A Self-Reflective Design Study of Three Visio and Visio-Haptic Artifacts For Use in Mechanical Engineering Design Education

by

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Abstract

The focus of engineering education in North America has shifted between application and theory-basis since the early 1900s. By the end of World War II, scientific theory was gaining dominance as the foundation of engineering, and scientists began filling vacancies in engineering faculties in North America. Over generations, this faculty transition continued until engineering practitioners all but disappeared from engineering education, and engineering schools shifted the responsibility for instructing elements of practical design to employers of new graduates. As those graduates proceeded in their design careers, some were made responsible for teaching the practical elements of engineering design to the next group of new hires. The effect has been a progressive erosion of practical design knowledge in the faculties and in industry. Collectively, these elements of practical design may be referred to as design esoterica.

Knowledge of the determination of dimensional tolerances based on ASME B4.2 Fit-Classifications is one element of mechanical engineering design esoterica that has progressively eroded and is now poorly understood in academe and industry. Where once mechanical engineering students would have designed, fabricated and assembled components, thereby developing an awareness of the meaning of Fit-classifications and their tolerances, few now have such experience. As a result, students and early-career mechanical design engineers are challenged to select appropriate Fit-types, and therefore to apply appropriate tolerances to their designs. Though unquantified, this leads to elevated industry costs associated with manufacturing and service.

With thirty years in mechanical engineering design, over twenty years in the application and instruction of geometric dimensioning and tolerancing (GD&T) in industry, and six years instructing GD&T at the University of Manitoba, the author of this study has observed a general absence of tolerancing knowledge in industrial and academic environs. Recognizing the challenges of learning and teaching mechanical design esoterica in general, and dimensional tolerancing in particular, the author proposes a collection of artifacts as a first step in reintroducing, into mechanical engineering design, a functional understanding of tolerances, and tolerance magnitudes.

Three visio and visio-haptic artifacts are designed for use in developing a cognizance of the clearance Fit-classes and the micron-scale tolerances associated with them. The artifact designs are based in the mechanical engineering design experience of the researcher.

A qualitative self-study accompanies the engineering design study of the artifacts. A rhetorical *Voice of a Design Companion* is invoked as anecdotalist to convey the researcher's design thinking, and to explore the evolution thereof.

The scope of the engineering design study is limited to ideation, concepting, and final design. Fabrication and evaluations of the artifacts are contemplated as future steps.

Dedications

With love and appreciation, I dedicate this work to my wife, Lee Ann, my son, Austin, and my daughter, KayLee. Please see my long road to this point as a reminder that you can do what you set your mind and your heart to; it just may take a while. I hope you all know what you mean to me.

Acknowledgements

I have been fortunate to have had mentors who provided me guidance and inspiration when I most needed them.

I want to thank Steven Burrell, for providing that first, simple tolerancing sample that set in motion a long chain of events from my first engineering job to this thesis. Next, Tom Schmitz, who forced me to take a long coffee break and, at the end of it, explained that my job was to build relationships with the network of people that would do the work that I would need to have done, and to make the pieces that I would need to have made. Next is Bruce Catoen, a mentor, collaborator, and friend, who has respected me and valued my contributions from our first meeting. Willie Miller, another mentor and friend, encouraged me to make my voice of dissent heard, and then rallied around, at a meeting, and then encouraged me to make my voice respected in industry. These fellows were instrumental in the early development of my engineering career.

In the second phase of my engineering career, I was fortunate to have Don Day as an instructor, then mentor, in GD&T. He paid me the greatest compliment when he told me that my application of GD&T for a highly complex functionality, surpassed what he could have developed, and that it was an elegant solution. On his passing, as he had been my GD&T guru, I became the guru for other instructors and practitioners.

Academics have never been my strength. I see myself as a practitioner. However, Dr Ron Britton saw both in me, and is the reason that I believed that I just may be able to complete graduate studies. Thank you, Ron, for the open conversations, friendship, and encouragement to drive changes from within. I was fortunate to first get to know Dr Marcia Friesen and Dr Jillian Seniuk-Cicek as colleagues, then to engage them as my co-advisors for this thesis. Your patience, encouragement, and direction leave me speechless, other than to say, *Thank you.* I also thank Dr Zana Lutfiyya and Dr Philip Ferguson for their participation on my committee. This thesis doesn't fit perfectly in either of your areas of expertise, yet you both answered my call. Thank you.

Finally, I want to acknowledge the colleagues, clients, and students who entreated me with their concerns about engineering education. I heard you all.

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Chapter 1 Introduction

My thirty-year engineering career has never been what most would call "conventional". I have never fit within the framework of the job description assigned to the work I did. I didn't set out to bend, much less break, rules and conventions of engineering practice, whether in design, communication, field service, consulting, or teaching. Yet the work frequently necessitated that I break conventions that wouldn't bend. "Unconventional" is a generous descriptor for my career, a brief overview of which is provided in Appendix C. I have developed and been recognized for subject matter expertise in several fields. I have developed new technologies and built a business unit around some of them within a global corporation. I was credited with the equivalent of almost twenty years of design and manufacturing experience within three years of graduating with a Bacherlor's of Engineering degree from Carleton University. I led the development of international voluntary standards. I have contributed knowledge and solutions in numerous mechanical design and manufacturing sectors. I gained a reputation as a fixer, someone who delivered solutions to problems where other efforts had failed.

Most of this happened because, almost immediately after graduating, I learned to question the status quo, the blind obeyance to convention and rules that are not based in engineering fundamentals. I learned that accepted, conventional or expedient practices were in place for median situations, and did not lend themselves to the critical, the emergent, the fringe and the unexpected situations that were sent my way. Because of this, I have experienced specialties, skills, and knowledge bases that resulted in my recognized subject matter expertise in many areas, particularly in design esoterica, the critical details that complete a design.

I teach what is, arguably, the most boring subject in mechanical engineering. It is a point of pride. At its core, I teach design esoterica. More specifically, I teach geometric dimensioning and tolerancing (GD&T), a highly specialized knowledge base and skillset that provides a clear communication of workpiece functionality through the application of tolerances to engineering drawings and CAD models. The ancillary content that I instruct is also design esoterica: drafting, Fits-based tolerancing, tooling considerations, surface finishes, and other design considerations as opportunities arise. Notable for this study, from experience, I recognize three elements of effective Fits-basis tolerance instruction; (1) understanding how mechanical parts mate and function, (2) determining tolerances, and (3) visio-haptic cognizance of what the tolerance values signify.

For critical applications, the type of mating condition (i.e. the Fit-Classification) can be selected from ten standardized ASME B4.2 (American Society of Mechanical Engineers, standard B4.2 [metric]) (ASME 1978) Fit-Classes, based on written descriptions of their interaction characteristics, as shown in Table 1.A. Written descriptions, however, do not provide a physical feel or context for how components interact and function.

The second element, above, is derived from the selection of the Fit class and other considerations; ASME B4.2 provides tables of tolerances based on fit selection and other factors.

The third element of effective instruction of tolerancing, cognizance of the magnitude of the tolerance value, is not, in my experience, effectively addressed in academics or industry. Precision tolerances, critical to many fields of mechanical design engineering, are in the micron and sub-micron range, mostly below the visibility threshold of 30-40 microns (i.e., 30-40µm, 0.03–0.04mm). We may ask, how can we physically appreciate the magnitude of something too small to be seen with the unaided eye? Magnification, perhaps. However, magnification skews the perception of the magnitude because the image of a micron-scale feature must be scaled up by orders of magnitude to be easily visible, and therefore we have no physical correlation to its actual magnitude. Can we gain a sense of magnitude by comparison to something known?

Table 1.A ASME B4.2 Preferred Fits (ASME 1978)

Fit Category	Fit Class	Application Description
Clearance[i]	Loose running	For wide commercial tolerances or allowances on external members
	Free running	For use where accuracy is essential, but good for large temperature variations, high running speeds, or heavy journal pressures
	Close running	For running on accurate machines and for accurate location at moderate speeds and journal pressures
	Sliding	Not intended to run freely, but to move and turn freely and locate accurately
	Locational clearance	Provides snug fit for locating stationary parts, but can be freely assembled and disassembled
Transition	Locational transition (1)	For accurate location, a compromise between clearance and interference
	Locational transition (2)	For more accurate location where greater interference is permissible
	Locational interference	For parts requiring rigidity and alignment with prime accuracy of location but without special bore pressure requirements
Interference	Medium drive	For ordinary steel parts or shrink fits on light sections, the tightest fit usable with cast iron
	Force	Suitable for parts which can be highly stressed or for shrink fits where the heavy pressing forces required are impractical

[i] Of the ten Fit Classes, only the five classes of the Clearance category are considered for Fit-class demonstration artifact development.

While we know the size of red and white blood cells (8µm and 25µm respectively) and dust mite feces (10µm), we can't see these unaided, either. From this, we comprehend that the number is small, but such comparison doesn't *adequately* improve our understanding of magnitude. Visual appreciation of the scale involved seems ineffective by itself. If we can't see them visually, is there another way to appreciate their magnitude?

It turns out that the human somatosensory system can detect minute changes in topology. In particular, the finger pad and the fingernail are ideally structured for haptic probing with significant sensitivity (Bolopion, et al. 2011, Y. Zhang 2010, Birznieks, et al. 2009, Sahli, et al. 2020, Seah, et al. 2013). We observe this capability frequently in society's work. Dermatologists may use this sensitivity to detect abnormalities in skin texture that could indicate skin cancer. In the moldmaking industry, mold finishing specialists (polishers) will gently touch a workpiece with their fingerpads and fingernails to detect inconsistencies in a metal surface. Garment makers will pass their hands over a garment to detect flaws in the textile, and parents will gently caress their babies, not just to sooth them, but to check if anything has changed on the baby.

Whether used independently or cooperatively, I believe that visual and haptic sensing can be used to develop a cognizance of the magnitude of precision tolerances.

Dimensional tolerancing and appreciating the magnitude of precision tolerances are elements in a broad field that I refer to as the esoterica of mechanical engineering design.

