Getting in the (tolerance) zone: GD&T successes and failures in the classroom

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Abstract

Research has shown that instructors face significant challenges when it comes to teaching geometric dimensioning and tolerancing (GD&T) in engineering and engineering technology classrooms. Some of these challenges are intrinsic to the topic – the syntax and semantics of GD&T are complex, the concepts require intensive spatial reasoning, and it can be difficult to appreciate it without the complementary background knowledge. Other challenges are extrinsic – instructor expertise is often lacking, there is limited time to cover the material, and there is a paucity of resources to leverage in the classroom. This work will highlight possible tripping blocks to avoid, successful strategies instructors can implement, and areas needing attention going forward. These insights are based on the authors' personal experiences teaching courses that involve dimensioning and tolerancing (including GD&T) in their classrooms which span the mechanical engineering, mechanical engineering technology, and engineering design programs at three different universities. Additionally, the author's industrial experience and complementary research activity will be referenced to provide further insights.

Introduction

Engineering drawings and the information contained within them are an absolutely critical information interface between engineers, designers, manufacturers, and metrologists. The dimensions and tolerances specified within dictate the geometric specifications that influence form and function, inform the selection of manufacturing processes, and drive overall production cost. Given these implications, it is surprising that a recent survey of ABET-accredited engineering and engineering technology (ET) faculty who teach dimensioning and tolerancing (D&T) revealed that they frequently encountered challenges related to the paucity of effective instructional techniques available to them [1]. Additionally, only 27% of instructors teaching D&T considered themselves as "extremely competent" (the actual rate is likely much less) in the subject of geometric dimensioning and tolerancing (GD&T) and only 3 of 67 respondents reported that they had attained professional certification in the topic. Taken as a whole, this is concerning, especially in the context of evidence that there is a significant gap between the proficiency of graduates from engineering and ET programs and industry expectations [2], [3], [4].

Early developments of a so-called 'geometric method' for tolerancing were developed during World War II to address the shortcomings of traditional tolerancing that did not make extensive use of concepts such as form, orientation, and position. Over decades, this system was adopted by multiple standardization bodies, eventually converging towards to predominant systems (which are highly similar), one maintained by the American Society for Mechanical Engineers (ASME), the other by the International Organization for Standardization (ISO). *ASME Y14.5 – Dimensioning and Tolerancing* is the standard which, in addition to supporting standards, describes the predominant system of tolerancing used in the U.S. today. This system is more commonly simply known as 'GD&T.' Herein, this is distinguished from D&T, which used to refer to alternate practices (none of which are comprehensively standardized). GD&T, when practiced correctly, offers the ability to capture product functionality through a tolerancing scheme, fully specify allowable geometric deviations from nominal conditions, and clearly establish measurement requirements that verify the specifications as set. GD&T is also distinguished by the extensive system of symbology and syntax that it uses to indicate tolerances on an engineering drawing. Further information on the fundamentals of GD&T and it's origins can be found in Ref. [1].

GD&T has been noted to present some unique and persistent pedagogical challenges: It is syntactically and semantically complex (Y14.5 has over 350 pages of definitions, rules, and examples), requires advanced spatial reasoning in three dimensions [5], [6], can be difficult to appreciate without complementary experience in manufacturing [7], and is often the subject of misconceptions and misunderstandings even amongst seasoned practitioners [2]. For all these reasons and more, there does not appear to be a widely accepted instructional model in current use.

There has been past work in the engineering education field that has attempted to address this predicament. Most of this work has been focused on developing innovative pedagogical techniques that address targeted concepts in an education research-based context. Readers can consult Ref. [8] for a recent review of literature. This research is important, and more such research will be required to develop effective instructional tools for GD&T. However, as part of this research community, the authors have observed a relative lack of practical and direct guidance that could be utilized by instructors *getting in the (tolerance) zone* as they prepare their courses and take on GD&T in their classrooms. This paper is intended to offer instructors a series of lessons learned regarding GD&T from the author's own teaching experiences. While the following sections organize perspectives according to the author who primarily contributed them, they reflect a consensus opinion.

