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Work In Progress: A Novel, Modular, Gaging System for Teaching Geometric Dimensioning and Tolerancing

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Abstract

Geometric dimensioning and tolerancing (GD&T) is a system of symbols and normative definitions essential for designing and manufacturing accurate engineering components. Conventional engineering curricula often fall short of preparing students for the level of GD&T proficiency expected by employers. This is largely due to a lack of time, insufficient instructor training, and limited instructional tools. This project aims to bridge this gap with a novel modular gaging system that demonstrates core concepts of GD&T that are typically challenging to visualize. The gaging system consists of a baseplate with a grid of threaded holes and interchangeable 3D printed components. Utilizing 3D printing allows for the rapid manufacturing of components that need to vary in size and function to adapt to individual workpieces. When attached to the baseplate, these components create datum feature simulators that define datum reference frames, i.e., gages. This work-in-progress is intended to provide a classroom tool that instructors value as being practical, inexpensive, and easy to replicate. Future efforts will evaluate the impact of the modular gaging system on student comprehension of GD&T concepts through surveys and select case studies.

1. Introduction

Specification, i.e., establishing engineering requirements, is a critical part of the design process. For mechanical components, the dimensional tolerances that appear on engineering drawings are the primary form of specification that serves as the interface between a design organization and manufacturing organization, driving cost as well as component fit and function in an assembly. Geometric dimensioning and tolerancing (GD&T) is the recognized term for the standardized tolerancing system that modern engineering practice has converged to, with the American Society of Mechanical Engineers issuing the primary governing standard used in the United States, ASME Y14.5. GD&T is constituted of a system of symbols that appear on engineering drawings as well underlying principles and definitions. GD&T is a rigorous and comprehensive tool that allows designers to specify allowable dimensional variations via tolerances that establish design intent, inform manufacturing process selection, and drive inspection requirements. Despite its prevalence, there is a widely held sentiment that GD&T proficiency remains a common shortcoming amongst engineers in the current workforce [1], [2], a sentiment supported by anecdotal and interview-based evidence in the literature [3], [4] as well as surveys of industry [5]. GD&T incompetency contributes to poorly set specifications that do not ensure final part functionality, increase the likelihood of manufacturing errors, and lead to failed inspections, thus raising production cost and time.

Prior research in the engineering education field has demonstrated a persistent gap between GD&T instruction and practical proficiency [2]. The abstract nature of GD&T makes it difficult for students to connect the symbolic representations to a physical outcome [6]. Additionally, as reported in [1], the lack of instructional techniques and physical aids to teach these concepts are identified as a top instructional challenge. In response to this challenge, researchers have attempted to bridge this gap with instructional innovations such as interactive lectures [5], [7], software-based lessons [6], [8], and low-cost three-dimensional demonstrators [9].

While interactive lectures can include thorough explanations, they are limited to reducing 3D parts and concepts to two-dimensional graphical representations. As a result, critical concepts of GD&T are insufficiently addressed [10]. Lessons that utilize software for visualization partially mitigate this limitation because models can be viewed and manipulated in three dimensions. However, these software tools may be proprietary in nature, meaning that demonstrations cannot be easily tailored to the lesson requirements. This puts emphasis on navigating the software's features rather than understanding the technical graphics [6]. Whether the instructors are creators of such software or not, becoming proficient enough to use the software effectively is not quick nor intuitive. Some instructors have incorporated hands-on activities to help students understand how topics in GD&T appear in 3D. Paige et al. [9] used inexpensive materials such as PVC, tape, colored paper, cardboard, and markers to fabricate physical demonstrators for tolerance zone concepts. While this uses cheap and widely available materials, it can be difficult to replicate with high geometrical fidelity. No two models will be identical, and assembling them by hand will make it difficult to control the precise geometrical features of the objects.

This paper presents early design efforts to develop a novel modular gaging system for GD&T education. The system is entirely 3D printed, which meets requirements for dimensional repeatability (in the context of a teaching tool) while also and enabling complex geometries to be produced for low cost and effort. The system is designed to be an instructional aid for understanding how datums and datum reference frames (DRFs) are formed from physical features on the part. The fundamental concepts behind this crucial element of GD&T are definitionally complex, difficult to visualize, and limited in how they can be represented with 2D graphics. The anticipated benefits for the system are that it allows students to tactilely experience how parts interact with datum simulators (i.e., gages), bridging the gap between abstract notation and physical outcomes, thus providing an interactive learning experience that enhances conceptual understanding.