Esoterica in Mechanical Engineering Design

Picture a hyperbolic funnel (i.e., a coin funnel). Introduce all the high-level machine design theories that are taught in core machine design courses into the large open end. Because design is iterative, these elements swirl around and interact with each other as they go from broad, isolated theory to specific, collaborative application, progressively narrowing as does the hyperbolic funnel. The output, the resolution to those inputs, emerges from the small opening of the funnel. Machine design theory addresses *core* design considerations such as the pitch diameter of a gear, the number of teeth and their pitch, loads, rotational speeds, and the shaft diameter. But *is the gear design complete*? *It is not.* Considering the metallurgy or metallurgies involved, design theory doesn't instruct students to anneal the gear body for ductility before case hardening the teeth for durability. Theory doesn't instruct the transitional geometries from web to flange, or to put a lead-in to engage the gear bore on its shaft. There is no guidance to add chamfers and fillets on the gear to make it safe for handling. These and other "finishing details" are not addressed in the instructed theory. *Theory is just the first step*. There are many additional design elements that are critical to the fit, form and function of the final design. Beyond that, we must ask and answer many questions. Does the specific material composition, grade, or homogeneity affect part characteristics and performance? How will the part be produced? Are allowances and features needed for tooling? What are the surface finish requirements? How do features engage with mating parts? How precisely must the features be located with respect to each other? How perpendicular is perpendicular? Is there a dynamic balance requirement? Do precautions need to be taken to protect the item from damage during normal use? The potential list of considerations is far more extensive than this, and while most machine design courses in undergraduate mechanical engineering programs in Canada do not explore these in detail, they *are* crucial in design practice. Collectively, I refer to these elements as design esoterica, elements of specialized design knowledge. Esoterica are things that require or exhibit knowledge that is restricted to a small group (Merriam-Webster.com n.d.). Many elements of mechanical engineering design fall under the broad banner of esoterica, and they are critical to a complete and robust mechanical design. In my experience, and as told to me by others, such mechanical design esoterica are generally not taught in core mechanical engineering design courses, relying instead on future employers to provide training in the relevant esoteric details.

The absence of design esoterica in machine design textbooks implies inconsequentiality to the field of engineering design (i.e., what may be perceived as *pure* engineering, as opposed to mere application of engineering technology) or at least to design education, perhaps relegating it to an afterthought at best, or to a domain of training thought to be the responsibility of specific industry sectors rather than undergraduate engineering education.

In practice, addressing such esoterica as a secondary consideration, or as an afterthought, can lead to significant redesign with its affiliated costs and delays. It also keeps students from experiencing some of the most interesting and eye-opening design discussions in their undergraduate education, which can shape their career goals. The inclusion of design esoterica in design education would give a more complete picture of the many aspects of design engineering. As a result, it would encourage in the students a sense of design completion and of closure to the design process.

Several of the elements of esoterica mentioned previously are tolerancing considerations. Above all other esoterica, tolerancing is at the core of functionality in mechanical engineering design. If parts don't fit, they don't function. For example, the precise tolerancing of the piston, piston ring, and cylinder bore in an automobile engine ensures that lubricating oil will not be drawn into the combustion chamber while simultaneously preventing the combustible fuel/air mixture from leaving the combustion chamber, either of which would damage the engine. Yet, tolerancing is rarely taught in university engineering programs. As a starting point, I sought a definition for mechanical design engineering, but none reflected the robustness and completeness of engineering design, as I had practiced. Therefore, in the context that will be discussed within this thesis, I am broadly defining mechanical design engineering (or mechanical engineering design, interchangeably) as *the determination, documentation and graphical communication of geometries and mechanical characteristics to define intended functionality of physical objects at the component and/or assembly levels*.

Research (Harrisberger 1976, Li, Ochsner and Hall 2019, Abellan-Nebot 2018) has established the effectiveness of experiential learning in engineering education. Furthermore, experiential learning supported with artifacts has been shown to be particularly effective in developing a deep understanding of elements of mechanical design engineering (Wood, et al. 2001). Attribute tolerancing is not commonly taught in undergraduate mechanical engineering programs and where it is taught, the focus has been on numeric models and algorithms relating to tolerance values. The literature does not provide evidence of development or use of artifacts in teaching or learning *precision* tolerancing practices. Without establishing cognizance of the micron-scale values involved, any determination of tolerance values is an exercise in theory.

But what is an artifact? If you were to ask someone what field of study would involve artifacts, you would likely hear anthropology or archaeology in response; it is unlikely you would hear *mechanical design engineering*. Merriam-Webster (n.d.) defines an artifact as "a product of artificial character … due usually to extraneous (such as human) agency". The etymology of artifact (original spelling *artefact*) provides meaningful guidance on the use of artifacts in engineering education. From Latin (Online Etymology Dictionary n.d.), *arte* meaning *by skill*, and *factum* meaning *something made*. Therefore, an artifact is *something made by skill. Skill* is not defined in this context, therefore I suggest that *skill* broadly encompasses the knowledge of both theory and practice, the tools, the experience, and the application thereof, to produce a desired outcome. As pertains to the discussion of mechanical engineering education herein, I define an artifact[ii] as *an item or assembly of items, whether of incidental historical production or by intentional manufacture for instruction, made by skill and used as a teaching exemplar*. Having established a definition of an artifact, I pose the question of how do we *experience* artifacts?

From an early age we are taught that we have five senses (vision, hearing, touch, taste, smell). That is at once overly simplified and a significant understatement of the sensory capabilities of the human body. As regards the perception of micron-scale tolerances, two senses are considered: vision and touch. We understand what vision is, and we know its typical limits. As regards our ability to perceive of very small magnitudes by touch, we are equipped with a somatosensory system with which we can perceive minute changes in pressure,

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[ii] In the literature, artifact, artefact, sample, aid, prop, and other terminologies are used synonymously.

temperature, pain and spatial position. The somatosensory system includes the brain and nervous system, and is dependent on nerve endings attached to skin, muscles, tendons, ligaments, bones, hair, as well as fingernails and toenails, to provide inputs to the system. Without thinking about it, we use both senses constantly to experience what is going on around us. In other words, it's a skillset that we already have, but it is untrained and therefore not as perceptive as it could be with a little training.

The purpose of this study is twofold. First, to design three visio and visio-haptic artifacts to be used in teaching dimensional tolerancing with the intent of developing cognizance of Fit-basis tolerances and their magnitudes. Second, to convey through a combination of self-reflective and conventional academic description, the humanity and collected experience behind the design evolution of the three instructional artifacts.

This thesis will comprise the intellectual and physical process before and during the design of three artifacts that may be used, mutually supportively, to visually and haptically foster learners' qualitative cognizance of the magnitude, fit and functionality of micron-scale tolerances used in high-precision mechanical engineering design. This thesis adapts a self-study qualitative approach in which my lived experience as a mechanical design engineer for over thirty years forms a body of knowledge and insight that, in qualitative work, carries commensurate credibility to the research literature and to external data. This methodology is unconventional within the quantitative, empirical world of conventional engineering design and to some degree within engineering theses. Consistent with the inherent nature of qualitative methods, the intention is to yield insights that are not available through quantitative approaches. I chose this approach for my thesis because it is reflective of who I am as a mechanical design engineer, and how I undertake my work. Each design engineer may have distinctions in their creative process, which distinguishes them from their professional colleagues, and their process may evolve with experience.

My personal and professional histories will be introduced as the foundation for how I have come to view mechanical design engineering, and the education of mechanical design engineers. My thoughts on engineering education are made explicit in order to contextualize the eventual artefacts for teaching mechanical design esoterica.

I visualize my evolving knowledge and lived experience as an inner voice that guides my design work. Though perhaps not unique, I have not found this inner voice discussed openly or with transparency, as relates to mechanical engineering design. Reliance upon and discussion of that inner voice in this writing are further departures from conventional design theses. I have dubbed my design process, or inner dialogue, perhaps, as *the Voice of my Design Companion*. I will use this voice as I recount anecdotes that provide introspective glimpses into my past and how they have shaped me as a person, and subsequently as a mechanical design engineer. And I will use this voice to reflect internal deliberations throughout the evolution of the three artifact designs.

The conventional voice used in academic writing seems all-knowing, and confident in that knowledge. In contrast, I have underlying feelings that I do not know enough, and that my knowledge may be false. There seems, among academic and practitioner design engineers alike, a reluctance to discuss their design considerations in a way that conveys their individuality and its effect on their design. Instead, they default to talking about design standards, numbers, theories, and principles invoked in their work. For me to write in an academic voice feels inauthentic and discomfiting. As an Engineer-in-Residence, students asked me about the professional practice of mechanical engineering design beyond the application of theory. I would respond with anecdotes interweaving my personal and professional histories, because the two are intertwined and each is formative to the other. This *feels* like my *authentic* voice. It allows me to share my knowledge, experience, and perspective without an overpowering element of authoritarianism that may discourage students. I am hopeful that invoking the Voice of my Design Companion may help validate to others that design is a personal process.

I consider myself fortunate to have had the opportunity to support young adults as they neared the start of their careers, and I reflect with sentiment upon our discussions. As I invoke the Voice of my Design Companion, I am addressing Aubrey, a gender-neutral amalgam of the students and early-career mechanical design engineers that have asked me questions and listened to my anecdotes.

To reinforce that the voice of my Design Companion is not reflective of conventional academic writing, it will appear in a distinct, yet informal, typeface and colour.

This thesis follows my design process that resulted in the design of three artifacts that may be used, through vision and touch, to foster a qualitative cognizance of magnitude, fit and functionality of micron-scale precision tolerances. I employ an unconventional methodology incorporating elements of a self-study qualitative voice and a conventional academic voice in which my lived professional design experiences are expressed as the underlying foundation of my design. I employ this hybrid approach throughout the writing.

Employing the *academic* voice in Chapter 2, the literature review, I focus on three areas of research: Tolerance as design esoterica in mechanical engineering education; Visual and somatosensory perception of small-scale magnitudes; and, Artifacts in mechanical engineering design education. I conclude the literature review with a reflection on how my lived experience as a mechanical design engineer has shaped my evaluation of the literature.

In Chapter 3, a discussion of artifact design methodology leads into considerations of epistemological, ontological, and axiological assumptions for this first context. These are followed with considerations of self-study methodology, and a discussion of epistemological, axiological, and ontological assumptions in this second context. From there, a discussion of positionality follows, exploring the evolution of my self-perceptions starting from childhood educational experiences through to industry experiences. The chapter culminates with an explanation of how a Devil's Advocate persona evolved into *the Voice of the Design Companion*.

Through this hybrid self-reflective design study approach, two topics are explored in Chapter 4. First, a collection of artifact design considerations is developed as both a precursor to concepting the artifacts, and as a potential tool for verification of design completion. Following that, design concept evolutions for the three artifacts are provided, and the three final artifact designs are determined.

Finally, Chapter 5 discusses the artifact design and self-reflections provided in this thesis, and considers next steps for the artifacts and the realizations from the self-reflective study.