Perspectives from J. Berez

Dr. Jaime Berez is an Assistant Professor of Mechanical Engineering at University of North Carolina at Charlotte. He teaches courses in manufacturing processes, GD&T, and dimensional metrology and conducts research in related areas. He is an ASME Senior Level Geometric Dimensioning and Tolerancing Professional (GDTP). The following instructional successes and failures draw upon his experiences from instructional contexts including introductory and advanced mechanical undergraduate and graduate engineering courses as well as short-courses delivered outside of a University classroom.

Teaching datums with the assistance of tactile demonstrators

Datums are a foundational topic in GD&T but they provide some of the greatest instructional challenges. Specifically, the process of (1) identifying a datum feature from a datum reference, (2) selecting the appropriate true geometric counterpart (TGC), and (3) deriving the datum point, axis, or plane form the TGC can be complex and challenging to visualize. Additionally, the extent to which a particular datum feature controls certain degrees of freedom when establishing a datum reference frame (DRF) is also challenging for most students.

To address this challenge, tactile and virtual demonstrations have been successfully used to reinforce static, 2D illustrations. For example, consider the workpiece shown in Figure 1.[1] In Figure 1 (a) a typical 2D illustration is provided. Figure 1 (b) shows a 3D printed demonstrator that is used to reinforce this concept. Note that the workpiece was modeled and manufactured with exaggerated errors: The datum features are not flat nor are they square to each other. The demonstrator provides tactile feedback of how a primary datum plane stabilizes one translational and two rotational degrees of freedom when pressed against the datum simulator (a relatively flat 3d printed planar surface), creating three points of contact. Similarly, the more subtle nature of how a secondary datum only controls one translational and one rotational degree of freedom when pressed against its datum simulator (a flat plane perpendicular to the primary datum simulator) benefits from the tactile feedback created by establishing two points of contact. Figure 1 (c) shows an example of teaching the same concepts but with an immersive augmented reality (AR) experience. Results from this approach were recently presented elsewhere [9]. Instructors are encouraged to use readily available objects or rapid prototyping tools to develop their own demonstrations. Students who experience these concepts via demonstrators can more easily translate their tactile experiences to more complicated examples.

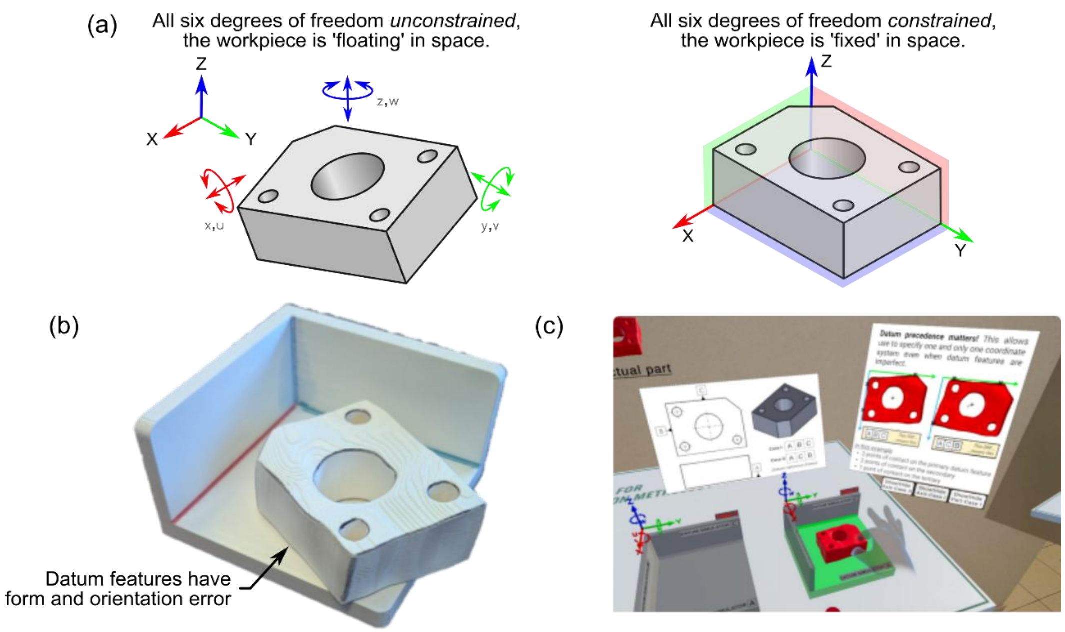

Figure 1. (a) A typical graphic used to teach how datum features control degrees of freedom. (b) A 3D printed tactile demonstrator. (c) An AR demonstrator.

