Session #1338

Virtual CAD Parts to Enhance Learning of Geometric Dimensioning and Tolerancing

Lawrence E. Carlson and Jason C. Trabert

University of Colorado at Boulder / Lockheed Martin Space Systems Company

Introduction

Geometric dimensioning and tolerancing (GD&T) is an important design tool that has gained worldwide acceptance for its ability to accurately control tolerances while allowing maximum manufacturing flexibility to control costs. Many mechanical engineering (ME) departments capitalize on external review boards composed of engineers from relevant industries to provide advice and help guide their programs. At the University of Colorado at Boulder, for example, our Industrial Advisory Committee (IAC) meets semiannually. At a recent IAC meeting, the importance of including GD&T in the ME curriculum was reiterated.

Companies typically send design engineers to intense courses to learn GD&T, often as long as 40 hours, which is approximately as many contact hours as a typical three credit-hour university semester course. Such a course is typically supported by a comprehensive reference text such as Foster.[1] On-line GD&T courses are also available.[2]

A logical place to introduce GD&T is in a first-year design graphics course. However, with the significant amount of other material that must be learned, often overlaid with learning computer-aided design (CAD) software, there is not likely to be room for more than an introduction of the concept of GD&T and a glimpse into its capabilities. While the topic of GD&T is included in a contemporary graphics textbook such as Bertoline,[3] it is the last chapter and therefore unlikely to be covered in any detail. Unfortunately, GD&T is dry and dull, particularly when compared to the glamour of CAD.

In this paper, I describe a method for students to gain insight into GD&T by using virtual measurement techniques. In a first-year graphics course, students learn solid modeling using SolidWorks[4] CAD software. To understand the meaning of manufacturing variation and how GD&T can monitor and control this variation, we have created several families of parts with intentionally distorted geometry. To illustrate the concepts, tolerances are large and variations are readily apparent. Parts within each family have different amounts of variation from perfect; some are within specification and others are not, mirroring the "real world."

A student's task is to "build" CAD fixtures, to measure the variation in each part and compare it to the GD&T specifications. Since each student is assigned a different part to inspect, s/he must actually measure his/her own part to get the correct answer. However, collaboration between students is encouraged, as it is well known to be an effective learning strategy.

Course Overview and Objectives

Computer-Aided Drawing and Fabrication is a required three credit-hour, first-year course for mechanical engineering majors. While traditionally offered in the spring semester, we are moving the course to the fall semester next year, for several reasons. We find that having students learn CAD modeling early greatly benefits their performance in the required *First-Year Engineering Projects* course, which is a hands-on, design/build experience. Also, CAD modeling is an excellent introduction to mechanical engineering. And, if students gain CAD proficiency in their first year, it opens up possibilities for internships in subsequent summers.

There are two aspects to the course:

- Gaining a working knowledge of CAD solid modeling (SolidWorks software application)
- Learning theoretical concepts of engineering graphics, including orthographic projection, auxiliary views and sectioning, general dimensioning and tolerancing, and geometric dimensioning and tolerancing.

The course provides one, 50-minute lecture, and two, two-hour labs weekly. Three lectures and five lab periods are dedicated to the topic of GD&T. The objective is to give students familiarity with the basic concepts and terminology of GD&T, including datums and GD&T control frames. However, we recognize that this short coverage of the topic does not create proficiency. Rather, the intent is to obtain familiarity with this important topic.

In the first attempt at introducing this topic in spring 2003, students studied GD&T by stepping through a series of PowerPoint® tutorials in labs explaining the topic, followed by short quiz exercises. However, students overwhelmingly complained that the tutorials were long, boring and hard to concentrate on. This approach was not considered effective, prompting the virtual inspection concept described in this paper.

Methodology

As shown in Table 1, a total of 14 GD&T geometric characteristics are controlled using GD&T symbols, grouped into five basic types.[1] Labs focus on four of the five basic types; a fifth lab focuses on creating a GD&T drawing.

For each of the four labs indicated in Table 1, students download one of four versions of a part from the course website, as assigned by their TA. Each part file has been saved in Parasolid format, i.e., text or binary files that contain all the geometric information of a SolidWorks part or assembly, but not the history of how the part was constructed. Therefore, students cannot simply look at the Feature Manager tree to learn how the part was "built," and thus, how much variation it contains. They can, however, modify the part by adding or removing material. In addition, all the usual SolidWorks functionality is present, including the Measure tool.