2. Background

Principles of GD&T that are mentioned several times throughout this paper are defined in Table 1 as per ASME Y14.5-2018 [11]. While a complete description of these principles is out of the scope of what can be communicated in this paper, a brief introduction to these concepts is as follows. A *datum feature* is indicated on the drawing and corresponds to a physical, imperfect geometrical feature on an as-produced workpiece. Geometric tolerances are expressed using a *feature control frame* (FCF) that controls characteristics such as position, orientation, runout, or profile, for example. FCFs can include references to datum features in a particular order that establishes precedence, where up to three datum features can be referenced, and they are known as the primary, secondary, and tertiary datum features, reading from left to right. When a datum feature is referenced without any modifiers, the datum feature is said to be referenced *regardless of material boundary* (RMB), meaning that the *true geometric counterpart* (TGC) is not fixed in size. A datum feature has a TGC, which is inverse in shape to the feature but perfect in form. While TGCs are theoretical boundaries, *datum simulators* are physical devices that mimic the TGC, such as gage pins, surface plates, and precision fixtures that are normally manufactured with extreme accuracy and precision. *Datums* are theoretical and perfect points, axes, or planes, which are derived from the TGC or datum simulator. Depending on the datums derived from the datum features, the part is located in a coordinate system known as a *datum reference frame* (DRF) in which relative measurements are made to verify the tolerance, thereby controlling the *degrees of freedom* of the workpiece.

Table 1. Definitions (as per ASME Y14.5-2018)

Term	Definition
Datum feature	A feature that is identified with either a datum feature symbol or a datum target symbol(s).
Feature control frame (FCF)	A rectangle divided into compartments containing the geometric characteristic symbol, followed by the tolerance value or description, modifiers and any application feature references.
Regardless of material boundary (RMB)	A condition in which a moveable or variable true geometric counterpart progressed from maximum material boundary towards least material boundary until it makes maximum allowable contact with the extremities of a datum feature(s) to establish a datum.
True geometric counterpart (TGC)	The theoretically perfect boundary used to establish a datum from a specified datum feature.
Datum simulator	The physical boundary used to establish a simulated datum from a specified datum feature.
Datum	A theoretically exact point, axis, line, plane, or combination thereof derived from the TGC.
Datum reference frame	Three mutually perpendicular datum planes and three mutually perpendicular axes at the intersections of those planes.
Degrees of freedom (DoF)	All parts have six degrees of freedom, three translational and three rotational, that may be constrained by datum feature references in a FCF. The three translational degrees of freedom are termed x, y, and z. The three rotational degrees of freedom are termed u, v, and w.

An example of an engineering drawing that requires an understanding of datum features is provided in Figure 1 (a), which shows a workpiece that has two 8-9 mm diameter holes positioned relative to the -ABC- DRF. Datum feature -A- is a planar datum feature, with a TGC that is a perfect plane, from which a datum plane is derived. Datum feature -B- is a cylindrical datum feature, with a TGC that is a cylinder perpendicular to datum -A- of maximum diameter that contacts the surface of -B-, from which a datum axis is derived. Datum feature -C- is a width datum feature, with a TGC that is two maximally separated parallel planes that contact the feature perpendicular to datum -A-, from which a datum center plane is derived. Figure 1 (b) shows the DRF which is simply three mutually orthogonal planes and their intersecting axes, established by those datums. The concepts required to bridge the symbolic indication of the DRF on the drawing and the textual descriptions of how the DRF is established are evidently complex and non-trivial to visualize. These concepts are targeted by the novel modular gaging system described herein.

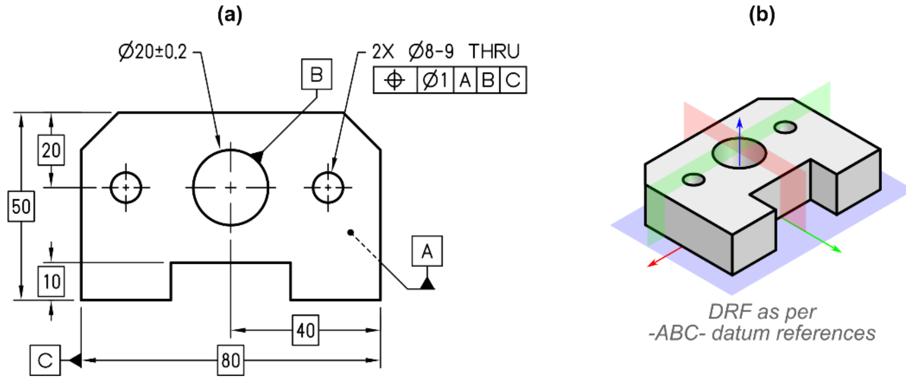

Figure 1: (a) An engineering drawing with a FCF referencing particular datum features. (b) A visualization of a workpiece placed in a DRF according to the referenced datum features.

3. Approach to modular gaging system development

The gaging system was intended for classroom use by both instructors and students. The following criteria were set to guide its development.

1. Every component of the system must be tactile.
2. All components must be either easy to find and purchase at a low cost *or* easily manufactured at a low cost.
3. The entire system must be easily scaled to create large sets for classroom use.
4. The components must be modular or easily modified so that instructors can develop customized examples or tailor the components to their needs.
5. The components must be capable of being produced with grossly exaggerated geometrical errors (i.e., semi-freeform geometry).