Teach metrology alongside tolerancing

In the research and standardization communities, geometric specification (tolerancing) has parity with geometric verification (metrology). The link between these topics is arguably inextricable

[1] It should be noted that Figure 1 shows the canonical DRF that is based on three nominally orthogonal planar datum features. This type of DRF is rarely the optimal choice when attempting to capture part functionality in a tolerancing scheme and on-going work is being conducted to develop more diverse examples.

and it should be clear why understanding of one is complementary of the other. Even so, because GD&T is (1) often taught in a context of design in academic environments and (2) metrology is an uncommon area of expertise, it appears that students rarely receive complementary instruction on how tolerances are actually verified. Instructors who have been asked "Okay, but how do you measure that?" may resonate with this.

Metrology techniques beyond calipers (which are ubiquitous, but only measure two-point size effectively) offer the opportunity to explore the 3-dimensional nature of GD&T. Expensive and complex coordinate measurement machines (CMMs) are not absolutely required to realize many GD&T measurements. For example, the characteristics of flatness, parallelism, perpendicularity, runout, and more can be measured with relatively simple tools such as surface plates, dial indicators, and other gages. Seeing is believing when a demonstration or exercise shows an indicator needle bobbing up and down as a workpiece surface translates beneath it. While these tools can be difficult to scale up due to space and expense, successes have been seen by using 2D graphics paired with pre-recorded videos or demonstrations using a document camera. An example of a graphic that may accompany a demonstration used to explain parallelism is shown in Figure 2.

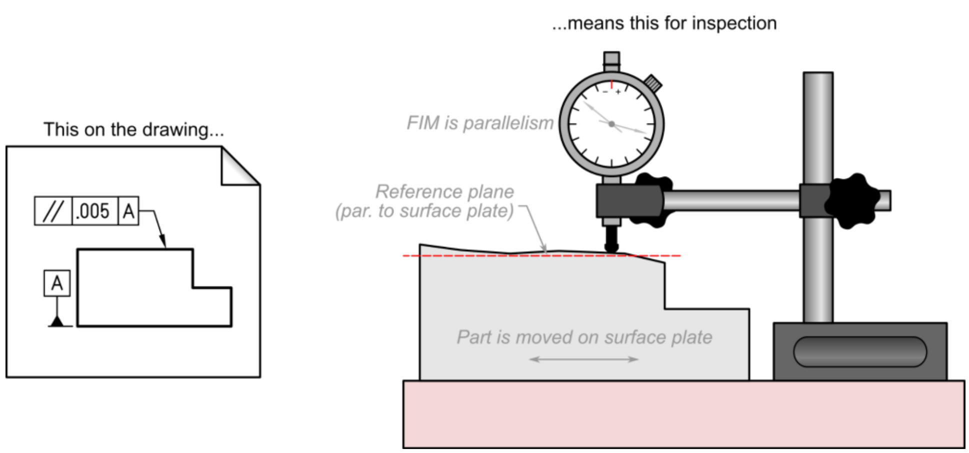

Figure 2. Graphic showing the measurement of parallelism using a surface plate, dial indicator, and dial indicator stand. The full indicator movement (FIM) is calculated as the highest dial reading minus the lowest, represented by the two positions of the dial on the graphic.

Another opportunity is to use the concept of hard gages to explain measurement. In fact, the ASME Y14.5 standard strongly leverages hard gage measurements as an explanatory tool. Modern rapid prototyping techniques such as 3D printing provide the opportunity for instructors to easily develop such instructional aids. For example, a simple workpiece with a hole positioned in a datum reference frame can be measured using a hard gage that has the appropriate datum simulators and a pin of the appropriate virtual condition, as shown in Figure 3. Variations of the workpiece (at nominal dimensions and with error) can be manufactured such that students can clearly see the gage accepting or rejecting the workpiece. This approach also emphasizes the functional nature of GD&T, showing how designers can control the virtual condition of a feature, which has a direct impact on assembly.

