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Spatial Demonstration Tools for Teaching Geometric Dimensioning and Tolerancing (GD&T) to First-Year Undergraduate Engineering Students

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Abstract

Geometric Dimensioning and Tolerancing (GD&T) is a design tool and symbolic language that allows design engineers to communicate design intent and requirements, with particular attention to function and relationship of the part features, to individuals who will manufacture the parts. GD&T can lower costs by reducing waste parts, and increasing uniformity, completeness and interchangeability of parts in manufacturing. GD&T is a topic that employers consistently request that undergraduate students know and understand, both at graduation and during undergraduate summer internships and coops, as early as the summer after their first year. GD&T can be a particularly tricky topic to teach due to its complexity, breadth of information, required spatial reasoning, and, commonly, lack of prior exposure to the topic. To assist students in developing spatial understanding, GD&T at a basic level has been developed for a first year undergraduate engineering CAD, sketching, and visualization course, including a set of hands-on demonstration tools and an interactive activity. This paper describes those tools and how to make your own set, along with some suggested activities to help students engage with and retain the concepts. The tools can be made with inexpensive materials, requiring only clear plastic sheets (PVC, acrylic, etc.), clear tape, permanent marker, and colored paper. These activities and materials have been used in a course with 9 sections of 50 students each, which indicates appropriateness and feasibility for classes of a similar scale.

I. Introduction

Although engineering students specialize in a variety of specialized areas, one essential part of the curriculum is learning and understanding measuring and modeling techniques that express the relationship between objects and space. Being able to visualize and conceptualize objects in 3-dimensional space is a skill that is critical to success in STEM coursework and retention in engineering programs over time [1]. Spatial conceptualization ability is the capacity to learn, understand, and reason about the relationships of objects as they relate to space or other objects. Learning to conceptualize spatial relationships is crucial to STEM education, as it is the foundation of skills that drive measuring, designing, and building, which are typical activities of STEM professionals. Spatial skills have been taught through traditional lecture methods and active learning methods [1]. They are often then assessed through mental rotation tests, such as the Purdue Visualization of Rotations Test (ROT) [2].

Active learning happens when students are involved and engaged in instructional activities, and use critical thinking skills for tasks like analysis and evaluation. In this paper, we present an active learning approach to teaching GD&T. An important design tool, GD&T is a highly complex symbolic language that is used to communicate the design of a machined part, its manufacturability, and its inspection criteria. Knowledge of GD&T and the skillset it represents is one of the only effective forms of communication and measurement standards across engineering disciplines in manufacturing, making critical to industry. GD&T is widely used in manufacturing and allows design engineers to research and refine the functionality, interchangeability, quality, and standardization of parts, thus eliminating waste and contributing to corporate profitability [3]. At Georgia Institute of Technology, we have found that many employers recommend that students learn GD&T during their undergraduate career so they are ready to implement their skills during internships, co-ops, and their fulltime jobs. GD&T is a challenging subject to which many students have had little previous exposure. Even highly qualified students may have difficulty grasping the basic concepts and applying those concepts to real world design problems. In this paper we will describe several interactive learning modules that can be used to provide undergraduate engineering students highly successful hands-on GD&T instruction.

II. Spatial Learning: GD&T Application

Studies have shown how spatial skills have been increased using modules and software. At Michigan Technological University, a course created was created with the goal of increasing the spatial skills of first-year engineering students. The course was initially structured as a 10-week course that included topic-specific lectures, problem sets that students worked on as individuals, and a 2-hour Computer Aided Design (CAD) lab that was intended to illustrate the content learned in lecture. Over the six years this course was offered, it produced promising gains in the spatial ability of students as demonstrated through pre- and post-assessments using the Purdue Visualization of Rotations Test. The overall gain in spatial ability indicated that a combination of multimedia software, instruction, and exposure could improve student conceptualization and spatial skills [1].

GD&T is often taught using 3-D modeling software. Such software is useful because it allows for students to see the constraints, tolerances, and the relationship between and among different types of geometric characteristics. It has been shown that constraint-based 3-D modeling software can help students conceptualize the application of GD&T to mechanical parts, even while learning how the software works. Weibe suggested that using constraints of the 3-D modeling software to show the relationship between datum planes and the modeled part's location and orientation are beneficial to GD&T instruction. One example is altering the size and shape of the holes and allowing the students to see how the part's specifications are affected, or how much tolerance is allowed before the part is out of spec. The demonstration of 3-D models in the constraint-based software allows instructors to discuss GD&T in relation to design, manufacturing and inspection [4].

III. Interactive Learning - Proposed Tools

Interactive learning tools have been created to assist students in learning, understanding, and implementing geometric characteristics through in-class GD&T exercises. Although 3-D modeling software can show the relationship between the different types of tolerances, hands-on tools have the advantage of allowing students to view a 3-D perspective. We exposed first-year undergraduate engineering students in a CAD class to three types of tolerances: form, orientation, and location. Form tolerances control the amount a particular shape is allowed to vary from the ideal shape. We created learning tools for flatness, straightness, cylindricity, and circularity to help students focus on form. Orientation tolerances control the amount of allowable variation in the angle of surfaces, axes, and planes. Tools for perpendicularity, parallelism, and angularity are the characteristics used to help students learn orientation. Location tolerances control the amount of allowable variation in the position of the center points, axes, surface locations, and similar characteristics. The tools created to help students learn about location are position, profile of a surface, and profile of a line.