Polymer material extrusion-based additive manufacturing, i.e., fused deposition modeling (FDM) 3D printing, was selected as a method for producing the system that would meet all the criteria. The use of 3D printing allowed for the rapid and low-cost creation of parts in large quantities while also allowing for the manufacturing of relatively precise geometry, both ideal and irregular. When paired with parametric CAD models of the components, individual instructors would also be able to easily tailor the overall system to their needs. The printers used to produce the components were the Prusa MK4s and the Bambu Lab P1S. Polylactic acid (PLA) was the selected filament material due to its wide availability, low cost, and ease of use.

Figure 2 illustrates the iterative workflow of the design and testing process. First, the GD&T concept was selected. In this case, the concept was based on a datum feature type. Then, conceptual designs were developed to capture the functional principles of the datum. After a candidate conceptual design was selected, the design was modeled in CAD using Autodesk Fusion. Prototypes were printed and evaluated for their functionality, robustness under rough handling, and manufacturability (i.e., high success rate in printing). After evaluation, the design and printing process were iteratively refined. At the time of writing this work-in-progress paper, three datum feature types have undergone this process.

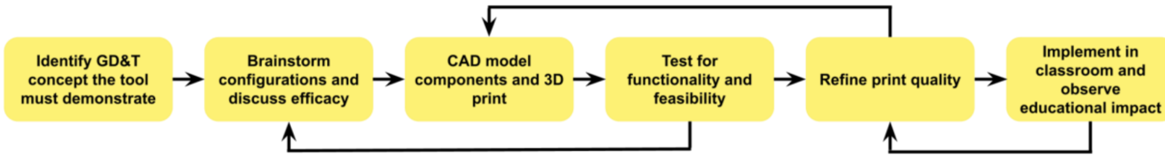

Figure 2: Iterative process for developing the 3D-printed datum simulators.

4. Results and Discussion

4.1 Overview of the modular gaging system

The gaging system with its modular components in their current design state is shown in Figure 3. The system includes a baseplate with threaded holes on a 10 mm grid, thumbscrews used to assemble the components with the base plate, shrinking parallel planes, angle plates, and expanding cylindrical mandrels. The overall intent of the system is to provide a modular method for building gages that act as datum simulators. An instructor would use this system to build a physical gage that corresponds to the datum references as specified in a particular FCF. The gages can be configured to a wide variety of part designs in a manner to mimic a specific datum reference frame. This is as opposed to alternative methods that would require a unique illustration or textual description that students may find challenging to visualize. Figure 4 shows two possible configurations of the gaging system, each utilizing select components to highlight different concepts. As will be later highlighted, one major advantage of the gaging system and the chosen method of manufacturing its components, 3D printing, is that parts with exaggerated geometric errors can be modeled and easily produced. This allows for the demonstration of concepts like datum precedence in a manner that would otherwise be difficult to realize.

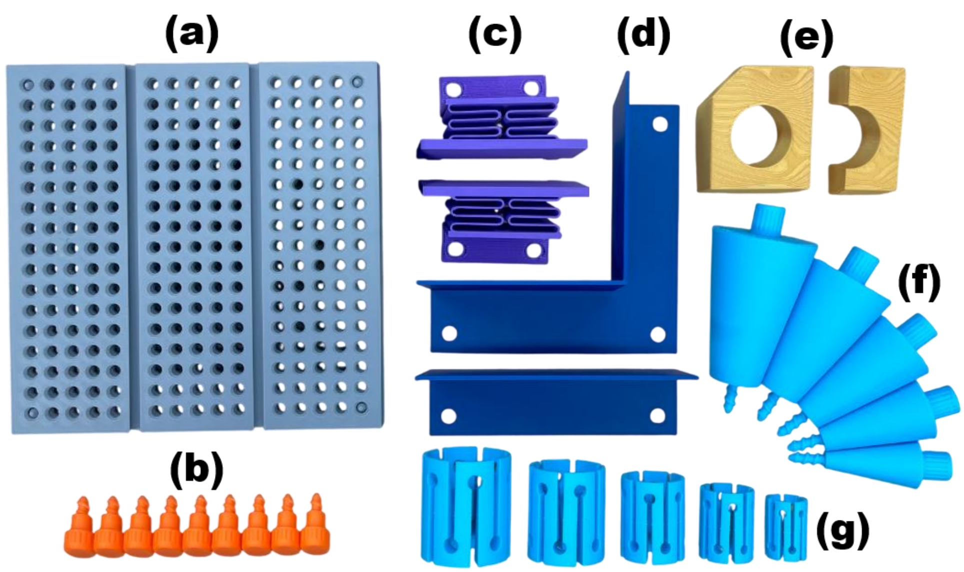

Figure 3: Components of the gaging system in its current state which includes the (a) baseplate, (b) thumbscrews, (c) shrinking parallel planes, (d) angle plates, (e) geometrically imperfect parts, (f) plugs, and (g) expanding cylindrical mandrels.