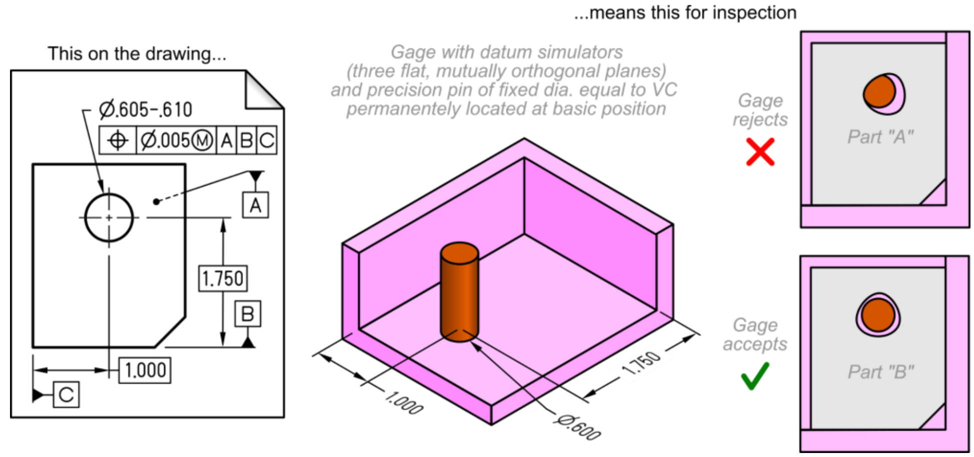

Figure 3. A workpiece and gage that could be 3D printed to explain the measurement of position as specified in the accompanying drawing. Workpiece A is rejected by the gage as out of tolerance. Workpiece B workpiece is accepted by the gage as in tolerance.

Selecting tolerance zone sizes

One can have a strong conceptual command of the syntax and semantics of GD&T but not know how to select the appropriate tolerance ranges. For example, one might understand the tolerance zone shape, size, and orientation created by a particular feature control frame but have no idea why a particular tolerance zone size was selected. While there are guides for selecting limits of size for cylindrical holes and pins (see ASME B4.1 and B4.2), these only encompass guidelines for a very narrow set of tolerancing scenarios. Many engineers who would state that they are proficient in tolerancing might cite intuition, knowledge of manufacturing process capabilities, or prior practices in their organization as a method for selecting tolerance values. The question is, how can this be taught to students who do not benefit from such background knowledge?

Efforts to address this issue have only been partially successful in the author's classroom. Individual comments about manufacturing process capabilities are difficult to turn into generalizable rules for every scenario. In the absence of specific guidance, students often tend to favor tight tolerances in scenarios where they are unsure of the proper approach. Some success has been achieved in encouraging students to choose loose tolerances when a particular characteristic is unimportant to function, but this relies upon a part-by-part analysis of functionality, another concept that is difficult to generalize. Other strategies tested by the authors include emphasizing how tolerances impact cost, encouraging students to visualize tolerances to-scale using calipers, and providing examples of sensible sheet tolerances. Recent attempts to incorporate the fixed and floating fastener rules (see ASME Y14.5) as well as the calculation of virtual condition were partially successful but still only a limited number of tolerancing scenarios. New strategies and resources are needed to address this challenge.

Perspectives from R. Ottway

Dr. Rudy Ottway is an Associate Professor in the Design Engineering Technology (DET) program at Murray State University. He teaches a variety of courses, ranging from introductory to advanced, that involve constraint-based/parametric CAD modeling and engineering drawing creation that conforms to American National standards. The following sections present two personal instructional successes and one personal instructional failure.

Have students narrate their drawing

To teach GD&T fundamentals, an in-class exercise is used where students create a physical infographic illustrating a specific geometric characteristic symbol and give a brief oral presentation. Students are provided with a large sheet of paper or poster board and colored markers. The infographic may include a title, key terms, the geometric characteristic symbol, an engineering drawing, and a graphical interpretation showing how the geometric tolerance may impact the physical feature that might be manufactured. Students are encouraged to utilize creativity and colorful imagery to enhance understanding. An example is shown in Figure 4. Students give a short oral presentation to demonstrate understanding and use technical terminology. The presentation allows faculty to clarify concepts and reinforce proper practices.