Positionality

I see myself as a pragmatist, a problem solver. It has been one of the prevalent *modis operandi* throughout my career and, when I reflect on it, my personal life as well. Another is a predisposition toward self reflection, endlessly re-examining my thoughts, words, and actions, and adjusting behaviours to improve future outcomes. Though my positionality is outlined in a few brief statements, my journey to recognize these statements of positionality is as important as their realization.

How I Came to Teach the Most Boring Subject in Mechanical Engineering

Career paths are strange things in so far as your plans are mitigated by your reality, at least mine have been. When I graduated from my undergraduate mechanical engineering program, I knew that I wasn't going into design, but the only job offer that I received was for a design job. I didn't have career goals, other than to remain employed. As projects were assigned, I learned what I needed to complete them, not intending to specialize in anything. When you do something often enough, well and creatively, and go beyond the minimum to develop deep understanding, you slowly become a specialist. I mastered several manufacturing technologies in short order and was soon recognized as a specialist in the area of design for manufacturing. One specialty leads to tangential work, leading to another specialty. In my case, a specialization in the design of electrodes for electrical discharge machining led to a project to reduce twelve electrode design variants into a single design. That, in turn lead to work on an industry standardization committee, which, in turn, led to a specialization on molded threads, which lead to the design of a falling-tup impact test device and impact test procedures. In essence, specialties are just esoterica; specialized knowledge held by few people. Then, others look to you to try solving something in a field that is new you, developing a new esoteric specialty. Soon, I was a specialist in the domain of design esoterica, no longer an engineering generalist.

My Journey into a Career of Design Esoterica

I view myself as a practicing design engineer, as opposed to an academic design engineer. The difference, from my perspective, is the depth and diversity of design experience in industry, beyond what occurs in a university education. I have designed molds and other technologies for three resin (plastic) molding technologies, as well as designing molded articles themselves. I have designed tooling and fixtures for numerous manufacturing processes. I have been directly or casually involved in design of automotive, aircraft, spacecraft, defense, and medical technologies, where design failures have meaningful consequences. I have worked on the development and adoption of international design, documentation, and testing standards, and have advised in all these sectors and more. In contrast with the focus of engineering education, most of the engineering design that I have been involved with did not revolve around numerical analysis of stresses, fluid dynamics, heat transfer, or the use of theoretical models developed to represent physical phenomena. Most of my designs invoked the general knowledge of engineering stresses, fluids, heat transfer, metallurgy, and other considerations. Academic design, to me, is theoretical design, often of limited scope or diversity. It is design for the sake of designing, without meaningful consequences for poor, incomplete, failed, or successful engineering design.

In 2019, my return to academic pursuits followed twenty-five years of active engineering design participation in industry. I recognize and appreciate that the classical, theory-biased courses in my mechanical engineering undergraduate program in the late 1980s through early 1990s provided a foundation for my design engineering career. They did not, however, instruct me on practical design. From formal education, I learned how to design bearings and gears, but in practice, most engineers select them from a catalog or contact a manufacturer to address customized specifications. Metallurgy textbooks informed me on the fundamental differences between metal types but didn't provide me with any guidance for determining which metal, much less which specific grade, to use for a particular application. As an undergraduate, I was instructed on several ways to specify tolerances on our board-drafted drawings, but not what those numbers signified or how to determine them. When I graduated with my Bachelor's degree in Mechanical Engineering, I was terrified of taking any design-related role in industry because I recognized that I knew little more than design theory and the prospect of causing harm was real and overwhelming. I even completed a concentration in management as part of my studies, expecting that would keep me out of design. Reality and opportunity, however, determined my career path: my reality was the 1993 global recession that I graduated into, with engineers displaced throughout North America; my opportunity, after more than two-hundred job applications, was an opening at a small mold shop[iii] that needed two entry-level designers.

[iii] Mold shops are businesses that engineer (design) and fabricate molds (forming tools), usually made of various metals, typically for use in molding of resins.

Hi Aubrey. I want to tell you about my first engineering job; it came with unexpected lessons. My practical engineering design education started maybe three months into my first engineering job. My work was initially overseen by a senior designer, and my initial instructions were to stretch and modify existing designs for new applications. A few months later, a master mold maker came into the design office and grabbed me, quite literally, by the ear. He dragged me out to the machine shop while saying something to the effect of "You've got some explaining to do, college boy." ***Lesson number one****: Many people consider college and university engineering to be the same thing, and correcting them is ill-advised.* The mold maker had several parts that I had designed, on a bed grinder, and let me know that the tolerances I had applied would cost extra hours of work to attain, compared with what he knew was appropriate for the functionality of the parts. He asked why I'd selected those tolerances, and I told him truthfully that I had been told to copy them from template drawings. ***Lesson number two****: No version of "I just copied what we did before" is acceptable to someone who understands their trade.* When asked why I didn't question those tolerances, I told him that I didn't really understand what the numbers meant... they were just numbers to me. I expected a physical response from him, but fortunately he just grunted "Come", and led me to the mold polishing area. He had a sample piece made for me; it showed a few stepped depths, one-ten-thousandth, five ten-thousandths and one-thousandth of an inch, as I recall, but my memory is hazy on this. ***Lesson number three:*** *When in doubt, ask the experts to explain.* In this case, the expert was a tradesperson, a master mold maker, schooled and apprenticed in mold making decades before. ***Lesson number four****: Expertise, including design esoterica,* *comes from many sources, not just engineering.* He showed me how to look at the sample, then how to use the fingernail of the index finger to feel the steps. ***Lesson number five****: Design esoterica have real, physical meaning, and are not just abstractions.* Those were my first steps toward understanding tolerancing, and the value of integrating visual and tactile sensing as a core element in learning engineering design, two significant elements of my design career. That day was effectively the start of my informal and intense engineering design apprenticeship, and most of those lessons came from the shop, not the design office. Today, I understand the physiological elements of haptic and visio-haptic sensing that I was introduced to that day. I understand how and why the fingernail and the pad of the finger detect static and dynamic loads differently. I've taught you how to use my sample pieces to figure out surface finishes and other details. As I recall, you were as surprised as I was, that a fingernail could detect and differentiate surface finishes as smooth as 0.05 microns.

As I exercised this new skill of visio-haptic sensing, I found that I could reasonably estimate depth changes at that scale by touch. I *physically* understood what the numbers represented.

Lesson number six: Don't be afraid or embarrassed to ask. People want to share what they know.

I applied the basic ideas of fluid dynamics, materials, and heat transfer to reduce one mold cycle from 38 seconds to 16 seconds, and I learned about the importance of chamfers, fillets and rounds when a sharp edge cut an o-ring (a polymer-compound seal) and caused the mold to leak during test. During eighteen months with that first employer, I learned about mold design and, as important to my design knowledge, enough about manufacturing techniques that my *second* employer recognized me as a design subject matter expert (SME) in several subtractive manufacturing processes (e.g., pantography, thread milling, electrical discharge machining, others).

As a sidebar, Aubrey, I should give you an overview of the fields of manufacturing. Component manufacturing falls into three broad categories; subtractive, additive, and forming. Each of these yields workpiece geometries that meet functional requirements or that become feedstock for further manufacturing processes. Subtractive, or material-removal manufacturing processes, progressively remove small amounts of material from a piece of material. Examples of subtractive processes include turning, milling, drilling, grinding, broaching, acid etching, laser ablation, polishing and many others. Additive material (AM) manufacturing processes build up layers of material. Spray-welding and 3D-printing technologies, including fuse deposition modelling (FDM) and selective laser sintering (SLS), are examples of an expanding field of AM processes. Forming processes distribute molten or solid material by means of externally applied forces. That includes sheet metal stamping and bending, casting, injection molding, and forging. I also developed expertise in manufacturing-tooling and workpiece-handling requirements; things like undercuts and chamfers. Though I didn't recognize it at the time, Aubrey, design esoterica were a significant part of my *work, and experiential learning supported by artifacts was a key element of my expanding knowledge base and skillset.*

My next employment spanned ten years with an international molding systems supplier. For the next eighteen months, the techniques, specialties, and esoterica that I had learned in the small shop were put to the test and expanded upon. I used spare parts, manufacturing scrap parts, test mold systems and molded articles as artifacts to support my learning.

Sometimes, Aubrey, a career trajectory will change unexpectedly. Three years after graduation, my employer recognized that my design, manufacturing and metrology knowledge and skillsets, were rather advanced, and promoted me to the senior-most levels of design engineering, and shortly after promoted me to product development and field service engineering. I was recognized for leading international industry standardizations in niche technologies: more esoterica. I became a specialist in geometric dimensioning and tolerancing (GD&T), more esoterica. You've seen and used the artifacts that I collected, surface finish reference and comparator samples, and other materials that supported esoterica.

I see no way for an undergraduate engineering machine design course to include *all* the specialized knowledge that industry relies upon. Arguably, though, there are many elements of esoterica that are common to engineering design and could be included as valuable content in machine design and similar courses.

My work with students started more than two decades before I met you, Aubrey. For my second employer, I frequently recruited undergraduate engineering students for co-operative and internship placements in several corporate divisions and for various job functions. I typically mentored some students directly and others indirectly with their supervisors. Slowly, I recognized that I enjoyed working with students and felt validation as a design engineer as I saw my efforts result in their skill and knowledge growth. That's why I enjoy teaching you. By the time I left my second employer, I had led their GD&T implementation in several business units on three international business campuses and participated in the selection and integration of manufacturing and metrology systems. Despite my patents, publications, and recognition for my accomplishments, I'm not sure that I truly felt like an engineer, at least not what I thought an engineer was. I'm not sure about your engineering role models, Aubrey, but growing up, I didn't know there were engineers in my family. I met an uncle who was a professional engineer, but not until years after he had retired. Walking the halls as an EiR, I even found a probable relative in one of the earliest engineering graduating class photos at the University of Manitoba. I didn't know any engineers when I was growing up. Believe it or not, Aubrey, I nearly went into electronics or computer science instead of mechanical engineering. As a kid, I helped my mother repair our old vacuum-tube television, somehow not killing either of us. Later I took a couple electronics shop courses in secondary school, again surviving the experience with high voltages and currents. My shop teacher submitted my name, and I was awarded a full scholarship to an electronics technologist program. From my financial background, that could mean an education without any *expenses, and a good start at a comfortable life. Other teachers and counsellors guided me toward professional engineering as a career path because of my grades. They sold it on the challenge and the long-term financial potential, so I went that route instead. I had no idea what engineers did other than the vague notions that civil engineers-built roads and bridges, and mechanical engineers designed cars. I'm not sure why I ended up choosing mechanical engineering, which I had no aptitude for, nor overriding interest in. Maybe it was because I had an interest in steam-powered locomotives and machinery?*

My next career step was starting my engineering support services business. I attained ASME-Geometric Dimensioning and Tolerancing Professional – Senior Level (GDTP-S) certification in 2005, then started teaching GD&T internationally to industry in 2006.