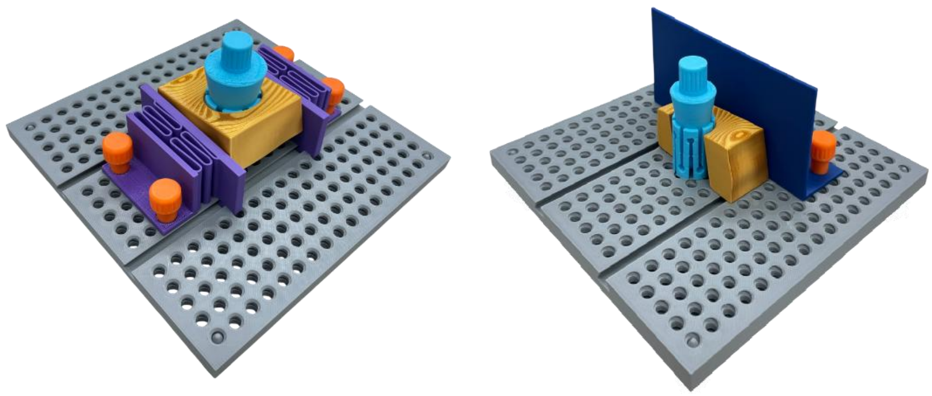

Figure 4: Two possible configurations of the modular gaging system showing (a) a DRF based on a bore, width, and plane, and (b) a DRF based on two planes and a bore.

The following sections present the design process for developing each of the major components of the gaging system. The first section presents the mechanical design choices behind the foundational components of the system. The subsequent sections each highlight (1) a key GD&T concept to be targeted, (2) the design choices behind the modular gage for said concept, and (3) an example of the gage in use demonstrating the concept.

4.2 Foundations of the modular gaging system

The foundational components of the modular gaging system are a baseplate with a grid of threaded holes and a custom thread form which together create modular interface for configuring gages. The baseplate is 180 mm x 180 mm in overall size, featuring threaded holes on a 10 mm grid to allow for demonstration parts to be designed using 10 mm increments. Two parallel dovetail tracks spaced 60 mm apart on centerline are integrated into the plate. These tracks, depicted in Figure 5, are designed to accommodate modular components such as the external width datum simulator. Additionally, four bumper feet are attached to the bottom of the baseplate, one to each corner, to elevate the plate from the working surface and provide a stable base.

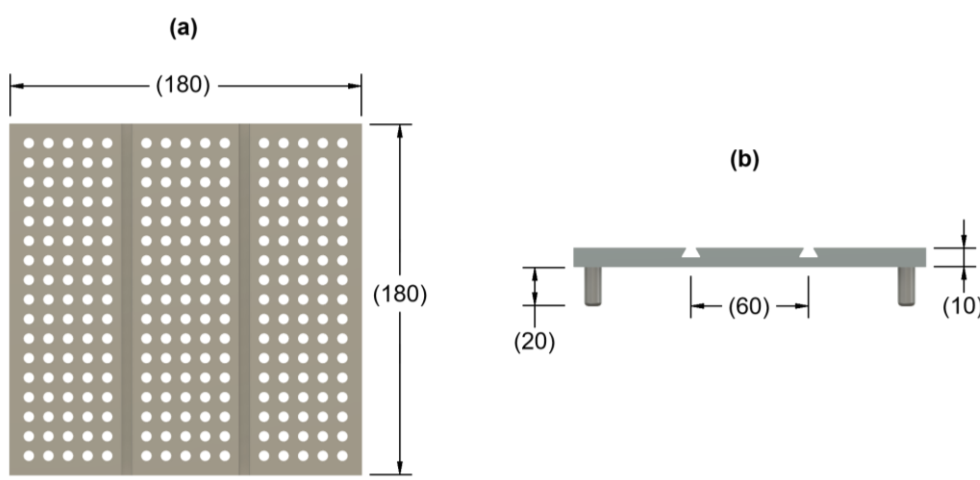

Figure 5: (a) Top view of the baseplate showing holes of a gridded pattern and dovetail joints. (b) Front view of baseplate showing the bumper feet placement. All dimensions are in mm.

A custom, universal 3D-printed thread, shown in Figure 6(a), was developed to serve as a component that can join the gaging components to the baseplate. Multiple design iterations were required to ensure manufacturability, strength, and ease of use. The pitch, screw diameter, and thread profile were iteratively adjusted to create a coarse thread that engages smoothly and quickly without cross-threading. The use of standard M5 threaded holes and studs was considered but ruled out due to their fine pitch and thus slow engagement as well as the inability to directly print them, necessitating costly and time-consuming alternative manufacturing processes. The custom thread was added to 3D printed thumb screws (used to assemble the modular gages) as well as the tapered plugs (used with the later presented expanding mandrels), shown in Figure 6 (b) and (c). Figure 6(d) shows the printed thread.