Geometric Characteristics of **Form Tolerances**

- **Flatness** is a 3-D tolerance that shows whether the material's surface is within the bounds of two parallel planes that are a specified distance apart, regardless of whether the surface is smooth.
- **Straightness** is a 2-D tolerance used to determine whether the edge of a part is within the bounds of two straight lines that are a specified distance apart, regardless of the smoothness of the edge.
- **Cylindricity** is used to determine whether the 3-D cylindrically shaped part is within the established diameter limits along a central axis.
- **Circularity** is a 2-D tolerance used to determine whether the circular part or portion of a part is within the diameter limits set by concentric circles, regardless of whether the shape is smooth.

Geometric Characteristics of **Orientation Tolerances**

- **Perpendicularity** is a 3-D tolerance used to determine whether a face of a part is within the bounds of two parallel planes that are at a 90° angle to the specified datum plane, regardless of whether the surface is straight or smooth.
- **Parallelism** is a 3-D tolerance used to determine whether a face of a part is within the bounds of two parallel planes that are also parallel to a given datum plane, regardless of whether the surface is straight or smooth.
- **Angularity** is a 3-D tolerance used to determine whether a surface is at a specified angle to the datum plane and within the angle tolerance limits, regardless of whether the surface is straight or smooth.

Geometric Characteristics of **Location Tolerances**

- **Position** is a 3-D tolerance used to determine whether the center point of a feature, such as a hole or axis, is within the bounds of three coordinating tolerance zones in three mutually perpendicular dimensions.
- **Profile of a surface** is a 3-D tolerance used to locate a surface and to control the size and form of the surface between two parallel but not necessarily flat tolerances surfaces that are a specified distance apart.

- **Profile of a line** is 2-D tolerance used to determine whether the profile of a part is of the shape specified, within the bounds of two parallel (not necessarily straight) profiles, no matter the smoothness.

Construction

Ten learning tools have been created to help students conceptualize basic principles of GD&T in 2-D and 3-D. In order to construct the modules, instructors use inexpensive materials commonly available at art supply stores for instructional use or projects, such as PVC, tape, and cardboard. These learning tools have been implemented using clear plastic sheets, tape, permanent marker, and colored paper. Instructions for the fabrication of 5 out of 10 of the learning tools are reviewed within the body of this paper. The remaining 5 can be found in Appendix A. In all example images, there is a blue piece of paper that simulates the surface of the part. It is wrinkled to indicate that as long as the surface is within the tolerance zone, variation in smoothness is permitted. All learning tools include the name of the tolerance, the GD&T symbol, whether the tolerance type uses a datum, and whether the tolerance type is a 2-D or 3-D tolerance.

The parallelism tool (Fig. 1) utilizes three clear sheets of plastic: one for the identifying sheet and two shorter pieces for the parallelism walls. This tool requires the instructor to first identify the edge of the identifying sheet that is going to be used as the datum plane (the bottom). The instructor then identifies the starting tolerance zone by marking the identifying sheet and drawing a line parallel to the datum. The instructor then measures the desired distance for tolerance from the first line, labels that point, and draws a line parallel to the tolerance from the first line drawn. Using the two shorter pieces of plastic, the instructor then tapes one on each line to create the walls in 3-D. Finally, the instructor labels the plane and tolerance zone.

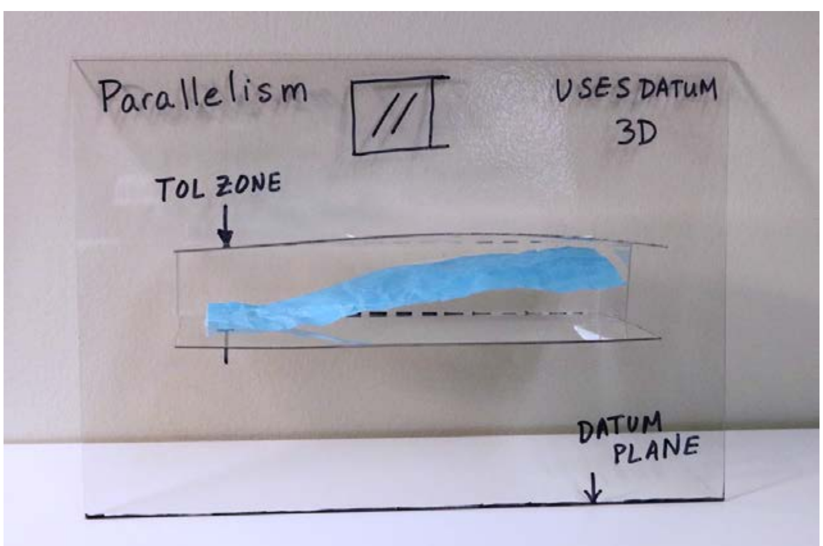

Figure 1. GD&T Spatial Learning Tool for Parallelism Tolerance

Figure 2. GD&T Spatial Learning Tool for Cylindricity Tolerance
A. Disassembled Components, B. Top of Concentric Cylinders Tolerance Zone,
C. Front View

The cylindricity tool (Fig. 2, A, B, and C) utilizes two rectangular sheets of clear plastic. One plastic sheet should be about 1-2 inches shorter than the other in width, but both should be the same height. The instructor takes one piece and connects the two longer edges to make a hollow cylinder, then tapes the entire connected edge. The instructor then does the same with the other piece of plastic. The smaller cylinder is then placed inside the larger cylinder. The bottoms of the cylinders can be connected by adhering them to a piece of plastic or cardboard, or they can be left as separate parts.