Engineer in Residence

The University of Manitoba's Price Faculty of Engineering recognized a deficit of design practice experience within the theory-driven foundations of North American engineering programs and recognized the benefits and value of bringing industry-based design experience into the Faculty. They introduced an Engineers-in-Residence (EiR) program as a bridge for integrating industry-based knowledge, skills, and practices in the undergraduate curriculum (Symonds and Britton 2012). Since the program's inception, EiRs have taught specialized courses, often in the broad realm of design practice, and supported capstone and cocurricular learning opportunities within the faculty. I held the designation of Engineer-in-Residence from 2016 through 2021.

You and your classmates never had trouble finding my EiR office, Aubrey … sometimes at two in the morning. I was fortunate that my office was next to that of Ron Britton, the originator of the EiR program. It's unfortunate that you and your classmates won't get to know Ron in person. Ron found a kindred spirit in my perspectives on engineering practice versus theory in education. I shared my backstory, and he shared his. Ron was surprised that I had not pursued graduate studies. Despite my insistence that no school would accept me this late in life, much less with my mediocre grades, he believed that my lived experience in engineering was exactly *why* I should pursue further studies. Before I jumped in, I unofficially audited Ron's grad studies course, *The Engineering Design Process* in the 2017/2018 session. Ron was lead author of a paper on the course in 2016, if you're interested (Britton, Ruth, et al. 2016). Anyway, the name was somewhat misleading; it wasn't about process, as I had thought, but rather it was about the philosophy of engineering. I was surprised that not only did I hold my own in discussions and classwork, but the registered students in the class frequently engaged with me about the interplay of life and profession. One of Ron's favorite topics was the difference between *doing* engineering and *being* an engineer; I have a copy of his book on this idea, if you want to borrow it; it's *On Design: A Philosophy of Design and Engineering* (2017). In Ron's view, my life experience in integrating engineering work and society meant that *I* was an engineer. After several sessions where students in his class had engaged me in such discussions, Ron expressed that the grad students, who represented the next generation of engineering, *also* considered *me* to *be* an engineer, and not just someone who does engineering work. If so, it was a generous compliment from them that still chokes me up a bit.

I started my graduate studies, and the road to this thesis, in September 2019. One of the courses that I undertook, *Teaching and Learning Engineering Design*, was customized for my interests and goals. I was to prepare literature reviews for five topics and, from them, draft a *Synthesis of a Personal Perspective on Mechanical Engineering Design Education* (Sykes 2019). In that final piece, I commented on my concerns about the EiR program that I was then still a part of:

> [The EiR program], however, has limited impact because the EiRs are not integrated into all design courses, capstone and co-curricular design projects and, overall, have limited exposure to the students as a result. …Put simply, the intrinsic *deep design knowledge* that EiRs provide is limited to their inputs requested at any given time, and by the timeline of their engagement. As a result, not all current students have the opportunity to benefit from the adaptive design expertise provided by today's EiRs, and future students will not have *any* opportunity to benefit from today's EiRs once the EiRs leave the faculty. (p4)

To be clear, it is my *opinion* that the EiR program's impact on student learning opportunities is limited in the context of overall broad exposure. However, it is also my *observation* that the EiR program has significant impact on the individual student(s) engaged in learning from the EiRs.

My involvement with the University of Manitoba EiR program was initiated by a corporate client of my GD&T training services. The client identified that Price Faculty of Engineering graduates had limited knowledge of several design skills critical to their sector, notably CAD drafting, and particularly in their understanding and application of geometric dimensioning and tolerancing. The client was concerned that significant time and resources were involved in training newly employed graduates in these technologies, and they were interested in helping the Price Faculty of Engineering provide enhanced learning opportunities in these fields. The client inquired as to whether I would be willing to teach these design skills in the undergraduate engineering program and proceeded to discuss the opportunity with the Price Faculty of Engineering's Centre for Engineering Professional Practice and Engineering Education (CE2P2E). Over the next six years, I taught a fourth-year mechanical engineering elective, Advanced Graphical Communication (AGC), for six sessions, including one online session during the COVID pandemic in 2021. AGC sessions included undergraduate and graduate students, and industry participants from companies that had partnered with the CE2P2E to fund the AGC course. The focus of AGC was the instruction and application of geometric dimensioning and tolerancing (GD&T) on student-created CAD drawings. In response to the feedback from industry, recent graduates and undergraduates, and depending on the experiences and needs of student and industry participants registered in each session, I added content on Fits-based tolerancing, surface finishes, etc.

As you recall, Aubrey, despite the content *of AGC being challenging and dull, you and your classmates generally found it one of the most engaging courses you had taken. I engaged you all with experiential learning as much as possible, using readily identifiable artifacts such as a deodorant container, a pipe cutter, a faucet, and such to demonstrate concepts. I incorporated anecdotes from my career and encouraged tangential discussions which led to a deeper understanding and appreciation of the value of*

GD&T specifically, and of design esoterica in general. One technique that you observed in class was that I would lead you all down the proverbial garden path*, point out the contradictions in your thoughts, then show you all how to sidestep the newly exposed contradictions. I tried to make the most boring subject relevant and engaging. Your understanding of the core GD&T content unfolded step by step, by intentional sidestep.*

Artifacts were important to understanding the concepts I taught in AGC. I used training kits with intentional imperfections exaggerated at a significant scale so that participants could readily see them. These coarse visualization artifacts (e.g., a flatness error of 7mm on a nominally flat surface, or a nominally cylindrical hole that looks more like a four-leaf clover) were effective at communicating the general concepts of geometric tolerancing, but they did not reflect tolerances at micron-scale. As mentioned previously, Fit-based tolerancing, and precision tolerancing in general, are in the micron and sub-micron ranges, typically below the unaided visibility threshold of 30-40 microns (i.e., 30-40µm, 0.03–0.04mm). Therefore, it is difficult to comprehend what a tolerance of 2.5 microns (0.0025mm) physically means because we have no experiential basis for comparison. There are some common items that I suggest for visualization at and above 10µm: a typical sheet of looseleaf paper is about 0.01mm (10µm) thick, and a common mechanical pencil lead is 0.5mm (500µm). Mechanic's feeler gages typically start at 0.03mm (30µm) or 0.05mm (50µm) thickness, which are still too coarse to appreciate the magnitude of precision tolerances.

In the winter of 2020, I had completed instructing the *core* content of my Advanced Graphical Communication (AGC) course just two days before the University of Manitoba announced that all remaining content must be delivered online. As was happening with the rest of the courses underway at the time, COVID-19 restrictions required me to pivot for my students to complete the coursework. The primary changes to my course were the removal of some *non-core* esoteric content, a complete restructuring of the final application-based assignment, and the conversion of the final examination for online delivery. The restructured assignment was adequate to evaluate students' GD&T application skills, and the examination results were strongly comparable to previous years. After completing the online examination, I provided students an opportunity to discuss the course. They expressed disappointment that the removed content included ASME Fit-based tolerancing and surface finishes, the latter of which would have included students using various artifacts (i.e., a set of surface finish comparators) to support their understanding.

Almost immediately thereafter, students requested that I provide something to occupy them as the summer session began and employment prospects were in question. I proposed a course or workshop that would include the missing AGC elements and other bits of esoteric design content that were not addressed elsewhere in the mechanical engineering curriculum.

As a result, during the early days of the pandemic, in June and July of 2020, I delivered an online Mechanical Design Skills Workshop (MDSW[iv]). Participants included undergraduate

[iv] MDSW was offered to the engineering public, with undergrads and graduate students, recent grads and experienced professional engineers participating remotely in Manitoba and Ontario, Canada. Content focused on design esoterica: device design breakdown – features,

and graduate students, recent graduates, and experienced engineers across Canada. MDSW content was essentially focused on design esoterica: material selection processes, tolerance determination, surface finish selection, and other elements. Unfortunately, students were still not able to engage with the various artifacts that I normally incorporate. For in-person instruction, I had a collection of artifacts that I could use to demonstrate to the students. Because of the significant uncertainty about the future of in-person engineering education, it was evident that the idea of a collection of artifacts that could be loaned to students for individual study would have merit.

My third teaching opportunity during the COVID pandemic lockdown was AGC, in the Winter 2021 session. For the most part, my in-person delivery style remained effective online, and students remained engaged and asked questions. However, recognizing the value of in-person experiential learning with group participation and accessing the same artifacts that I had used previously, I was able to include in-person tutorials with the class sectioned into groups and socially distanced, and with access to sanitized artifacts. This was made possible by an easing of pandemic restrictions. Overall, course outcomes were comparable to conventional in-person sessions. Students commented that access to artifacts was a significant factor in their satisfaction with the course and made them feel better prepared for employment.

Additional student-engagement responsibilities in my residency included annually advising several fourth-year mechanical capstone teams as they developed, documented and

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functionalities and interfaces; tolerancing - Fit-basis, manufacturing and other considerations; material selection; mechanical fasteners; surface finishes.

communicated solutions to single-semester design projects provided by industry partners. The value of deep design knowledge in supporting the capstone teams was recognized and I was asked to advise the first two-semester projects, which would include fabrication and validation requirements for the first time.

Throughout my residency, and after its completion, I advised cocurricular design/build/test teams in areas of design, fabrication, test, and operation. Also, during and following my EiR role, I coached engineering and commerce students on the Engineering and Commerce Case Competition Team (EngComm) on ideation, wholistic systems approach, sustainability, presentation, and other skillsets.

Through my EiR residency, I had discussions with engineering faculty and students locally, across Canada and the USA, and internationally. Just as I had no opportunity to develop an understanding of tolerances in my undergraduate engineering program three decades before, at Carleton University, I recognized that the same situation exists for today's students. As an international instructor in Geometric Dimensioning and Tolerancing (GD&T) since 2006, it became apparent that the lack of understanding of the physical meaning of micron-scale tolerances was global, and not limited to new graduates and early-career design engineers. As an industry-centric instructor, I had always taught a mixture of design, manufacturing, and metrology personnel. The negative impact of designers not understanding the tolerance values they applied was repeatedly made clear in conversations with machinists, inspectors, and assemblers.