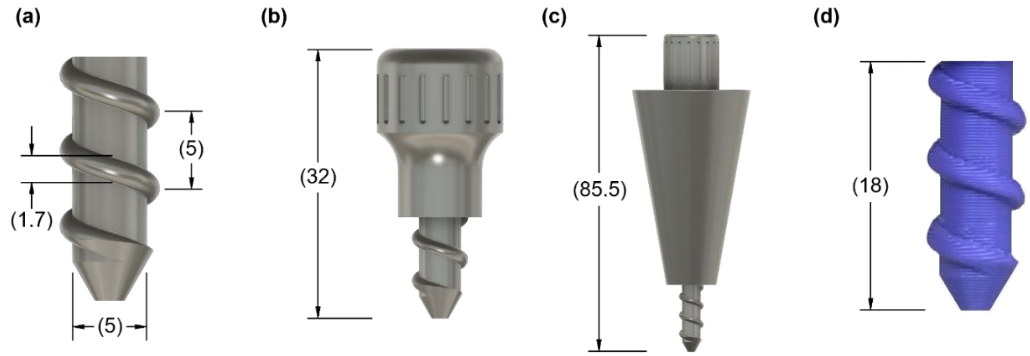

Figure 6: (a) Custom thread and its critical reference dimensions. (b) Custom thread on thumbscrew. (c) Custom thread on tapered plug. (d) As-printed custom thread. All dimensions are in mm.

4.3 Datum simulator gage for planar type datum features

The first gage targeted for development was intended to act as a datum simulator for a planar datum feature, a relatively trivial concept that is shown in Figure 7. First, a datum feature is indicated on the drawing. The TGC for a planar datum feature is a perfect plane that rests on the ‘high points’ of the imperfect datum feature surface. A datum plane is derived from TGC (in this case, it is simply a coincident plane) and represents the ideal reference from which dimensions and tolerances are defined.

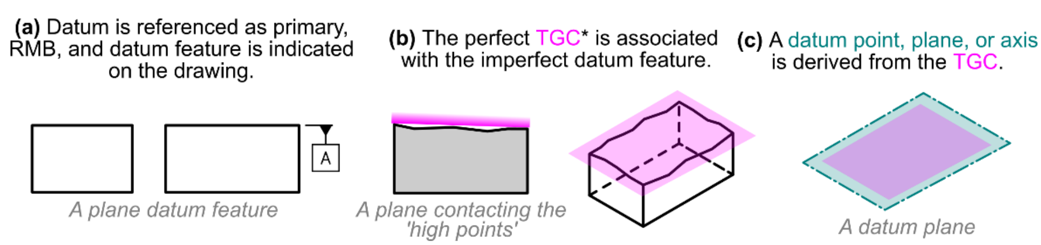

Figure 7: Conceptual illustration of a (a) planar datum feature, (b) its TGC, and (c) and its derived datum plane.

Figure 8 shows how the modular gaging system can be used to realize these principles through physical interaction of a workpiece with modular gages that act as datum simulators. According to the drawing shown in Figure 8 (a), the modular gaging system has been set up to use the base plate as the primary datum feature simulator and a modular right-angle plate as the secondary datum simulator (datum simulators being the physical components that act like the TGC). Figure 8 (b) establishes the -AC- DRF. Since -A- is referenced as the primary datum feature, the workpiece is placed against a planar datum simulator to constrain three DoF: translation normal to the primary plane and rotation about the two in-plane axes. -C- is referenced as a secondary datum feature, and it is eligible to constrain the same DoF relative to itself while respecting the precedence of -A-. As such, the -C- datum controls two additional DoF: translation normal to the secondary datum plane and rotation about the axis normal to the primary datum plane. A tertiary datum feature could also be referenced, but this would be difficult to show in a 2D figure (note that tactile interaction with the gage would make this demonstration trivial). Together, the primary and secondary planar datums define how the workpiece might be designed to mate with other components, as well as how the workpiece should be fixtured or located in a real-world manufacturing or inspection operation.

Figure 8 (b) and (c) show the differences in locating the part in the DRF according to the precedence of the datum features as specified in the FCF. By modeling and printing a workpiece with grossly exaggerated errors (In this case, the datum features being non-flat and non-perpendicular), principles of DoF constraint and datum precedence not otherwise obvious are made clear. Someone interacting with the gage can observe the three points of contact between the primary datum feature and the datum simulator and two points of contact between the secondary datum feature and its datum simulator. They can also see and feel the difference in the located feature's position and orientation.