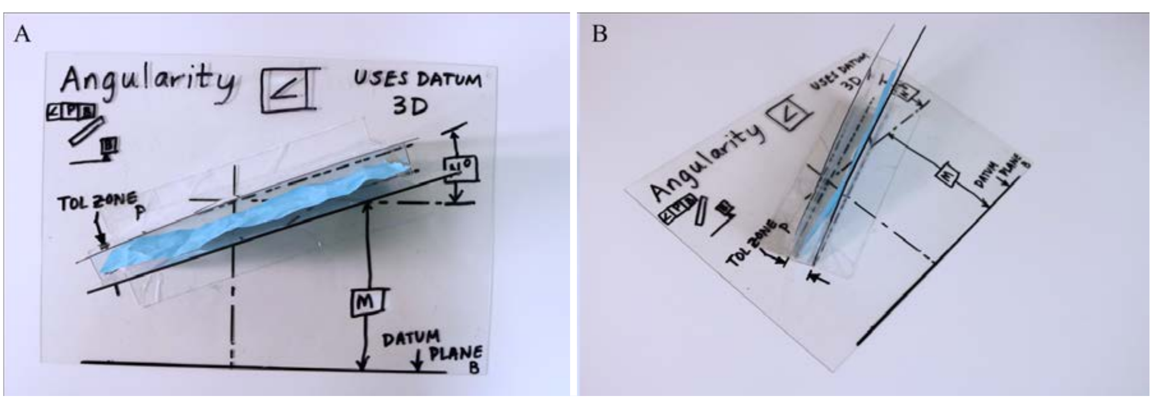

Figure 3. GD&T Spatial Learning Tool for Angularity
A. Front View, B. Isometric View

The angularity tool (Fig. 3, A and B) is illustrated above, showing a tolerance zone between to parallel flat planes at a specified angle. One large backing piece of clear plastic is used as the base of the tool. Two smaller pieces of clear plastic of the same size are taped a uniform distance apart, at an angle relative to the bottom edge of the backing. These pieces are held apart by two small pieces of plastic that are cut to be the width of the tolerance zone, and taped to the edges of each of the angled pieces, to create a kind of rigid box form. The instructor finishes the tool by marking the datum plane along the bottom edge of the backing, the tolerance zone and angle of the two planes defining the zone.

The position tool (Fig. 4, A, B, and C) is illustrated next, depicting the three perpendicular datum planes and corresponding tolerance zones. First, the instructor uses two large plastic pieces, and a third cut to the width of the shorter side of one of the larger pieces to create a half-box. These are then labeled "A", "B" and "C" to denote the three mutually perpendicular datum planes in space. Next, three separate pieces, no larger than each corresponding side of the half-box, are drawn upon separately to demarcate three coordinating tolerance zones that combine to create the position tolerance. In two dimensions, here on datum planes "B" and "C", the zones are two parallel lines. In the third dimension, here on datum plane "A" the zone is a circle, centered