Conversations and commiseration over common experiences and issues are natural human tendencies, and I recognize that comments may be skewed for dramatic effect. I enjoy a good rant as much as the next person; if done passionately, it's great entertainment! And yes, Aubrey, I know you endured some of my favorite rants in AGC, but they always delivered something meaningful! I also made sure you and your classmates had the time you needed to vent. Overall, I don't take what I hear as gospel, or even necessarily as literal, but I have listened for the general theme of comments. In that light, and from these engagements, I felt that there was a tangible link between what you, your classmates, and industry were indicating as their experiences, or lack of experience, with tolerancing.

Beyond the knowledge that students took away from our engagements, I took away an understanding of their student experiences with, and thoughts on, their engineering programs. Though more than twenty-five years separated their undergraduate education and mine, there was striking continuity of the feeling of being ill-prepared for post-education employment, particularly in practical design knowledge. While their programs had the benefit of visualization assists such as videos and simulation software, it seemed they had less opportunities for hands-on engagement with devices, systems, and learning artifacts that were used in my program. From my perspective, those elements missing from my students' programs had helped bridge theory and practice in my undergraduate program at Carleton University, and started my engineering cohort on our way to developing deep knowing.

Recognizing and Addressing Issues in Undergraduate Mechanical Engineering Education

My perspective is that the focus of undergraduate engineering education should be to prepare students to think, behave, communicate, and perform within the expectations of licensed Professional Engineers as established by regulatory bodies. I recognize that there are many career paths that new mechanical engineering graduates may follow; however, my principal interest is in students who are interested in mechanical engineering design careers. For those students, I believe that undergraduate engineering programs should imbue students with design knowledge and skills that they can immediately apply in industrial employment. Society is, by default, a stakeholder in all aspects of engineering, including education. Faculty and staff involved in engineering education are key stakeholders in engineering education because it is their livelihood. Private-sector employers, notably manufacturing industries, are stakeholders as employers of new mechanical engineering graduates. However, I have had occasion to feel that those stakeholders may forget that engineering students are not just products of the system, but also stakeholders in it as they prepare for their careers. I have designed as well as instructed and advised on engineering design in many industrial sectors that employ engineering graduates in engineering design roles. I have had discussions with personnel across engineering design and design-tangential roles including co-operative and internship students, new graduates, veteran designers, machinists, metrologists, assemblers, mid-level management, and executives. Reasonably, given my technical focus, few discussed "soft" skills[v] development in engineering programs, but rather focused on technical design and graphical communication skills that they have found wanting in new graduates.

These concerns reflected my own journey from graduation to engineering design practitioner and SME in several fields. Stakeholder commentary and my observations showed that today's graduates bring with them cursory knowledge of CAD (computer aided design) software, analytic software tools for stress and fluids analyses, and an eagerness to learn. In most cases, these same graduates have no knowledge of drafting practices and require employer-investment in training to develop productive skills in those same software packages. One persistently voiced concern of industry was the insufficient practical design knowledge held by new graduates, including tolerancing. Consistently over time, recent graduates expressed their fear that their lack of practical design skills would be discovered, and they anticipated negative impacts on their careers.

The Use of Artifacts in Tolerance Education

Almost anything can be a mechanical engineering design artifact if it is intentionally made to suit a purpose, but that does not mean almost anything will provide meaningful learning opportunities for undergraduate mechanical engineering students. But what makes an artifact an effective learning tool? Fortunately, there is some guidance to be garnered from the literature, and from shared and personal experiences.

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[v] "Soft" skills is the term historically, and commonly used to reference what some now referred to as "professional skills", including communication, negotiation, ethics, professionalism, engineering in society, etc.

For design guidance, I often turn to one of my editions of Machinery's Handbook (1996, 2020). The contents of Machinery's Handbook (MH), first published in 1914, are relied upon by design engineers and machinists alike for the stability and diversity of its content over time. My preferred reference for fit-basis tolerance determination, MH includes both ANSI B4.1 [inch] and ANSI B4.2 [metric] standard limits and fits; see Table 1.A for the ten ANSI B4.2 [metric] fit-basis functionality descriptions. Though these design standards have been in use for decades, Fit-basis tolerances are understood primarily as an abstraction because there are no physical demonstrators of the component interactions.

Here is the underlying issue: today, precision tolerancing is taught as a theory, with no physical cognizance of the magnitude of micron-scale tolerances, nor of the fit classifications themselves. Recalling the three elements that I identified as necessary for effectively understanding tolerancing (i.e., determining how parts mate, determining tolerances, and understanding what the tolerance values signify), I propose that a set of standardized artifacts can be designed which will help instructors, or be incorporated into independent learning modules, to provide students with relative and proximal cognizance of micron-scale tolerances, including demonstration of Fit-basis interactions.

Having outlined elements of my history that have led me to the study explored in this thesis, it is appropriate to summarize my reflexivity.

Statements of Positionality

My positionality toward the subject can be encompassed by the following statements:

1. I have always had a positive stance toward mechanical engineering design and the education of future mechanical engineering designers.
2. I have experienced that *better* is attainable when the *genuine will* to listen and to act is present.
3. I have had a varied career over 30 years which has led to attributed expertise in geometric dimensioning and tolerancing.
4. I have been actively self-reflective throughout my career to evaluate my own education and training against the expectations of my professional roles, and an awareness of where I obtained education informally.
5. I have translated this self-reflection into action to develop ways of thinking and doing to support my own learning and to share with emergent designers.

The evolution of my positionality is provided in greater detail in Chapter 3.

Chapter 2 Literature Review

In broad terms, this literature review reflects an exploration of three related themes:

1. Tolerance as design esoterica in mechanical engineering education.
2. Visual and somatosensory perception of small-scale magnitudes.
3. The role of artifacts in mechanical engineering design education.

First, I explore the evolving focus of engineering education in depth, and how a changing focus led to reduction in practical knowledge about tolerancing in mechanical engineering design education. Next, as the design elements of this thesis are focused on developing cognizance of micron-scale tolerance magnitudes for use in instructing dimensional tolerancing, I provide insights into how magnitude is instructed for conventional magnitudes. While those techniques have little direct application in context of the scale under consideration, they provide a starting point for addressing research into visual, haptic, and visio-haptic perceptions at appropriate scale, which is of direct relevance. Finally, the design and use of artifact in the instruction of mechanical engineering design is contemplated, including criteria for their design and use.

Tolerance as Design Esoterica in Mechanical Engineering Education

In simplest terms, mechanical engineering design tolerances prescribe the maximum allowable deviation from the ideal or perfect geometries of a feature on a workpiece, while still ensuring the workpiece will function as intended. Not every mechanical engineer needs to understand what an H8/f7[vi] tolerance represents. The same may be said for some mechanical *design* engineers, but for those mechanical design engineers who are responsible for releasing drawings for production, understanding the appropriate application of tolerances is critical. However, as the focus of engineering research and engineering education shifted from practice to theory (Sheppard, et al. 2009, Issapour and Sheppard 2015, Case 2016), the knowledge and skills required to appropriately *instruct* students on the application of tolerances to mechanical engineering design work were eroded (H.-C. Zhang 1997, Pegna, Fortin and Mayer 1998). Where knowledge of tolerancing was a mainstream component of mechanical engineering education, it gradually shifted to being an element of design esoterica.

Design Esoterica in Mechanical Engineering Curricula

Beyond the textbooks that I retain from my undergraduate engineering studies, I collect reference materials as they become relevant to my design work or to my personal interests, and I have been fortunate to be gifted still more materials by mentors and an uncle who preceded me in the profession by up to a half-century. The text that served as the backbone for the undergraduate machine design course that I completed was Shigley & Mischke's *Mechanical Engineering Design, Fifth Edition* (Shigley and Mischke 1989). *Shigley's Mechanical Engineering Design, Eleventh Edition*, was released in 2020 (Budynas and Nisbett 2020), and a comparison of its contents shows no significant changes to the theoretical nature of the resource. For design's more practical aspects, its esoterica, I have collected reference materials

[vi] H8/f7 specifies a Close Running Hole Basis metric fit per ANSI B4.2-1978 (ASME 1978)

such as Machinery's Handbook 25 (1996) and 31 (2020), DIN standard 509 (DIN 1998), fastener selection cards, finish comparison standards, and others.

In my experience, and as told to me by others, mechanical design esoterica are generally not taught in core mechanical engineering design courses, relying instead on future employers to provide training in the relevant esoteric details. It was not always this way. As follows, I will demonstrate how the focus of engineering education has swung as a pendulum between the extremes of empirical and theory basis.

Initially rooted in practice, engineering education curricula introduced foundational theories as the first shift towards a theory-based curriculum in engineering education (Sheppard, et al. 2009, Issapour and Sheppard 2015, Case 2016). This change was driven faster and further by the need for radical advancement during the late Industrial Revolution, World War II, and the Cold War (Issapour and Sheppard 2015, Case 2016). Industry, the largest employer of engineering graduates, made its voice heard again (Issapour and Sheppard 2015) and the current shift toward balance began with the new millennium as design took primacy of place in North American engineering education, directed by respective engineering education program accreditation boards (Issapour and Sheppard 2015, Case 2016).

In the early days of engineering education, before scientific theory and process suffused into engineering education, instructors would have been experienced practicing engineers. As the focus of engineering education shifted toward the sciences, those same science faculties became the source of new engineering instructors (Case 2016). Implicit with this change of instructor credentials, instructors' practical design knowledge and skillsets became less valued until engineering design was largely seen as a primarily theoretical exercise.

Inevitably, the practical design knowledge held by engineering instructors would have trailed these changes. Crawley et al. (2014) summarized the issue present in many engineering faculties, and steps needed to improve the education opportunities of students:

> There is little reason to expect a faculty that has been recruited as a cadre of researchers to be proficient in many of the skills of engineering practice. And there is no reason to expect that these faculty researchers would be able to teach these skills. Therefore, if we are to successfully support student learning, we must develop approaches to enhancing the skills of engineering faculty. Likewise, faculty have, by and large, been educated using pedagogical styles based on information transmission, such as lectures. If we are to develop a learning-focused education, which relies on active and embedded learning, current faculty must be supported in their personal development and use of these techniques. In both cases-engineering skills and teaching-the transformation will be broader and more effective if there is a well-planned effort to build faculty competence, by bringing individuals with this background to the team and enhancing the competence of the existing team. (p38)

The result, arguably, is a recognized lack of significant design practice and practical knowledge in engineering education today, and, by extension, few elements of design esoterica enter the curriculum. There was, however, some literature dealing with the teaching aspects of geometric dimensioning and tolerancing (Gust and Sersch 2020, Rong 2017, Rios 2018, Sun, et al. 2014, Devine 2012).