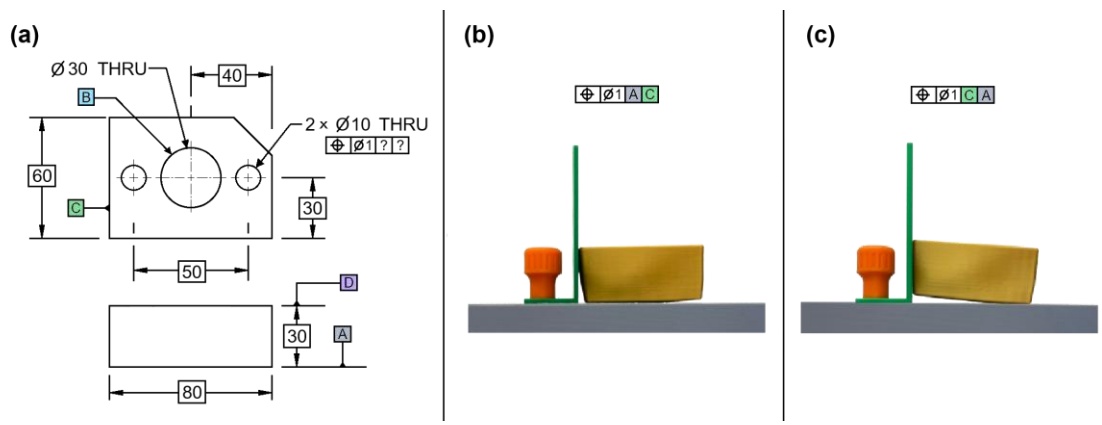

Figure 8: (a) Drawing with planar datum features and an incomplete FCF. ***Note: All dimensions not required to interpret the positional tolerance are omitted.*** **(b) The modular gaging system acting as a datum simulator if FCF were to have datum references -AC-. (c) The modular gaging system acting as a datum simulator if FCF were to have datum references -CA-. The workpiece is shown in yellow.**

4.4 Datum simulator gage for internal cylindrical type datum features

A second gage was developed to act as a datum simulator for an internal cylindrical datum feature, which can be used to demonstrate the concepts shown in Figure 9. First, the datum feature is indicated on the drawing. In this case, it is the cylindrical surface of a hole. Since the datum feature is specified RMB, the TGC is the perfect cylindrical surface that expands to make maximal contact with the hole. A datum axis is derived from the TGC.

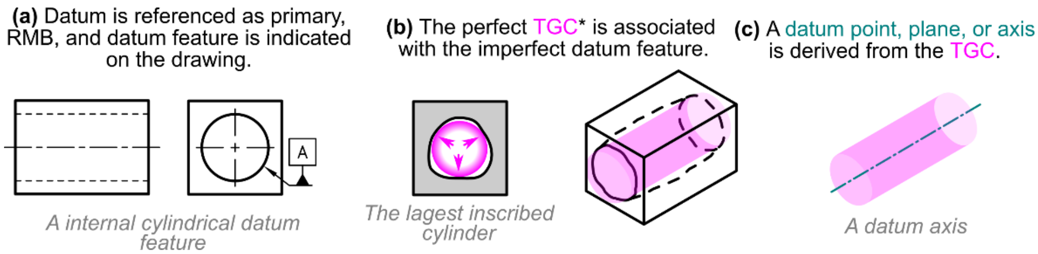

Figure 9: Conceptual illustration of an (a) internal cylindrical datum feature, (b) its TGC, and (c) its derived datum axis.

An expanding mandrel was designed to function as an internal cylindrical datum simulator for cylindrical features referenced RMB. The final design is fully parametric, such that modifying a single dimension in the CAD model automatically updates all dependent dimensions. The different dimensions tested were the taper angle A, thickness B, height C, number of slots D, and outer diameter E. The design underwent numerous refinements to ensure proper scaling of all features of the mandrel to maintain printability. Early iterations of the mandrel had severe scaling issues, where tall, narrow mandrels produced relief holes that were too large and slot lengths that were too short, while short, wide mandrels produced relief holes that were too small and slots that were overly thin. Through design refinement, proportional relationships were established to maintain flexibility and structural integrity across all reasonable mandrel sizes. Overall, the mandrel had to be flexible enough to expand and contract while remaining strong enough to resist failure or deformation during normal use. Figure 10 shows (a) the critical mandrel dimensions and (b) the five selected mandrel sizes. Each has a range of diameters it can be expanded to, using a mating tapered plug that screws into the baseplate, continuously covering internal bore diameters from 20 to 50 mm. Note that the tapered plug is not shown in the figure.

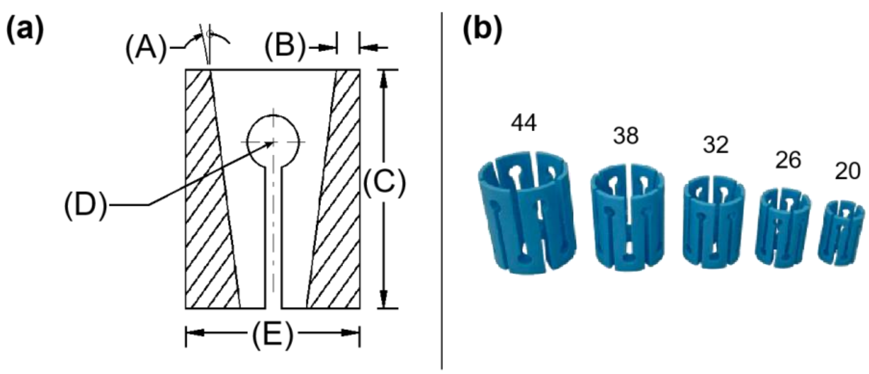

Figure 10: (a) Design details of the mandrels with critical reference dimensions. (b) Assorted mandrel sizes and the range of their outer diameters. ***Note: The tapered plugs used to expand the mandrel are not shown in the figure.***