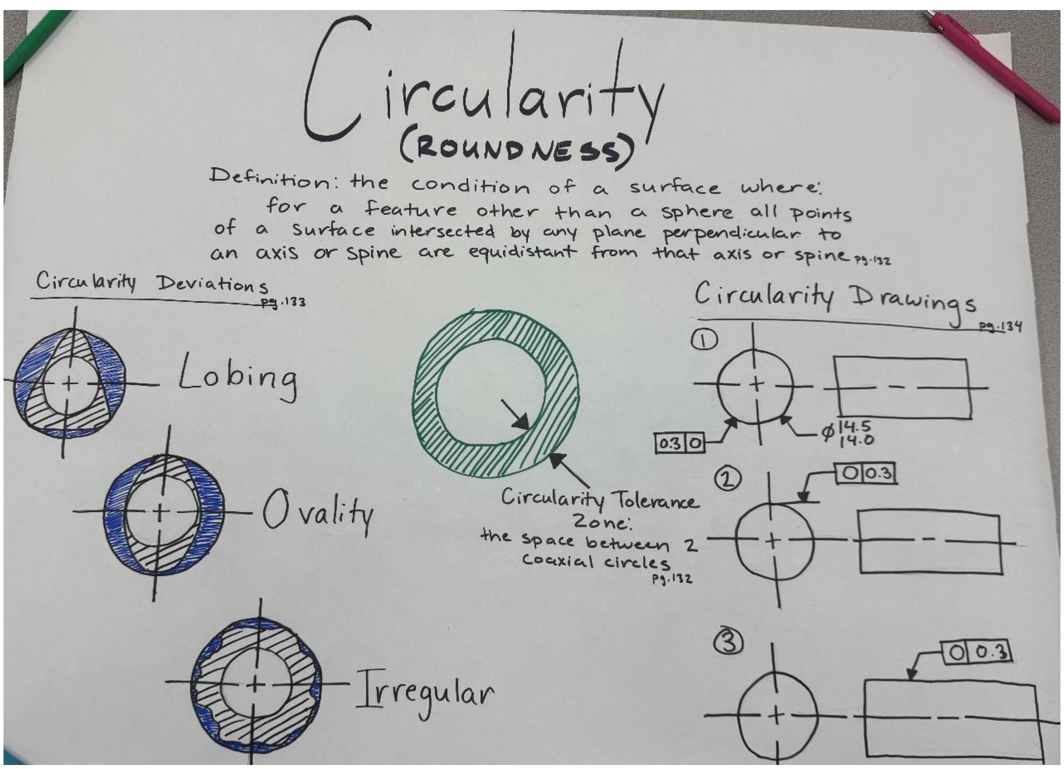

Figure 4. Example of student infographic showing information regarding circularity.

This exercise connects GD&T to functional meaning. Limiting each activity to a single geometric characteristic symbol allows students to focus on proper symbol usage, standards-compliant feature control frame structure, and interpretation of allowable feature variation. Assessment emphasizes correct application of the symbol, accurate construction of the feature control frame, clarity of the graphical explanation, and the student's ability to verbally articulate understanding of the concept. CAD software is intentionally withheld at this stage to prioritize conceptual understanding. Subsequent CAD assignments reinforce these concepts through the creation of a 3D model and corresponding 2D, engineering drawings.

Redlining drawings – Example student work, peer, or one-on-one

Students in a CAD course are typically required to use CAD software to reproduce a 3D model and generate a corresponding 2D engineering drawing based on ASME standards. From faculty experience, students often struggle to move from understanding D&T concepts to applying the same concepts to complete engineering drawings. This gap highlights the need for direct, detailed evaluation to support learning and build student confidence. This section examines three approaches, 1) faculty redline review, 2) partner-based peer review, and 3) classroom-wide peer review, that can be used to provide feedback.

With the traditional faculty redline review approach, students submit drawings either digitally or as a printed hard copy. Faculty provide feedback using digital markup tools within CAD software or course management systems, or by marking printed drawings with colored ink. While digital submission requires file management on the part of the student and faculty, and relies on students to independently review feedback, hard copy submission emphasizes in-person accountability and allows feedback to be returned during class. Providing structured time for students to review marked drawings and ask questions supports reflection and understanding.