Tolerancing as Esoterica in Mechanical Engineering Design

Geometric Dimensioning and Tolerancing[vii] (GD&T) is a symbol-based language developed for use on mechanical engineering drawings to convey the design intent (i.e., the functionality), of every feature on a workpiece. GD&T controls four characteristics of each feature: location, orientation, size and form. GD&T standards instruct how to control the four aspects, but do not provide any guidance on tolerance value (i.e., magnitude) determination. In my experience, there are three elements of effective tolerancing-instruction: (1) determining mating feature engagement functionalities, from which the ASME Fit-Class[viii] is determined, (2) calculation and apportioning of tolerance into the four aspects as necessary to attain the required functionality, and (3) understanding what the tolerance values signify. Of these three, literature (Turner and Wozny 1990, Voelcker 1998, H.-C. Zhang 1997) only considers the second element, the apportioning of the tolerance, as a focus of instruction and research, with the anticipated result that while students can calculate tolerances (Rong 2017), I found no mention that students understand what the numbers mean in a practical, physical sense.

There was a surge of research into dimensional tolerancing in the late 1990s, resulting in a number of published papers (Nassef and ElMaraghy 1997, Pegna, Fortin and Mayer 1998,

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[vii] Because of my experience in the instruction and application of the 1994 and 2009 revisions of the American Society of Mechanical Engineers (ASME) Y14.5 Geometric Dimensioning and Tolerancing standards, the ASME Y14.5-2009 standard will be referenced unless otherwise specified.

[viii] Of the four geometric characteristics, ASME Fit-basis tolerances only address size of the features.

Turner and Wozny 1990). This coincides with an observed improvement in CNC (computer numerically controlled) manufacturing and CMM (coordinate measuring machine) inspection technologies, and the release of the 1994 revision of the ASME Y14.5 GD&T (1995) standard. There was a small resurgence in publications on the topic of tolerancing in the late 2010s (Colosimo and Senin 2011, Walter 2019, Devine 2012, Rao and More 2014) which focused primarily on automated calculation and apportionment of tolerances. The latter publications were generally not relevant to my research.

Engineering Education – A Brief History for Context

To appreciate why specialized tolerance-instruction artifacts are needed in mechanical engineering education, I will first outline how engineering education came to its current state.

Grayson (1993) effectively conveys that, over its history, the focus of engineering education has shifted. France's military *Corps de Génie* (Corps of Engineers) (1676), initially trained its members under the apprenticeship model (Grayson 1993). To formalize training for design and construction of military engineering structures such as fortifications, canals, and bridges, France's military established the first permanent engineering school, *Corps des Ponts et Chaussées (Corps of Bridges and Roads)* (1747), and included a parallel civilian curriculum funded by the French government (Grayson 1993). Renamed as *École Nationale des Ponts et Chaussées* (National School of Bridges and Roads) (1775), and using the apprenticeship model, it is considered the first formal engineering school (Grayson 1993). Following the French Revolution, Napoleon created the *École des Travaux Public (School of Public Works)*, addressing public and industrial needs, and based on a polytechnic model which combined formal study and practical application (Grayson 1993). Renamed the *École Polytechnique*, it was the model for some early engineering schools in the United States. However, Britain's apprentice-engineer training model was adopted across most of the Commonwealth, and by the late 1700s it was adopted in the United States (Case 2016). Experiencing growth due to the Industrial Revolution, apprentice-engineering education for industrial applications was funded by individuals, rather than governments. Both systems, Polytechnic and apprenticeship, focused on the development of practical skillsets based in empirical knowledge, while the updated Polytechnic model included engineering sciences as a theory-centric anchor for the practical skillsets (Case 2016). It is reasonable to anticipate that, for mechanical engineering education, this meant that students would inevitably develop a physical understanding of how mating parts would interact statically and dynamically. By the late 1700s, the United Kingdom, France, Germany, Hungary and Turkey had their own structures for educating engineers (Case 2016). At the *École Polytechnique*, skills-apprenticeship persisted alongside formal academics until Germany's technological superiority led to the defeat of Napoleon in the Franco-Prussian War of 1870. This shifted the focus of France's Polytechnic engineering education away from application, toward theory.

In early 1900s' North America, scientific research was elevated as the driver for progress in society and industry (Case 2016). New materials, processes, mechanisms, and energy sources were sought, and engineering research funding became dominated by government grants which favored advancement of engineering theory over practice. Then, as the world industrialized and electrified, the Great Depression (1929-1939) curtailed North American governments' research funding capacity and caused funding for engineering research to shift to industry (Issapour and Sheppard 2015). Thus, the focus of university research and education shifted in response to industry's needs, a focus that was largely application based. Shortly, with the accelerated militarization of World War II, research again shifted, focusing next on the development of new materials and technologies, and again military and government funding overshadowed industrial investments in research (Grayson 1993), and continued post-World War II as western nations were determined to fortify their military dominance throughout the Cold War. In mechanical engineering, analytical models for static and dynamic systems were developed and theoretical models of thermodynamics evolved, rooted in and reflecting empirical reality. With each shift in research funding and regional priorities often rooted in geopolitical objectives, the focus of engineering education followed. Whereas experiential learning in shops and laboratories had long been critical elements of undergraduate engineering education, the shift to an academic focus resulted in the removal of student-accessible machine shops (Lamancusa 2006) from most mechanical engineering programs in North America and the progressive reduction in hands-on laboratories to the point where many students' pandemic-restricted experiences in 2020 included running electronic simulations (Javaid, et al. 2021, Allen and Barker 2021) and, as recounted to me by students, remotely observing a lab technician operate equipment and call out observations for undergrads to record, and take-home lab toolkits. I was heartened to see the creative methods that instructors used to sustain the current level of laboratory experiences and deliver a meaningful learning opportunity to their students.

Around the time that I was studying engineering in the late '80s to early '90s, industry was making the engineering profession aware of their concerns about the state of design in the engineering curriculum (Sheppard, et al. 2009, Issapour and Sheppard 2015). In response, the engineering profession in North America recognized that practical design knowledge and skillsets had declined as theory-based knowledge became the focus of undergraduate engineering education. In a late 1990s education shift, engineering education accreditation programs directed a greater emphasis on experiential learning of design throughout the curriculums (Issapour and Sheppard 2015). Where historically engineering accreditation boards had supported an inputs-based system focused on meeting the ever-shifting needs of national interests, the next shift in engineering curricula was to reflect an attribute basis. In 2000, ABET (USA Accreditation Board for Engineering and Technology) transitioned to an attribute system, followed by the Washington Accord and its signatories, including Canada (Case 2016).

As in all things, change of both funding and focus in engineering education is inevitable. In *The wisdom of winter is madness in May,* Cheville et al. (2019) discuss the evolution of thinking and historical expectations on engineering education in the United States, and proffers that it is headed to online and micro-credentialed offerings. These are already available from industry and open-access education services to some degree; however, the number of offerings is growing rapidly due to the ability to offer specialized content at whatever level the user needs, introductory through expert. Some institutions have been increasing their online and independent-study course offerings since the 1990s (Petre, et al. 1998). By 1998, Petre et al. had identified that the content from in-class instruction could not simply be "translated" for online use; rather, it must be rethought to reflect the benefits and limitations of the medium. The Cheville et al. guest editorial (2019) highlighted imminent changes to engineering education influenced by the demands of upcoming students as they prepare for their industrial futures. Little could Cheville et al. have anticipated the urgency that their guest editorial of April

2019 foreshadowed to the changes that would befall engineering education as the COVID-19 pandemic necessitated an emergent shift to remote learning less than a year later.

By late 2021 and early 2022, research, articles, and editorials by Manierre et al. (2022), London et al. (2022), and others, addressing accommodations and changes to pedagogy began appearing. However, they didn't directly address translating versus rethinking content during the rush to shift online at the start of the pandemic shutdown. Though a small study, Manierre et al. (2022) found that most of their subjects did not make significant changes to their pedagogy. They wrote (2022), "Four instructors we interviewed did not make substantial changes to their pedagogical styles because changes were not necessary to continue effective teaching and still achieve established learning outcomes" (p900). I would argue that most instructors did not have time, between the realization of the significance of the COVID-19 pandemic in the last weeks of 2019 and the shutdown in March 2020, to restructure all course content for effective online delivery. More problematic, the labs, teaching artifacts and co-curricular activities that provided students with experiential learning opportunities were made largely non-viable or less effective and instructors had to scramble to find ways to replace them with online visuals and demonstrations.

Arguably, the specialized knowledge and skillsets required for the diversity of industry employment opportunities for engineering graduates cannot all be addressed with conventional course delivery. Self-directed learning (Crawley, et al. 2014, Abellan-Nebot; 2018, Ulseth and Johnson 2017, Marra, Hacker and Plumb 2022), however, has the potential to provide on-demand instruction when and where needed by the learner, and therefore, as indicated by Petre et al. (1998), delivery content and media must be rethought to meet these new opportunities. Crosslin et al. (2018) quote Kop and Fournier (2011), "*The goal of any course should be to push learners into a place of learning how to learn about the course topic, so they can become self-directed learners*" (p7). Per Crosslin, conventional classes are instructor-lead, an approach that puts the instructor, rather than the content, as the center of the knowledge. This means that the instructor must remain available for supported learning, rather than the learners depending on the content. The authors (Crosslin, et al. 2018) add, *"... learners don't need you to just convey a bunch of factoids that they can look up online or in a book. They will want you to show them how to take control of the overall direction of their learning, something that is often referred to as 'self-directed learning'"* (p9). From this, Crosslin et al. support a constructivist model wherein learning is self-determined but guided, and offer three teaching methodologies: pedagogy as an instructor-centric method; andragogy centered on the learner's life experiences and knowledge as the basis for further learning; and, heutagogy as a self-determined learning, centered on how to learn rather than what to learn. Theoretical, formulaic, and algorithmic content needs to be rethought to provide an engaging experience, whether being taught in a conventional setting, or using the new media. The all-knowing instructor and their personal teaching artifacts may not be present to support remote or independent learning, and therefore standardized teaching artifacts must be integrated into the content and made available to the learner. One further aspect considered by Crosslin et al.

(2018) is the importance of the openness of the course content and incorporated artifacts to usage by all, including those with disabilities or different capabilities and capacities[ix].