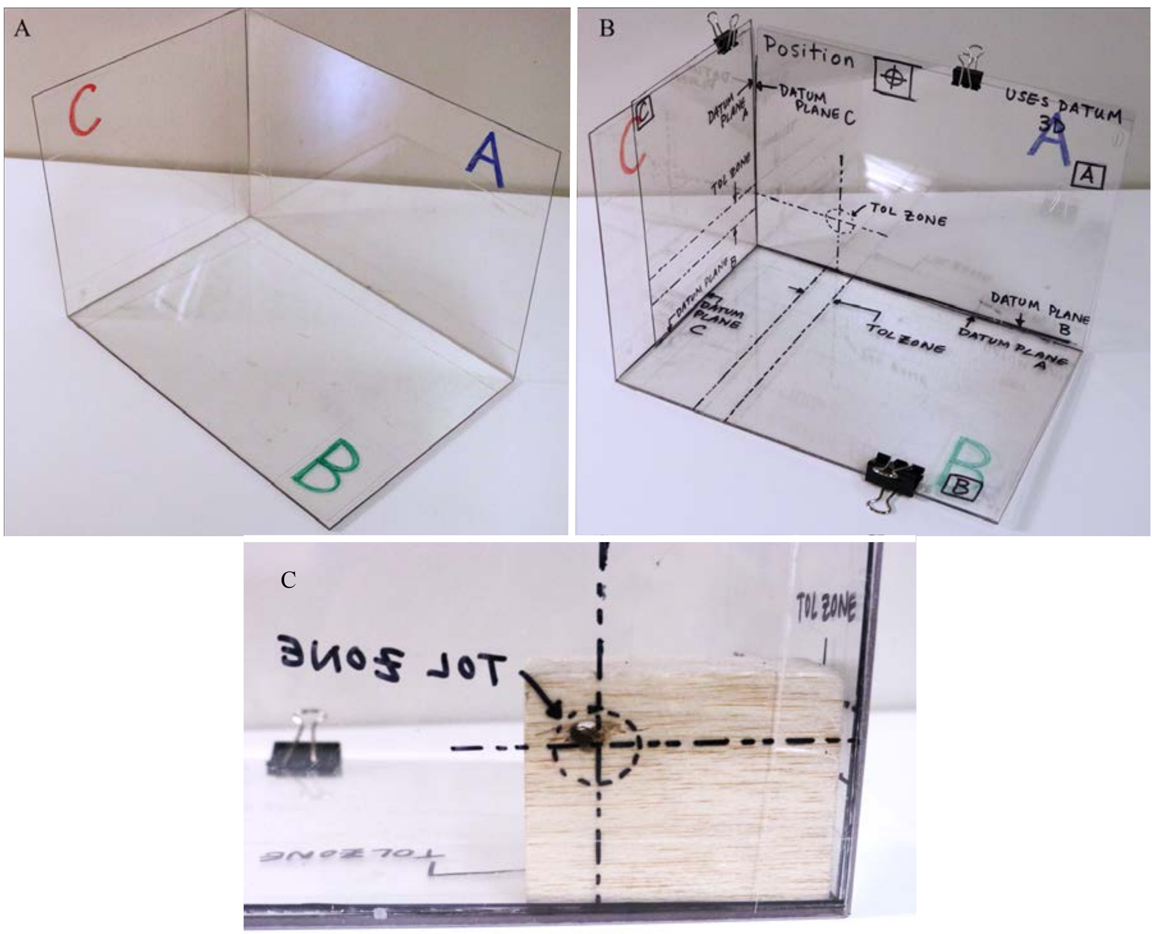

Figure 4. GD&T Spatial Learning Tool for Position Tolerance
A. Datum Planes only, B. Datum Planes with Position Tolerance Overlays,
C. Wooden Block with Hole in Spec (Supplemental views can be found in Appendix B)

about the intersection of the middle of the two previously defined zones. For a hole to be within spec, the diameter must not be outside the circular zone on datum plane “A”. The wooden block shown in Figure 4C depicts a hole that is within spec for the specified tolerance zone. Appendix B shows orthographic views of each of these three tolerance zones.

The profile of a surface tolerance describes a tolerance zone within two parallel, but not necessarily flat, surfaces (Fig. 5, A and B). Using three similarly sized pieces of plastic, the instructor creates a half box as shown in Figure 5. The bottom piece will be datum plane 1 and the left piece will be datum plane 2. Using two slender pieces of plastic, the instructor then measures and makes two arches from datum plane 1 to datum plane 2. The instructor tapes one piece to both planes creating the first arch. To create the tolerance zone, the instructor cuts the second piece of plastic so that the desired tolerance is achieved, and tapes the piece to both planes creating the second arch. Finally, the instructor labels the planes and tolerance zone.

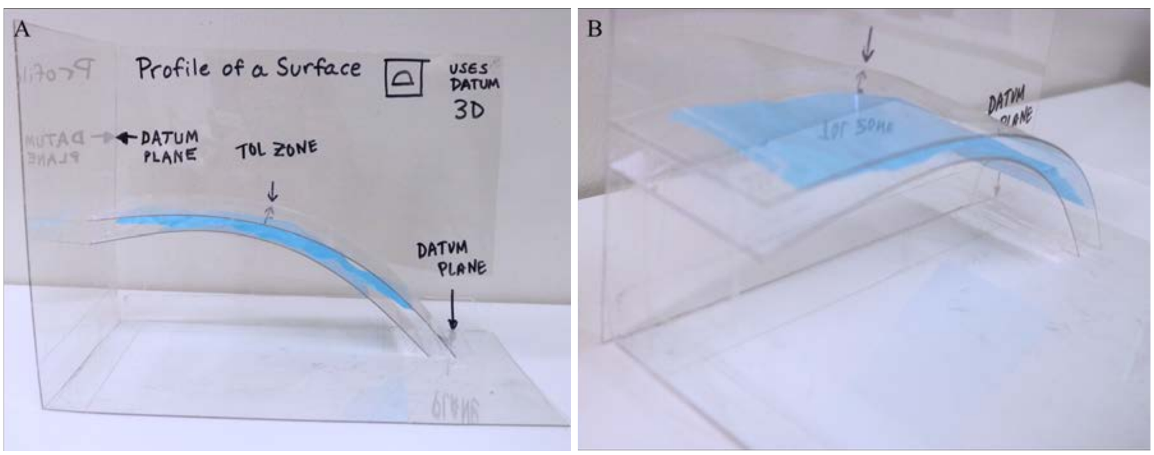

Figure 5. GD&T Spatial Learning Tool for Profile of a Surface Tolerance,
A. Front View, B. Isometric View

These spatial learning tools allow students to physically experience the concepts, rather than explaining them through 2-D drawings and schematics. For such a spatially motivated topic and set of skills, demonstrating the concepts in this manner can strengthen student understanding and retention. Note that for first year students, this is their first exposure to the topic of GD&T, so some of the more complex tolerances, such as run-out, are not included.