Lab	GD&T Geometric Characteristic	GD&T Type
1	Flatness	
	Straightness	
	Circularity (roundness)	Form
	Cylindricity	
	Profile of a line	Profile
	Profile of a surface	
2	Perpendicularity (squareness)	
	Angularity	Orientation
	Parallelism	
3	Circular runout	Runout
	Total runout	
4	Position	
	Concentricity	Location
	Symmetry	

Table 1. GD&T geometric characteristics and types, with lab focus indicated.

Flatness Lab — The simplest lab focuses on the characteristic of flatness, because this specification does not require a datum references. As shown in Figure 1, the part is supposed to have a flat top. Each SolidWorks file, however, has a wavy top. Students need to understand that this GD&T specification implies perfect parallel planes 0.050 in. apart. If all regions of the top surface lie within these two planes, the part is within specification. The planes, however, may be oriented at any angle with respect to the part.

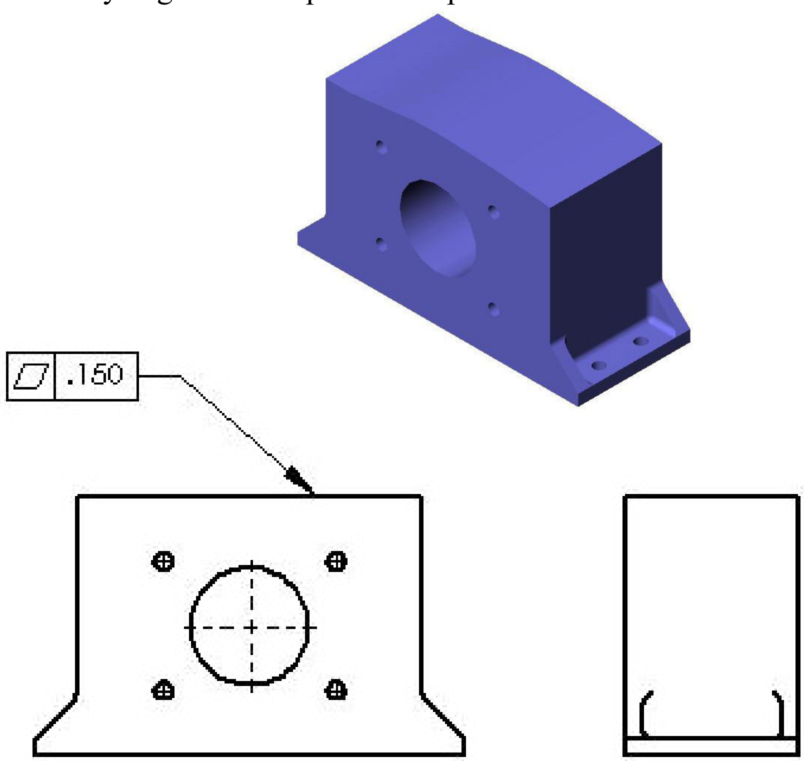

Figure 1. Flatness GD&T specification and sample part.[1]

[1] Students are given completely dimensioned drawings to give them practice "reading" engineering drawings. Only the GD&T specifications are shown here for clarity.

Perpendicularity Lab — The part shown in Figure 2 has a central hole that is supposed to be perpendicular to the bottom surface of the part within 0.020 in. To measure the part, students must first construct a virtual gage in SolidWorks with a central pin that is perfectly perpendicular to a base. They next must create a SolidWorks assembly with their gage and the test part, setting the appropriate coincident mate to simulate the datum reference specification. By moving the test part until the pin contacts the edge of the angled hole, they can next use the Measure tool to quantify the deviation from perpendicularity (Figure 3).