With the partner-based peer review, students are encouraged to work with a classmate for a peer assessment of the drawing prior to submission. Students are initially expected to work on their own for the drawing creation and then have a live discussion with a classmate to compare, contrast, and review the ASME rules and practices together. This approach promotes active learning, builds collaboration among students, offers an opportunity to practice communication skills, and mimics a team environment that they may experience in a job role. Students often learn to justify decisions, negotiate interpretation of standards, and articulate reasoning with peers.

With the classroom-wide peer review, students complete a drawing and upload the digital file to a course management system or shared drive. The faculty asks for a volunteer who is willing to demonstrate their work in front of the class. Students are given time to review the drawing to make notes regarding practices. An open discussion occurs celebrating proper practices while highlighting areas that need to be improved. Students are required to focus on the discussion and not allowed to make edits or changes to drawings in real time. This classroom critique encourages shared learning, normalizes errors, and allows students to observe and discuss a wide range of decisions. The faculty must facilitate the discussion to keep the tone constructive and the environment positive for learning.

Low frequency of engineering drawing interaction in the curriculum

An observed failure of engineering and ET programs is that student interaction with engineering drawings is not scaffolded throughout the course of their entire degree program. Typically, students are introduced to D&T early in their academic career, prior research reports that approximately 60% of students take these courses their freshman or sophomore year [1]. During the single semester course, content commonly covers 3D modeling practices, assembly creation, and the creation of 2D, engineering drawings. To facilitate learning and application at this level, the complexity of 3D models and 2D drawings is quite simple. One course does allow sufficient time for students to develop strong 3D modeling habits, learn fundamental D&T rules, and create properly detailed drawings.

After completing this single, introductory course, students rarely enroll in a course that reinforces the learned content. As students embark on completing a senior design project, the expectation is that they will use CAD to generate a set of detailed and comprehensive engineering drawings. Unfortunately, a significant amount of time has passed and students find themselves lacking the skills necessary to design the complex geometry and produce correct engineering drawings. Course instructors find themselves teaching the basics of CAD and engineering drawings instead of focusing on design solutions.

A practical solution is to embed several design/build experiences throughout all four years of the curriculum, rather than relying on a single introductory CAD course. When students work with CAD and engineering drawings repeatedly over time, they strengthen their 3D modeling skills, engineering drawing competencies, and understanding of ASME standards. These design projects should increase in difficulty as students advance and provide students with feedback regarding CAD modeling practices and the quality of engineering drawings. This repeated practice allows skills to build and avoids the common problem of students losing skills between freshman and senior year. By the time students reach their capstone course, they will already have created multiple drawing sets and will be much better prepared to handle complex documentation. This approach also aligns more closely with industry expectations, where engineers routinely create, revise, and interpret drawings as part of everyday professional work.

Perspectives from R. Webster

Dr. Rustin Webster is an associate professor with the ET department at Purdue University. He teaches a variety of courses in the Mechanical Engineering Technology (MET) program that involve D&T, ranging from introductory to advanced courses that involve constraint-based/parametric CAD modeling and engineering drawing creation that conforms to American National standards. He is also a ASME Technologist Level Geometric Dimensioning and Tolerancing Professional (GDTP). The following sections present one personal instructional successes and two personal instructional failures.

Standardized engineering drawing template and rubric

An observed instructional success has been the creation of a standardized digital drawing template across relevant MET courses. By adopting a single, curriculum-wide template, students repeatedly engage with industry-aligned drawing elements and conventions, while faculty benefit from improved consistency, reduced ambiguity in expectations, and increased instructional efficiency.

The drawing template was created in accordance with ASME Y14.1 – *Decimal Inch Drawing Sheet Size and Format*. A digital template using a D-size drawing sheet size (24 x 36 inches) was chosen because it provides greater area for drawing views and annotations while remaining readable when physically printed on common 11×17-inch paper, which most modern office printers can use (i.e. does not require a plotter). The larger drawing sheets have also been beneficial during reviews/redlining sessions and public demonstrations (i.e. increased readability). Consistent with Y14 standards, the template includes borders, zoning, a compliant title block and revision block with required subfields (e.g., title, drawing number, scale, sheet number), and proper line conventions and lettering as referenced in ASME Y14.2 – *Line Conventions and Lettering*. Additional features include a prepopulated general notes bank and tolerance block informed by the author's industry experience, a third-angle projection symbol, smart title block subfields that auto-populate from 3D model properties, and adjusted document properties to support compliance with ASME Y14.5 – *Dimensioning and Tolerancing*.