IV. Hands-on GD&T Measurement Activity

The learning tools presented in Section III and Appendix A were used in a first-year engineering visualization and CAD class before engaging in a hands-on activity that used their recently acquired knowledge. Each section of this class has an instructor and two graduate student teaching assistants. One week of the course is spent focusing directly on GD&T, which related material and analysis included in a 3-D printing project. The 3-D printing project requires students to design two interlocking parts and achieve a satisfactory fit between the parts while

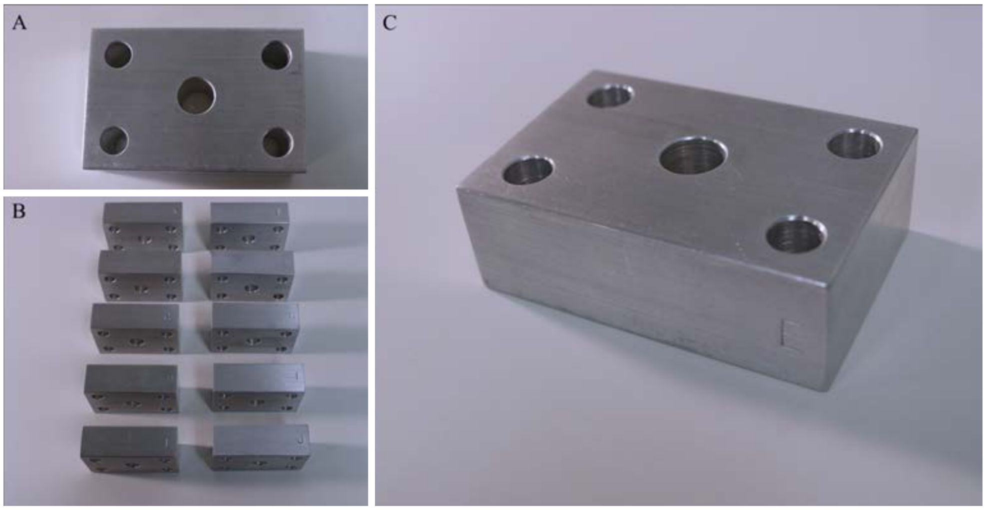

Figure 6. Ten Aluminum Blocks with Holes for Measurement Activity
A. Top View of one Block, B. Set of Ten Blocks, C. Isometric View of Block E

taking into account and analyzing the differences between ideal dimensions and manufactured dimensions. In this activity, ten metal blocks were machined with 5 holes in each of them (Fig. 6), and each block was labeled with a letter "A" through "J". The block shown in Figure 6 C is block "E". The students were separated into groups of 5, and each group was given ideal specifications in the form of a GD&T drawing (Fig. 7), one dial caliper measuring instrument, and one of the machined blocks. Many of the students had not used dial calipers before, so a short lesson on how to read and use them was taught first. Students in teams were then tasked with determining whether the block meets the specifications outlined in the GD&T drawing ("in spec"). Only two out of ten of the blocks were machined to be within specifications. All other blocks varied beyond the specified tolerances in the size of the holes and location of the hole centers.

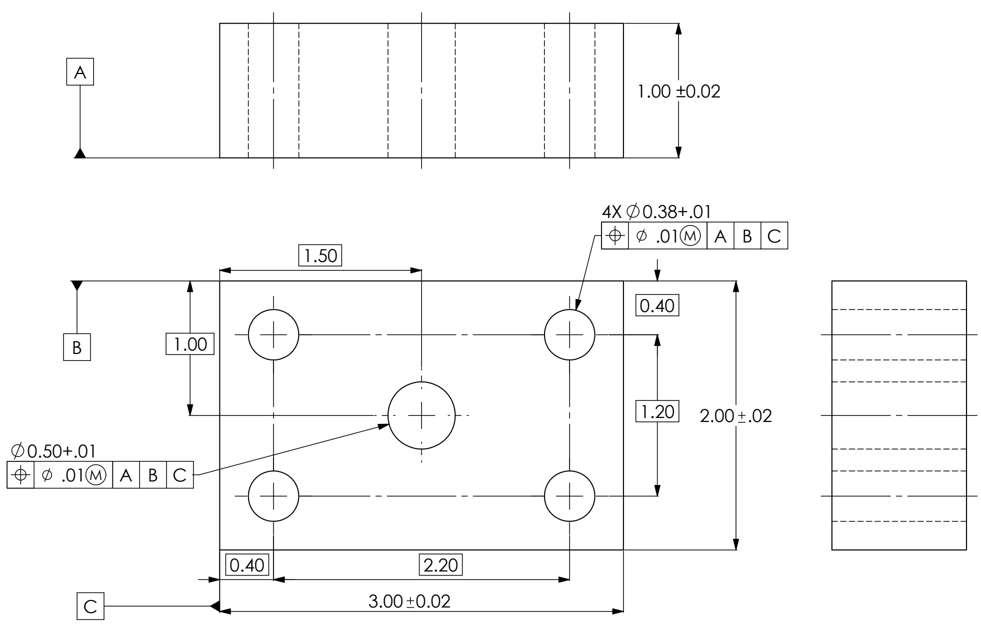

Figure 7. GD&T Drawing of Ideal Block

This activity challenges students a few ways. First, it requires them to identify which faces of the part are the datum faces. Since the part is vertically and horizontally symmetric, this is not an obvious determination if the part is “out of spec”. Students then have to determine how to find the location of the center of a hole, which takes some creativity. The measurement of hole diameter is relatively straightforward task if one knows how to read the dial calipers, but still requires students to interpret the tolerance range from the drawing and determine if the hole diameter is “in spec”. The learning objective of this activity is to impart an understanding of the steps and challenges that come with measuring parts using GD&T, helping them to know how quality control is achieved in practice, and how it could relate to cost (as correlated to labor required for measurement). Anecdotally, students seemed highly engaged in this activity, and enjoyed the competition aspect of reporting out their findings at the end of class.