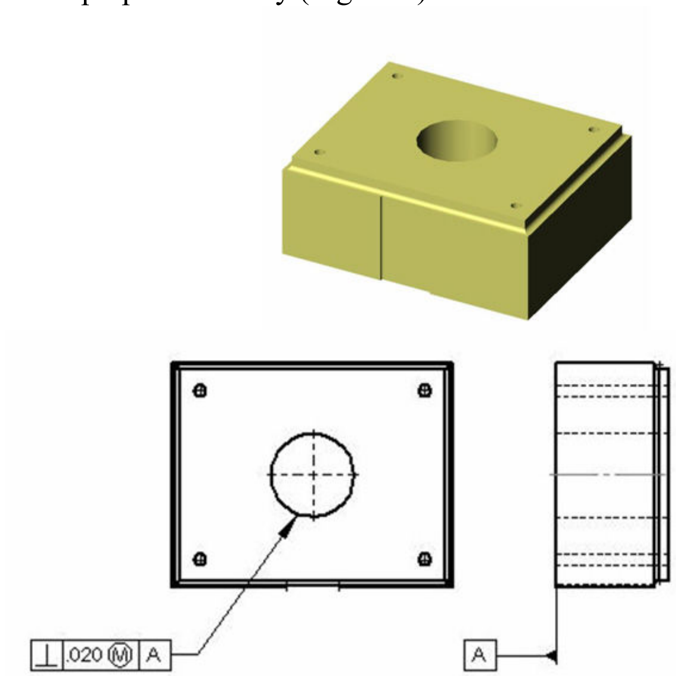

Figure 2. Perpendicularity GD&T specification and sample part.

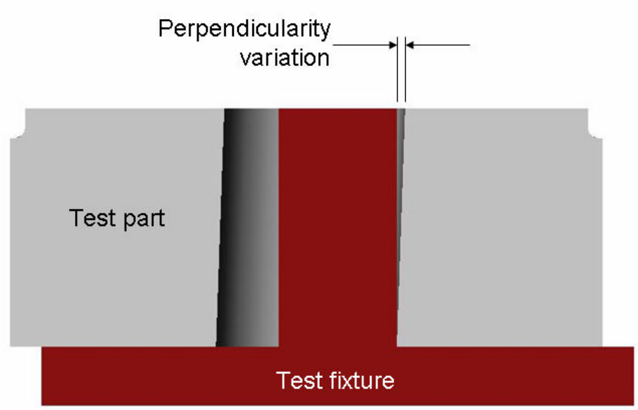

Figure 3. Section view of part assembled on test fixture to measure perpendicularity.

Runout Lab — The brake rotor shown in Figure 4 contains a hole that is not perfectly centered in the disk. To measure the part, students must first "build" a test fixture as shown in Figure 5, which contains a central pin of the appropriate diameter, and a bent-up edge that provides a measurement reference plane. They apply appropriate mates between the part and the test fixture so that the rotor can rotate around the pin but is constrained in other directions. Because the deviation is intentionally large, students can rotate the part and see, by eye, where the maximum and minimum circular runout occurs, and the SolidWorks Measure tool allows them to quantify the runout. There is also a total runout specification on the part drawing. For extra credit, students can quantify this deviation.

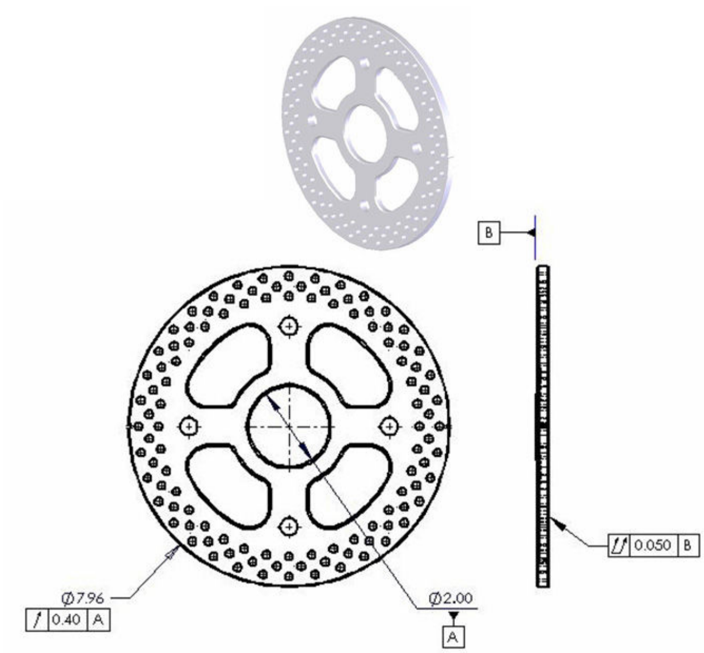

Figure 4. Runout GD&T specification and sample brake rotor test part.