When an internal cylindrical feature is referenced as the primary datum feature RMB, it is mated to the datum simulator, which constrains four DoF: translation on the two axes normal to the simulator axis and rotation about those two axes. Figure 11 shows the effect of referencing a cylindrical datum feature as primary versus secondary. In (b), the cylindrical feature is referenced as primary, and it controls four DoF, whereas the secondary planar feature only controls one translational DoF along the cylindrical datum simulator axis. This can be understood via tactile interaction with the gaging system by screwing the plug into the baseplate, expanding the mandrel until it makes contact with the datum feature (controlling four DoF), then sliding the part down the mandrel until datum feature -A- makes contact with the base plate (controlling one DoF). Note that the workpiece shown in yellow is intentionally cross-sectioned to make these principles more visible.

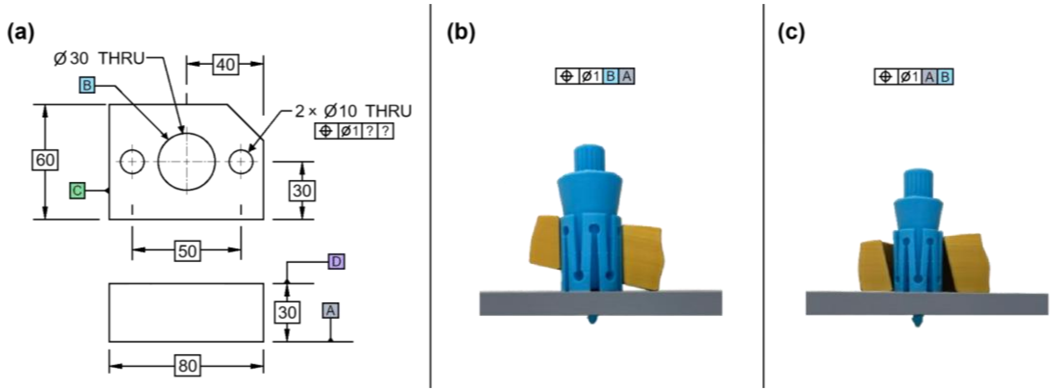

Figure 11: (a) Drawing with a cylindrical datum feature and an incomplete FCF. *Note: All dimensions not required to interpret the positional tolerance are omitted.* (b) The modular gaging system acting as a datum simulator if the FCF were to have datum references -BA-. (c) The modular gaging system acting as a datum simulator if the FCF were to have datum references -AB-. The workpiece is shown in yellow and presented in cross-section.

4.5 Datum simulator gage for external width type datum features

The third gage was developed to act as a datum simulator for an external width datum feature, which can be used to show the concepts in Figure 12. When an external width is referenced RMB, its TGC is two flat, parallel, minimally separated planes that contact the feature. The datum plane derived is the center plane of the two datum simulator planes.

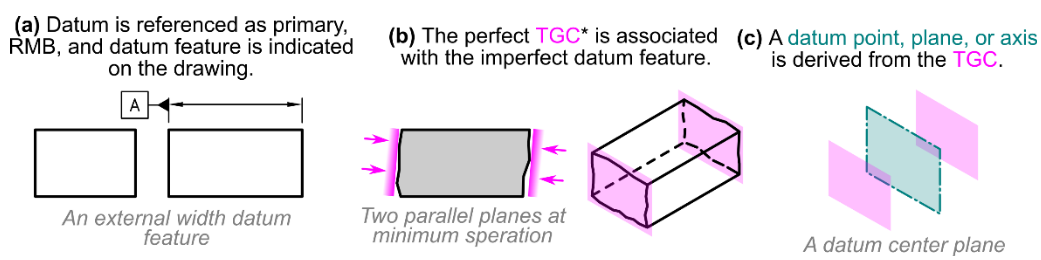

Figure 12: Conceptual illustration of (a) an external width datum feature, (b), its TGC, and (c) its derived center plane.

The datum simulator developed to demonstrate this concept is a pair of planar surfaces connected to springs, allowing them to compress and reach a state of minimal separation around the part surfaces. The springs were created to be parametric, such that the key geometric features that impact their flexibility could be easily adjusted. The different geometries altered were the inner radius A, the outer radius B, the width C, and the height D, as shown in Figure 13 (a). Initial spring designs, when attached to the planes, made the datum simulator compliant in nearly all directions, thus not meeting the requirement that the planes remain parallel. To address this, sliding dovetail joints were integrated into the planes and the baseplate to prevent vertical lift and maintain parallelism between the two planes. Figure 13 (b) shows how the springs are integrated into the part design and how the planes are joined to the plate using thumbscrews and dovetail joints. While this did improve stability, binding is now possible. Further redesigns are needed to balance flexibility and stability, especially to accommodate parts with non-parallel surfaces making up a width.