V. Future Analysis of Effectiveness of Tools in Classroom Setting

The purpose of this paper is to share a set of learning tools used to teach GD&T to first year engineering students. The effectiveness of the tools has not been assessed or validated yet. Based on anecdotal experience of the authors, the tools help to engage students in what can otherwise be an overwhelming, highly technical, complex topic. The authors plan to assess the effectiveness of the learning tools in the near future, through a direct measurement of GD&T knowledge acquisition and retention, in addition to self-reported satisfaction and self-efficacy data collection from the students. These data will be compared with a control group of a similar population taught GD&T in a more traditional manner, such as through diagrammatic lecture-based delivery.

References

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Appendix A: Construction Instructions for Remaining 5 GD&T Learning Tools

Flatness tool (Fig A-1, A, B and C) utilizes two pieces of clear plastic, each of which has the same width but different heights. The taller piece will be the back plane. Using a separate piece of plastic, the instructor creates three smaller pieces. The instructor uses these pieces as a separation barrier for the top and bottom pieces of plastic by taping the pieces between the sides, as shown in Figure A-1.

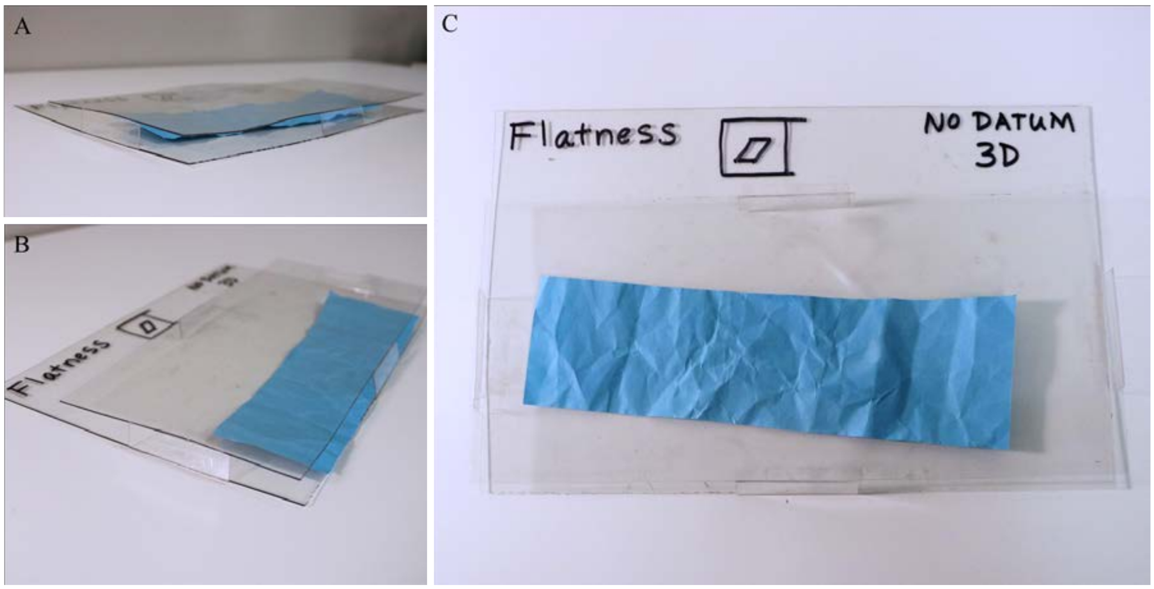

Figure A-1. GD&T Spatial Learning Tool for Flatness Tolerance
A. Side View, B. Isometric View, C. Front View

Circularity tool (Fig A-2) is used to demonstrate 2-D characteristics. Using one piece of plastic, the instructor draws two concentric circles with dash lines. The instructor then cuts out a circular, but not perfectly round, shape from paper that is within the desired specifications.

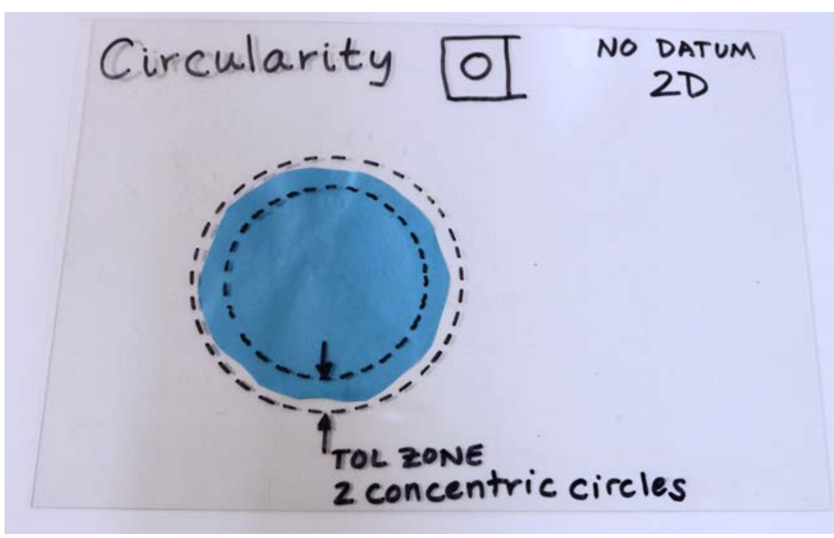

Figure A-2. GD&T Spatial Learning Tool for Circularity Tolerance

Straightness tool (Fig A-3) is also used to demonstrate 2-D characteristics. Using one piece of plastic, the instructor draws a line on the bottom of that piece, which determines where the object begins. Then using desired height, the instructor draws a line a specified distance from the initial line. Then, below the maximum height line, the instructor draws a tolerance line.