The master "alpha" template file is faculty-controlled to preserve accuracy, compliance, and long-term version stability. Students access the template through a shared instructional document containing a hyperlink to the approved version and step-by-step setup instructions. Students retain flexibility to modify template elements when needed; however, the unified template ensures that all drawings begin from a professional, standards-based foundation.

Aligned with these efforts, a standardized engineering drawing grading rubric has been adopted across relevant MET courses. The rubric evaluates a variety of drawing elements including line conventions, view types and/or layouts, D&T accuracy and/or conventions, notes, and title block content. The use of a standardized rubric reduces ambiguity in instructor feedback, promotes more uniform grading across courses and/or sections, and enables faculty to concentrate additional time on topics such as correct drawing view selection and/or placement, the correct application of dimensions and/or tolerances, and the communication of design intent.

Sharing industry examples

It is common practice in engineering education to expose students to real-world artifacts in order to illustrate professional-level work and, ideally, to increase student engagement with course topics. However, when the author introduced personal engineering drawings from prior industrial practice (see Figure 4 for a single example) into an introductory engineering drawing course, the instructional outcome differed from what was intended. Although the instructor viewed the drawing as exemplary (e.g., fully compliant with ASME Y14.5 and reflective of standard industry conventions), students lacked the foundational knowledge required to interpret even the most basic elements of the engineering drawings. Specifically, they had not yet developed sufficient familiarity with core engineering drawing conventions, projection methods, the types and application of dimensions and tolerances, datums, and feature control frames to meaningfully interpret the content. As a result, the industry drawings that were intended to inspire instead left students uncertain about how to read and understand the information presented.

This experience highlighted the need to introduce technical complexity gradually and to align instructional materials with students' developmental readiness. Introductory engineering drawing courses should therefore use examples that are intentionally simple, yet accurate and aligned with ASME Y14 rules and conventions. Only after students establish proficiency with foundational topics, such as view selection/layout, traditional D&T (e.g. coordinate dimensioning with plus-minus/limit tolerancing, etc.) are they prepared to analyze, critique, and fully appreciate authentic and more complexed industry artifacts. The broader instructional lesson is that authenticity alone does not guarantee learning; real-world examples must be deliberately selected and sequenced to ensure they are accessible, meaningful, and supportive of early competency development.