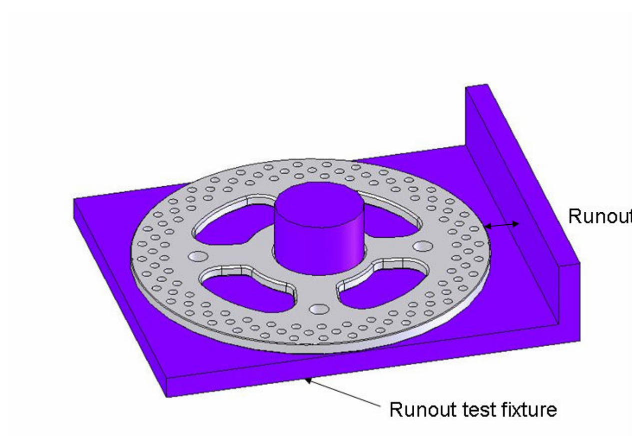

Figure 5. Runout test fixture with sample part mounted.

Position Lab — One of the more powerful capabilities of GD&T is position tolerancing, for example to ensure that a pattern of holes fits over an array of pins. Careful use of GD&T in this situation can maximize allowable tolerances while still guaranteeing function, which therefore minimizes cost while maintaining quality. One reason is that the allowable tolerance zone for each hole is a circle centered about the theoretically correct hole center, as opposed to the square tolerance zone specified by coordinate (+/-) tolerancing. For the same value of tolerance, this represents an increase of 57% allowable area where actual hole centers can be located and still function as designed. A second reason is the concept of *maximum material condition* (MMC), which relaxes tolerances based on actual part dimensions. This, likewise, reduces cost while still ensuring proper fit. For example, if a hole is larger than its minimum specified diameter, its center has more latitude on where it can be located and still fit over a pin in a defined location. In other words, there is a *bonus tolerance* associated with part deviations from their MMC.

Unfortunately, this concept is difficult to communicate to students at an abstract level (such as lecturing). Position tolerancing is also the most complex GD&T specification because typically three datum references are required.

This lab has several components. The sample part is a hub with a circular array of six drilled holes (Figure 6). Students first use the SolidWorks Measure tool to gage and tabulate the diameter of all six holes, calculating the deviation from MMC (if any) and the resulting positional tolerance for the hole centers. They next insert a reference axis into each hole and measure the X and Y locations of each axis, which allows them to calculate whether or not each hole meets the location tolerance specified.

This is a relatively labor-intensive process and would be even more so in the real world. In a production environment, this type of measurement verification is typically done with a *functional gage*, typically a “go, no-go” situation. A precise physical gage is accurately constructed such that parts that are within specification fit over the gage, while parts that are out of specification do not. Since SolidWorks automatically creates solid models that are mathematically exact, it is relatively easy to create a virtual high-precision gage (Figure 7). Students first create this gage, then bring their test part into a SolidWorks assembly model. By establishing a concentric mating relationship between the large central hole and the large gage pin, they can use the collision detection feature of SolidWorks to see if the test part can fit over all six gage pins.

Assessment

The topic of GD&T was introduced to this course in the spring 2003 semester and covered again in 2004. The main difference between the course offerings was that in 2003, the topic of GD&T was studied in the labs using detailed PowerPoint tutorials, while in 2004, students used the virtual approach described in this paper. However, the tutorials covered a broader variety of general graphics topics such as orthographic projection, sectioning, general dimensioning and tolerancing, etc. The topic of GD&T represented approximately the last half of these tutorials, which alternated with much more effective tutorials teaching students how to use SolidWorks.