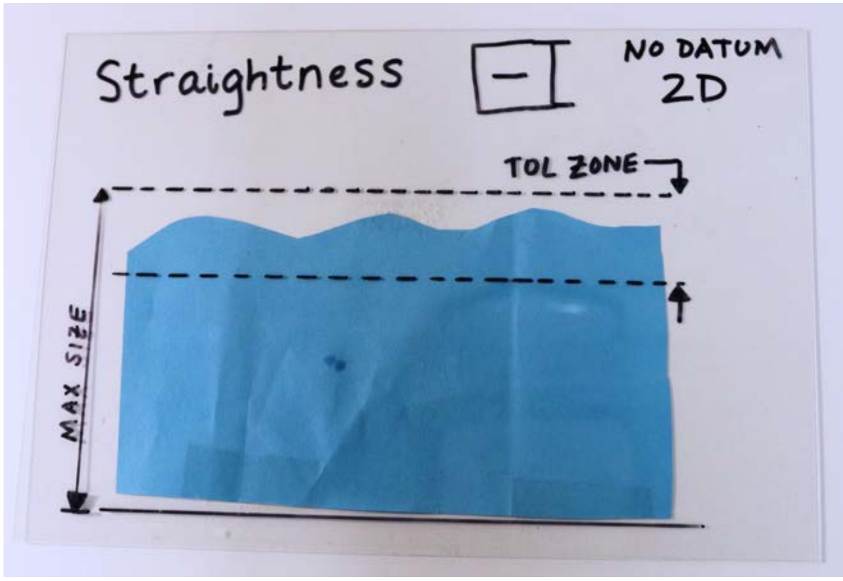

Figure A-3. GD&T Spatial Learning Tool for Straightness Tolerance

The profile of a line tool is also used to demonstrate 2-D characteristics. It uses one piece of plastic. The instructor draws and labels two perpendicular datum planes on the plastic. Using the planes, the instructor draws the shape shown in Figure A-4 or a desired similar one. The instructor then determines a desired tolerance, and draws the same shape within the desired tolerance distance. The instructor then cuts a piece of paper in the shape drawn that is within the specifications.

The perpendicularity tool utilizes three clear sheets of plastic: one for the identifying sheet and two shorter pieces for the 3-D parallel walls. The instructor defines the datum plane at the bottom of the identifying sheet, then marks two parallel lines that are perpendicular to the datum plane and at the desired tolerance distance apart. The two shorter plastic pieces are then taped along the perpendicular lines. To keep the pieces parallel, a small piece of plastic the width of the tolerance zone is taped between the two parallel pieces and the end opposite from the datum plane.