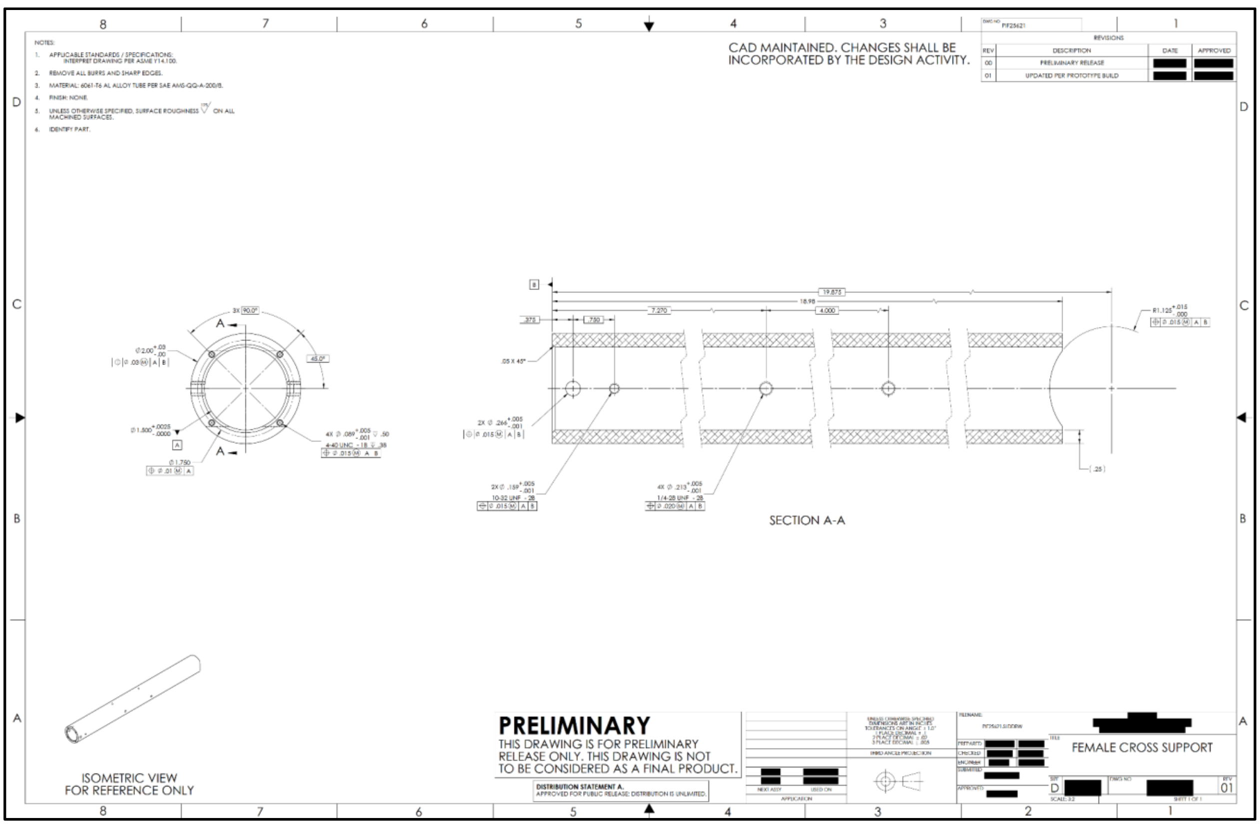

Figure 3. A single drawing from a larger drawing package: Industry example

Balancing workforce needs and accreditation guidance

A second observed instructional challenge emerged from assumptions made by the author about the depth of GD&T knowledge, skills, and abilities (KSAs) expected of his MET students, informed in part by accreditation guidance. For ABET-accredited MET and similarly named programs, ABET lists "application of principles of geometric dimensioning and tolerancing" as one of twelve required curricular topics, which was initially interpreted as implying that students needed high KSAs levels in relation to GD&T *application*. It should also be noted that ABET permits substitution of the twelve required curricular topics, provided that the program's faculty and primary constituents approve alternative, mechanically related technical subjects that support attainment of the program's educational objectives.

However, feedback gathered by the author over time from industry site visits, employer conversations, and graduate and alumni input suggested some misalignment between his initial interpretation and actual regional workforce expectations. Employers frequently indicated that, for many entry-level roles, a basic *understanding* of GD&T (e.g. basic dimensions, geometric characteristic symbols, datums, etc.) was sufficient. In contrast, application of geometric controls and the establishment of datums and datum reference frames were typically developed through on-the-job training if needed or associated with more specialized roles held by others.

This experience highlighted the risk of equating accreditation language with uniform workforce expectations without sufficient contextual validation. While ABET appropriately establishes broad competency requirements, the instructional lesson was that curricular emphasis must be carefully calibrated to regional industry realities, entry-level role expectations, and student developmental readiness. In this case, overemphasizing GD&T application in introductory courses reduced instructional efficiency and diverted instructional time from reinforcing foundational engineering drawing rules, industry best practices, and print reading KSAs that employers explicitly identified as essential. The failure underscored the importance of continuously triangulating accreditation criteria, industry feedback, and graduate outcomes to ensure instructional priorities remain both compliant and workforce-relevant.

Conclusion

Collectively, the instructional successes and failures presented in this paper reinforce that challenges associated with teaching D&T, including GD&T, are not attributable to a single pedagogical deficiency or issue but rather emerge from complicated multifactor interactions between the subject matter and the instructional environment. This finding is particularly concerning given the central role D&T plays in the engineering product lifecycle and the growing, albeit largely anecdotal, evidence of a persistent gap between the D&T proficiency of graduates from engineering and ET programs and industry expectations.

To extend this work, the authors are undertaking an industry-facing investigation that documents how D&T and GD&T, is applied in current practice and which competencies employers most frequently seek. Perspectives from professionals in all industries interacting with engineering drawing from roles such as design, engineering, manufacturing, and metrology will be gathered and analyzed. The resulting evidence will support a more precise, workforce-grounded interpretation of D&T competency expectations, a more fully defined picture of the D&T skills gap, and help guide D&T instructional strategies.

Acknowledgment

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