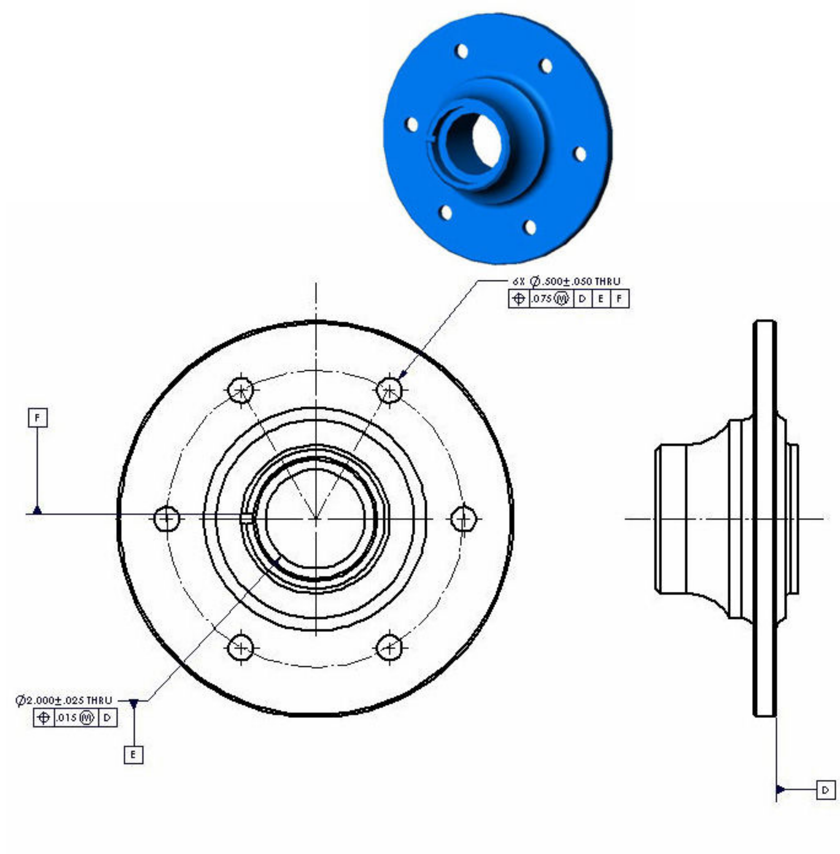

Figure 6. GD&T position specification and test part.

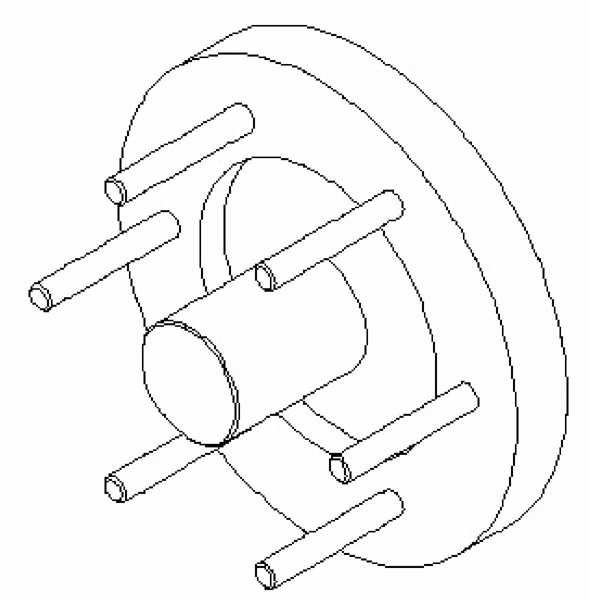

Figure 7. Virtual position test gage for hub in Figure 6.

A mid-course survey in spring 2003 confirmed anecdotal feedback (i.e., student complaints!) that the PowerPoint tutorials were ineffective. On a Likert scale of 1-5 (1 being “very ineffective” to 5 being “very effective”), the use of the PowerPoint tutorials was rated 2.7; i.e., below “OK” on the ineffective side. The SolidWorks tutorial labs, on the other hand, were rated 4.6/5.0. Students clearly liked learning to use the solid modeling CAD software, but disliked the dry, boring topics delivered in a non-interactive format. It is difficult to make a direct comparison with the second course offering because the virtual GD&T labs took place after the mid-course survey.

On the standard university-wide faculty course questionnaire (FCQ) administered at the end of each semester, two custom questions addressed dimensioning and tolerancing:

- Rate your level of understanding of general dimensioning and tolerancing
- Rate your level of understanding of geometric dimensioning and tolerancing

While overall course and instructor FCQ ratings both semesters were the same (B+/B+), students’ self-reported level of understanding of general dimensioning and tolerancing increased from C+ to B+, and their understanding of GD&T remained steady at C (Figure 8). This was the lowest score of a variety of topics surveyed, which ranged from C to B+. Students apparently do not feel confident with their knowledge of GD&T, regardless of how it is studied.