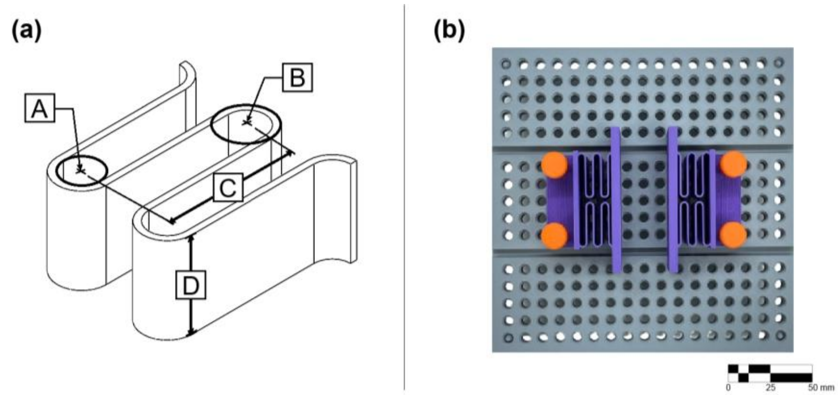

Figure 13: Design detailed of the springs on shrinking planes with critical reference dimensions. (b) Shrinking planes oriented on the baseplate.

When an external width is referenced as the primary datum feature RMB and mated to the datum simulator, three DoF are constrained: one translational axis normal to the central plane, and two rotational axes about the in-plane axes. Figure 14 shows the effect of referencing an external width feature, datum feature -D-, as primary versus secondary. In (b), the external width feature is referenced as primary and a planar feature, -C- is referenced as secondary. This can be demonstrated by allowing the -D- to center inside of the shrinking planes first, then moving the part down until -C- makes contact with the baseplate. The reverse is true when the plane is referenced as primary and the external width as secondary. The part makes three points of contact with the plane, then the shrinking planes center themselves around the part in its given orientation, as depicted in (c).

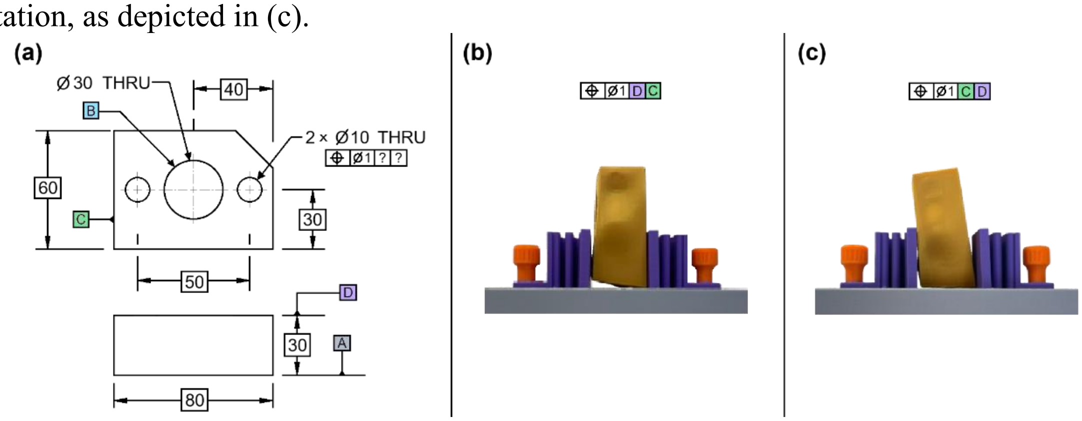

Figure 14: (a) Drawing with a width datum feature and an incomplete FCF. ***Note: All dimensions not required to interpret the positional tolerance are omitted.*** **(b) The modular gaging system acting as a datum simulator if the FCF were to have datum references -DC-. (c) The modular gaging system acting as a datum simulator if the FCF were to have the datum references -CD-. The workpiece is shown in yellow.**

5. Conclusion

A novel modular gaging system was developed to address the acknowledged instructional challenges of GD&T. The concepts of datum features, TGCs, datum simulators and DRFs were targeted. The modular gaging system consisting of a baseplate with a grid of threaded holes and datum simulators for planar, internal cylindrical, and external width features, was developed that could be produced with 3D printing. The criteria for building this system were as previously described: Every component needed to be tactile, inexpensive to manufacture, easily scalable and modifiable, robust sunder handling, capable of being produced with exaggerated geometric errors, and compatible across different 3D printers. Once completed, the modular gaging system will support innovative GD&T pedagogy and the development of skills aligned with industry expectations.

Future work is still required in several areas. The gaging system is not yet complete, and more components (additional datum simulator types) and improved component designs are still required. Lesson plans that leverage the gaging system which can be deployed by instructors will also need to be developed. Once complete, source CAD files and 3D printing files will be made available via an open-access repository. Critically, interventions in the classroom that test the effectiveness of the gaging system as compared to conventional teaching approaches are required. Informal reactions from students and experienced instructors so far show positive reception of the gaging system, with faster and more complete uptake of the targeted concepts. It is anticipated that a more rigorous study will confirm these impacts.

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