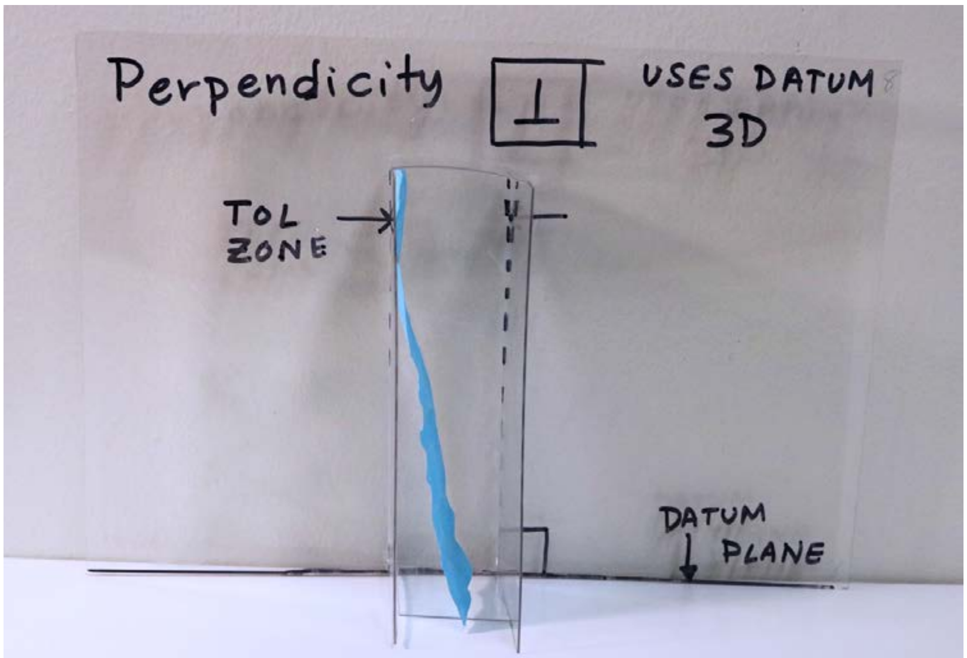

Figure A-5. GD&T Spatial Learning Tool for Perpendicity Tolerance

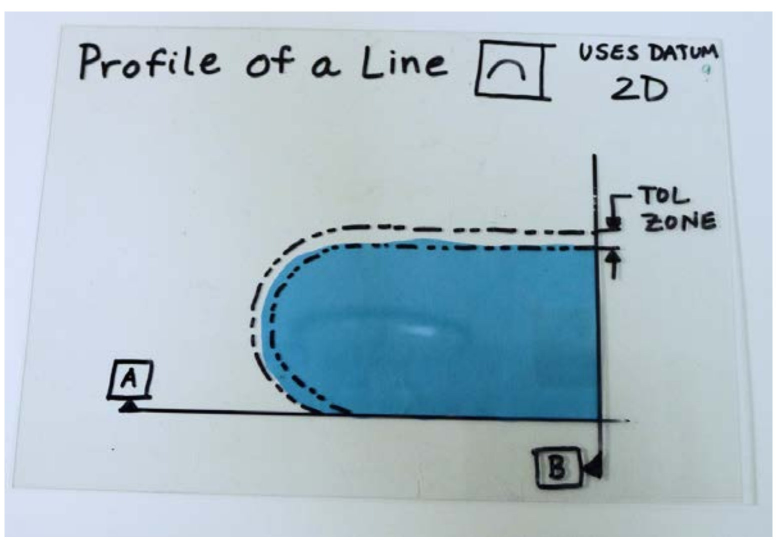

Figure A-4. GD&T Spatial Learning Tool for Profile of a Line Tolerance

Appendix B: Datum Plane Pictures for Position Tool

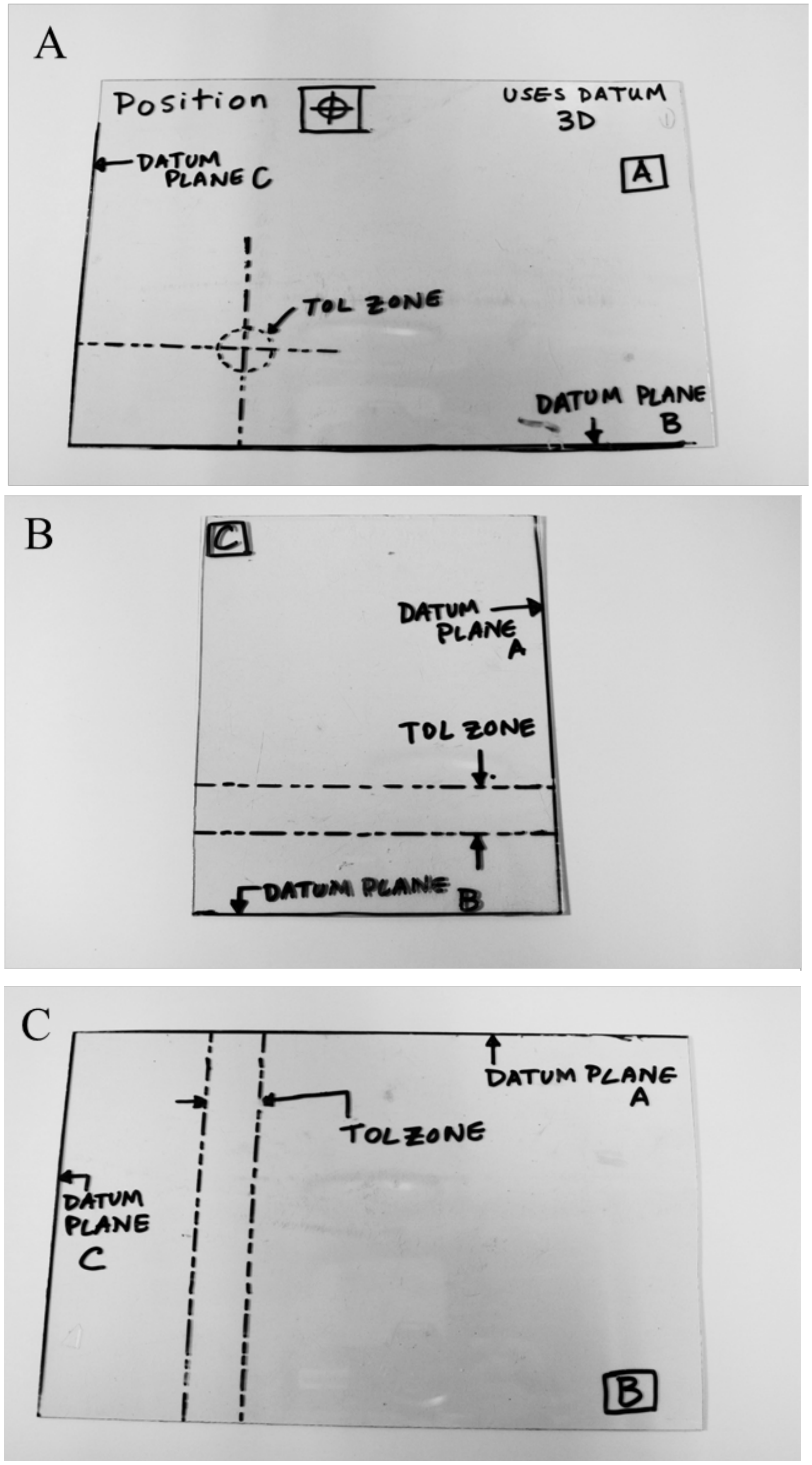

Figure B-1. Supplemental Views of GD&T Spatial Learning Tool for Position Tolerance