In addition to these self-reported surveys, students also took online quizzes. However, it is difficult to make meaningful comparisons between the two semesters based on the quiz results because there was a quiz each week in spring 2003, which covered general lecture material, including GD&T. Quizzes were reduced to four in 2004, covering only GD&T topics. Average scores ranged from 39% on one question to 95% on others.

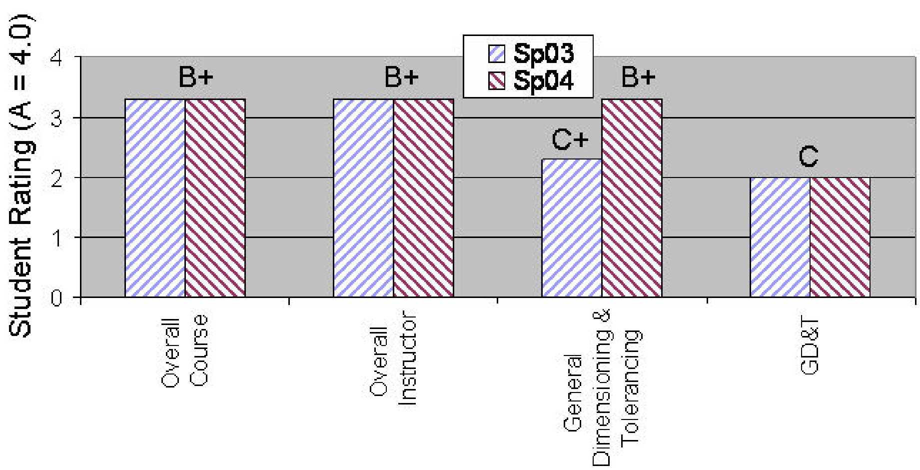

Figure 8. End-of-semester student ratings of course, instructor and their understanding of dimensioning topics (both general and GD&T).

Conclusion

It appears that the study of GD&T still remains a dry, boring topic in the course, especially in contrast to learning powerful 3D CAD modeling software such as SolidWorks, which students tend to find exciting and fun. However, this approach of having students verify the geometric characteristics of virtual CAD parts is at least an improvement over the previous non-interactive lab exercises. In addition, requiring students to create virtual gages to measure part variation provides further CAD modeling practice, as well as introducing students to typical manufacturing verification tools and techniques.

We intend to continue to evolve this approach, using student TAs to improve the labs. Previous years' quiz results will be analyzed to determine areas of confusion, and additional lecture time will be allocated to GD&T problems. In addition, we intend to create a SolidWorks model of a virtual dial indicator that could be used in a virtual CAD assembly to check critical dimensions by establishing tangent mates between the part and the tip of a dial indicator model. We also plan to use more interesting parts that students can relate to, such as a snowboard binding, DVD, Lego® blocks, etc.

Bibliographic Information

1 Foster, Lowell W., *Geo-Metrics III*, Addison-Wesley, 1994. pg. 349.
2 American Society of Mechanical Engineer, On-Line Courses http://elearn.asme.org/courses/geodim.htm
3 Bertoline, Gary B. and Wiebe, Eric N., *Fundamentals of Graphics Communication*, Fourth Ed., 2005, pg. 642.
4 SolidWorks Offers Software and Services to Help Manufacturers Get Products to Market Faster. SolidWorks Corporation. Accessed February 7, 2005. < http://www.solidworks.com/ >.

Biographical Information

LAWRENCE E. CARLSON is founding co-director of the Integrated Teaching and Learning Program and Laboratory, as well as professor of mechanical engineering. He received his M.S. and D.Eng. degrees from the University of California at Berkeley. His primary educational passion is real-world design. In addition to CAD, he teaches a first-year engineering projects design/build course and an upper division *Innovation & Invention* course.

JASON C. TRABERT is a senior level structural design engineer who has worked for Lockheed Martin Space Systems Company for over seven years. He received his B.S.M.E. from California State University, Chico and M.S.M.E. from the University of Colorado, Boulder. His primary responsibilities are design and integration of structural and mechanical components for defensive missile systems under the National Missile Defense program.