Teaching and Learning of Dimensional Tolerancing

Walter (2019) provides a high-level history of the development of tolerancing technologies from the early craftsmanship period of industry where each piece was individually fit to its mating components, and thus designed without consideration of tolerance, to ongoing tolerance optimization via evolving algorithms and ever-increasing computing power. Devine (2012) includes some of today's emerging trends in tolerance engineering: a holistic approach to tolerancing which encompasses environmental impact and human factors, the use of AR/VR for tolerance visualization, and tolerances for additive manufacturing. In *Advanced Tolerancing Techniques*, Zhang (1997) recognizes the changes in mechanical engineering education that progressively removed instruction of dimensional tolerancing techniques from the curriculum, to the detriment of industry: "...[T]he ignorance involving tolerancing techniques in engineering colleges has created problems in today's manufacturing industry" (p xii). Commenting on the status of GD&T in the curriculum, Zhang (1997) adds, "Most engineering professors know nothing about GD&T, many view tolerancing as picky or boring or both, and there is no strong industrial pressure to teach GD&T" (p6). Pegna et al. (1998) support the narrative that tolerance selection methodologies have been historically poorly understood, and this condition

[ix] This is included in Considerations for the design and use of artifacts of design esoterica in mechanical engineering education, later in this document.

worsened by engineering education's shift from practical to theory basis. Pegna et al. (1998) expand on this with a quotation from Gabriele et al. (1994):

> Historically, the task of setting product design tolerances, which can commit as much as 80% of the cost of manufacturing and maintenance of a product, was often left to the draftsman who generally acquired competence over decades of trial and error. The absence of formal education in the engineering curriculum led engineers to consider this critical task as a black art. In design education, matters were made even worse by a move of the curriculum toward more engineering science and less engineering practice [(Gabriele, et al. 1994)]. (Pegna, Fortin and Mayer 1998, p428)

As established in *Advanced Tolerancing Techniques* (H.-C. Zhang 1997) and by Pegna et al. (1998), when tolerancing is taught in a mechanical engineering program, or when it is a topic of engineering research, it is the schema of formulae and algorithms for calculating tolerances that is the focus, rather than an understanding of the underlying significance of the tolerance and resulting functionality. In other words, the focus is on the "*how*", rather than an understanding of the "*why*". Given that, by the early 1900s, the focus of undergraduate mechanical engineering education had started to shift to a focus on engineering science, it is understandable that professors, educated under that focus, would teach only what they know and are comfortable with: the theories of tolerancing. Worse perhaps, because it drove instruction ever further away from practice and toward theory through the 1990s, any postsecondary focus on GD&T was on research rather than on instruction. Pegna et al. (1998) noted, "…Geometric Dimensioning and Tolerancing (GD&T) has gone from black art to the forefront of computer aided design research. Despite this prominent position in industrial and academic research, GD&T is seldom taught in universities" (p428).

Seldom taught, indeed, yet Devine (2012) references literature establishing the manufacturing sector's need in engineering graduates tolerance interpretation skills, noting "the literature is replete with work indicating that engineering and engineering technology students should receive instruction in the area of tolerancing concepts" (p7), particularly in the area of GD&T. Devine cites papers covering various course developments and restructurings to address the interpretation and verification (inspection) of tolerance callouts through the inclusion of CAD tools to simulate inspection, as well as coordinate measuring machines (CMMs) and handheld measuring devices to inspect workpieces. Of these, Devine (2012) concluded that using the common hands-on measuring devices "seemed to ground the abstract tolerance concepts into knowledge that students can better understand and use" (p12). Student performance and feedback suggest this "back to basics" experience was positive and improved their understanding of dimensional tolerances. Though not distinguished in the study, the visual appreciation of the tolerance would have been an evident benefit to this developed understanding. The obverse perspective to Devine's course restructure, wherein the interpretation and verification of tolerances is critical in its reflection of manufacturing's needs, is that of the designer who must, with an understanding of the scale and significance of a tolerance, apply appropriate tolerances to the engineering drawing. Furthermore, the tactile aspect of a tolerance gives the designer both physical and cognitive "*feel*" for how components will interact, an important element in a designer's understanding and confidence in their tolerance determinations.

Experiential Learning of Tolerancing

A three-article literature review by Morse and Dandu (2011) indicates the incorporation of experiential learning of tolerancing in design/fabricate/verify courses in the early years of engineering programs starting in the 1990s and into the 2000s. Hoadley and Rainey (2007) discuss three freshman lab courses focused on machining, casting and welding processes. Students collaboratively process-plan and machine two projects. Ferguson and Berry (1995) discuss a two-course approach to concurrent engineering design starting in the junior year, which includes use of their state's educational manufacturing resources. Ray and Farris (2000) discuss the introduction of a freshman course comprising instruction and labs in 3D solid-modelling practices and the realization of their designs by instruction and use of basic manufacturing technologies. Coursework included fabricating workpieces that must assemble, requiring the application and verification of dimensional tolerances to ensure that parts mate appropriately. Such courses sought to address the (Morse and Dandu 2011) "challenge for beginning mechanical designers [to] make judicious decisions on appropriate design tolerances" (p2) through awareness and experiences early in their education. From their freshman course, Morse and Dandu (2011) found the students' zeal for perfection lead to unnecessarily tight tolerances in the design and fabrication, suggesting perhaps that the students did not appreciate the functional nature of the tolerances as may be developed through visio-haptic evaluation of the functionalities. Interestingly, Morse and Dandu (2011) observed that, when students evaluated others' designs for production, they readily identified specified tolerances that were inappropriate and non-producible with available resources. This suggests that a robust understanding of tolerance application should include an understanding of its producibility by various technologies. Furthermore, Morse and Dandu (2011) found that class participants applied the tolerance-selection considerations from this experiential class to subsequent design projects, and that local employers reported (Morse and Dandu 2011) that "[s]tudents have a firm enough grasp of practical tolerancing to begin to apply these concepts to design and production judgments in their part-time jobs in local industry" (p11). Though such courses are hands-on, meaning that students will handle the parts and measure them, there is no indication that intentional visio-haptic engagement with the workpieces was an instructional focus.

Approaches to Teaching GD&T

The literature discusses various approaches to teaching GD&T. Gust and Sersch (2020) reviewed teaching approaches for GPS (Geometrical Product Specifications), the ISO version of ASME's GD&T (Geometric Dimensioning and Tolerancing).[x] They established four instruction-basis groupings; literature, e-learning, seminars, and university courses. Of these, Gust and Sersch (2020) determined that literature was most effective for understanding theories of GPS, whereas seminars were effective for instructing skilled personnel. Within these delineations, only seminars and university classes offer any function-based, physical context of the geometric tolerances, and then only in a metrology environment. Pegna et al. (1998) compared two approaches, conventional and reverse-engineering instruction, both following similar

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[x] The core distinction between ISO GPS and ASME GD&T is the intent of the language. ASME GD&T, from which the original ISO GPS standard evolved, is rooted in conveying the functionality of each feature on a workpiece. ISO GPS, on the other hand, focuses on a rules-based definition of each geometric control. In other words, ASME is based on physical interactions of features whereas ISO is based in mathematical definitions, or theoretical equivalents, of features.

approaches for teaching the fundamental concepts of GD&T. They indicated that École Polytechnique de Montréal's approach to teaching tolerance selection was based on analyzing drawings to determine component interactions, whereas Rensselaer Polytechnic Institute's approach was experiential wherein students disassembled systems to determine component interactions. By 1997, Voelcker (1998) identified that CAD systems already allowed advanced modelling of mechanical components as ideal geometries; that is, geometries of perfect size, location, orientation, and form, the four characteristics controlled through application of GD&T. He (Voelcker 1998) notes that tolerance selection was largely sourced from two centuries of design practice, derived from machine shop practices, which is to say they were empirically derived from historical machining processes and aggregated capabilities. Such is the foundation of ASME and ISO Fit-based tolerances[xi]. As Voelcker (1998) notes, historically there were no mathematical bases for the tolerances applied to a design. In his historical review, he identifies the need for mathematical definitions of geometric tolerances was evident in the 1980s and discusses worst-case versus statistical tolerancing approaches. Rios (2018), recognizing the common difficulty of students' necessary visualization of 3D geometric tolerance zones, describes the use of large-scale additive-manufactured (AM) parts to demonstrate various GD&T concepts. Rong (2017) describes a succession of courses that he used to develop an understanding of tolerance classes and their application. Starting with a drafting course, students develop an understanding of the functionalities and mating requirements of each feature on each component. The project work and knowledge of functionality from that first

[xi] ISA Bulletin 25 (1940), ISO 286 (1962) based on ISA Bulletin 25, ANSI B4.1 (1967) [inch], ANSI / ASME B4.2 (1978) [metric] based on ISO 286.

course are carried forward to the second course, wherein tolerancing principles are instructed. Based on the functionality, manufacturing process capabilities and other considerations, students select appropriate Fit-Class designations, and then standards-based tolerances for each feature. Rong (2017) asserts that, "[a]t this point the students also really mastered the choice of tolerance with the method" (p21). Huerta et al. (2019) identified six aspects of technical drawings, delineating them into modules for development of AR/VR content and animations; four modules were tolerance-related. Humienny and Berta (2015) discussed a new concept of teaching ISO GPS via computer simulations and animations, considering it appropriate for open and distance learning.

Overall, these efforts largely focused on calculations, or theory of tolerancing, with a few including visualization elements, which were typically not reflective of the micron-scale of the tolerances being used. The various approaches and simulation technologies indicated improved student engagement in the learning activities or were otherwise considered by their authors as effective means of instruction. However, given the descriptions of the content and methods applied, it would be apropos to ask whether the students had a greater sense of tolerance application, or merely an ability to follow rules and formulae. More succinctly, did the students have a physical appreciation for what the tolerance classes physically represented for component interactions, and did they have any perception of the scale magnitude of the tolerances they were applying? These are not facetious questions; in my experience, the Fit-Class definitions remain nebulous to most engineers long after graduation. None of these approaches intentionally included visio-haptic aspects of these Fit-Classes and micron-scale tolerances, and therefore did not effectively correlate the Fit-Class and the physical magnitude of the tolerance.

