year evaluation of student progress towards mastery is still in its infancy, observations show that students who have taken these courses are developing a strong grasp of the key concepts and are well on their way to a professional level of expertise as they near the time of graduation.

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