The Focus of Research in Tolerancing

What does the literature tell us about the focus of research in tolerancing, and what does this mean for teaching tolerances to the next generation of engineering students? In a 2002 comprehensive review of some 270 research papers over a span of 30 years, Hong and Chang (2010) classified existing tolerancing research into seven categories with the sole focus on tolerances as abstract numbers with no consideration of the relevance of visual or haptic understanding of the significance of tolerances in the design process. This is not unique. Indeed, Rao and More (2014) identify that design tolerances are "an informal compromise between functionality, quality and manufacturing cost" (p1), and propose an optimization algorithm to determine an optimal tolerance selection. Nassef and ElMaraghy (1997) identify that tolerance allocations in the literature typically focuses on minimizing manufacturing costs, and that same literature focuses largely on conventional plus/minus tolerancing schemes. Further, they correctly identify that this approach to geometric tolerances is problematic in that geometric tolerancing offers multiple ways to achieve similar but slightly different results. Their solution (Nassef and ElMaraghy 1997) is to focus on "mismatch probability" (p106) and "genetic algorithms to reduce the probability of rejecting good parts or accepting bad parts" (p101) as new criteria. Giving a nod to the practical nature of tolerancing, Nassef and ElMaraghy (1997) concede that "[t]he proposed algorithms do not completely exclude the use of the expertise of tolerance designers" (p106), particularly in the selection of the specific geometric control to be applied. Sun et al. (2014) identify a need to reform a "mechanical precision design and testing[-

based]" (p1) course to reflect an escalating need for precision engineering as manufacturing shifts from high-volume/low-variety to low-volume/high-variety production. As regards the "precision" elements of the course, they (Sun, et al. 2014) propose that existing content be abstracted, and content not directly related to the theme of precision should be deleted. In this light, the proposed reformation appears to remove any aspect of physical appreciation of tolerances in preference for the abstraction of tolerancing as a purely numeric concept. The book, *Geometric Tolerances* (Colosimo and Senin 2011), explores the impact of geometric tolerances on design, metrology, and statistical process control in manufacturing. *Part I - Impact on Product Design* (Armillotta and Semeraro 2011) focuses on total tolerance determination, and (Polini 2011) distribution of total tolerances to its constituent geometric controls. Tolerance values, and how they are apportioned for the four aspects of features (location, orientation, size and form) are critical; they impact the cost, functionality, and even lifespan of workpieces. Understandably, tolerance calculations should be a focus of research. Some of that research may bear fruit for improvements in manufacturing and in precisely defining product lifespan. Unfortunately, as each generation of researchers becomes instructors, we move further away from instructing undergraduates on why a particular tolerance Fit-Class should be chosen and away from what that tolerance physically represents at micron-scale. Revisiting the 1990s-onward focal shift of engineering accreditation boards on practice and design (Issapour and Sheppard 2015), it seems the absence of a link between instructing a robust perspective of theoretical and practical aspects of tolerancing in support of research into tolerancing technologies, is a missed opportunity to contribute to meeting accreditation guidance.

Visual and Somatosensory Perception of Small-Scale Magnitudes

The human eye has a vision threshold of 30 to 40µm (Deering 1998). How, then, can smaller magnitudes be physically understood by design engineers?

Teaching Scale - How Small is Small?

Jones et al. (2008) compared novice and experienced teachers' concepts of spatial (dimensional) scale from nano to cosmic. They found that while both groups most accurately grasped human scale, and both more accurately grasped large scale than small scale, experienced teachers better understood nanoscale than novice teachers. Most critically, they recognized that direct experience with objects and distances influenced perception of scale. Preceding studies (Tretter, Jones and Andre, et al. 2006, Tretter, Jones and Minogue 2006) on how students (middle and secondary school) learn about size and scale, found students hold distinct, distinguishable categories of size, and that comparative size was more easily grasped than absolute size. Most relevant, they found that physical engagement of objects increased the students' spatial appreciation of the size and scale. Collectively, these three studies (Jones, Tretter, et al. 2008, Tretter, Jones and Minogue 2006, Tretter, Jones and Andre, et al. 2006) suggest that instruction of micron-scale linear dimensions would be aided by incorporating artifacts for two elements; one, a comparison of known or understandable entities near the same scale; and two, samples that physically exemplify the scale.

Jones and Taylor (2009) studied adult professionals for personal historical experiences learning scale. They related professional domain with importance of scale in their work including applications and types of scale, and tools used in their work. Jones and Taylor (2009) found that professionals used relatable anchor points as a scaling strategy: "These anchor points served critical roles as quick mental benchmarks that composed the individual's sense of size and scale. Anchor points were rooted in repeated experiences and in many cases were analogies or models for formal English or metric measurements" (p468). Some anchor points represented specific sizes, while others represented approximate sizes, but they all stood as the defacto standard for other measurements, particularly through repetition. The study found that in-school understandings of scale were often related tools of measurement and science, whereas out-of-school experiences with movement tended to develop a sense of scale, observing that objects became larger/smaller as they moved closer/farther. Though not indicated in the Jones and Taylor study (2009), a haptic or visio-haptic detection of movement at micron-scale should have the same effect as larger-scale movements. Jones and Taylor (2009) considered participants' thinking about scale, finding automaticity and visualization were important elements. Over time, using and changing scale became automatic, and participants mentally visualized their work at the different scales relevant to their work. This is an expected outcome from visio-haptic incorporated tolerance artifacts.

The Engineering Research Focusing on Haptic and Visio-Haptic Inputs

Though engineers experience the physical world through a combination of senses, each engineer's perception is unique and not easily communicated. Gow et al. (2007) noted that, "With most physical systems, our understanding of them comes from some combination of visual, aural, and tactual information. The tacit knowledge gained through such physical interactions is not easily shared between individuals but thought to be valuable for the process of engineering innovation" (p1). We constantly and unintentionally combine our senses, but sometimes we need to rely on specific combinations to garner specific information. ASME B4.2 metric Fit-Classes characterize component interactions into three categories (clearance, transition, interference), which yield ten Fit-Classes (recall Table 1.A ASME B4.2 Preferred Fits (ASME 1978)) from free running to force fit. For clearance Fit-Classes, which ensure a gap between two nested components, the gap range specified per the ASME B4.2 can vary from 16μm (0.016mm) for a locational clearance fit of nominal Ø1mm features, up to 800μm (0.8mm) for a clearance fit of nominal Ø500mm features. The visibility threshold of the human eye is about 30 to 40μm (0.03 – 0.04mm) (Deering 1998). Therefore, for many of these Fit-Classes, the gap will not be quantifiable with unaided vision, and for most, any deviation from those gap limits is likely to be undetectable by vision alone. Similarly, a micron-scale step on a surface may be visually detectable, but not large enough to visually quantify. Kinesthetic awareness of the spatial position and even miniscule movements of the parts of the body is accomplished by means of sensory organs (i.e., proprioceptors) in the muscles and joints. Haptic response of proprioceptors in the fingers and visio-haptic inputs seem particularly useful in physically comprehending the feel and scale of Fit-based tolerances.

Engineers often look to nature's elegant solutions for inspiration. Understandably, research into how natural design and evolution have allowed the human finger to "feel" it multiple ways will be followed by research into duplicating the sense of "feel" in synthetic systems. Following, I have divided relevant literature on haptic and visio-haptic sensations into two fields: physiological mechanisms of somatosensory systems in fingertips, and biomimicry for robotic systems.

Haptic Response of Proprioceptors in Fingers

Within the broad somatosensory system, proprioception (sensation of body motion and position) relies on the nerve endings of muscles, skin, joints, tendons and other tissues to provide information to the brain to convey spatial location and movement of any part of the body (Tuthill and Azim 2018, Birznieks, et al. 2009). The human fingertip is loaded with proprioceptors in the connective tissue attached to the fingernail, as well as the pulp and dermis of the finger pad (Birznieks, et al. 2009). Of concern in my work is the ability to sense micron-scale linear distances and micron-scale movements using the fingertips of a human hand. More specifically, experientially, both the leading dorsal edge of the fingernail and the ventral pad of the fingertips are effective in sensing minute changes in topology or movement, though with different context sensitivities. Detection of micron-level static distances is easily achieved by dragging the dorsal edge of the fingernail unidirectionally from the higher surface to the lower surface. Finger pads are sensitive to small dynamic movements, but less sensitive to static distances than fingernail detection. While literature (Tuthill and Azim 2018, Birznieks, et al. 2009) reflects that proprioception perceives a distance of movement, research on proprioception in the finger tip (nail and pad) has focused on detection of pressures or forces in proprioceptors (Birznieks, et al. 2009, Blanchard, et al. 2011, Gao, et al. 2019, Seah, et al. 2013). Still, both pressure and force can be related to displacement. Therefore, while we do not have threshold detection forces, and therefore threshold displacement values, the extension of somatosensory to detect micron-scale magnitudes, as experientially verified, is reasonable.

The reader can gain an appreciation of the relative sensitivities by conducting two simple demonstrations: first, with a sheet of loose-leaf paper, then with a rotatable doorknob.

Demonstration A: Place the sheet of paper on a rigid surface, then gently drag the dorsal edge of their fingernail over the edge of a standard sheet of loose-leaf paper, thereby detecting a change of approximately 10µm (0.01mm). Next, gently drag the pad of the finger over the edge of that same sheet of paper. You can easily perceive a greater "significance" in the thickness of the paper with the fingernail than with the finger pad. See Figure 2-1.

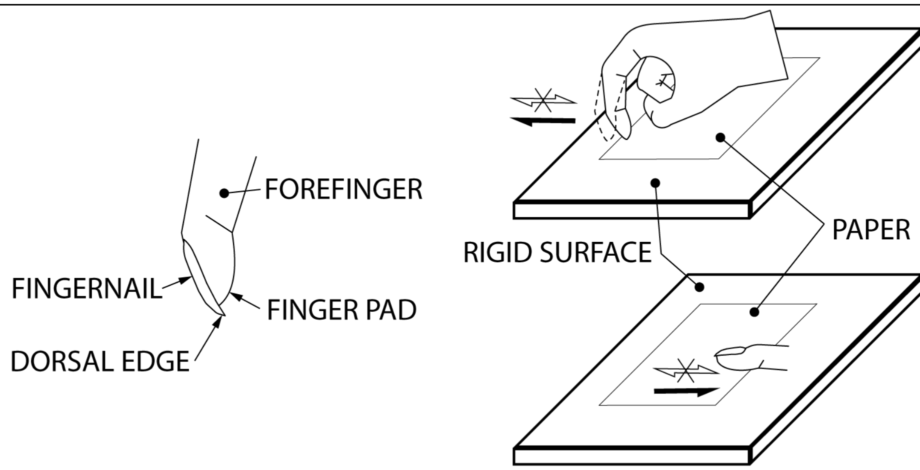

Figure 2-1 Demonstration A

Demonstration B: Use the leading edge of the thumbnail and forefinger nail to engage at diametrically opposite locations on a doorknob, then try to detect any motion in the doorknob as you move it up and down, in and out. Next, try the same gently using the pads of the thumb and forefinger. With the fingernails, you may detect something, but with the finger pads, you will more likely detect a slight shift radially and axially and may even detect the slight yaw that will be present. See Figure 2-2.

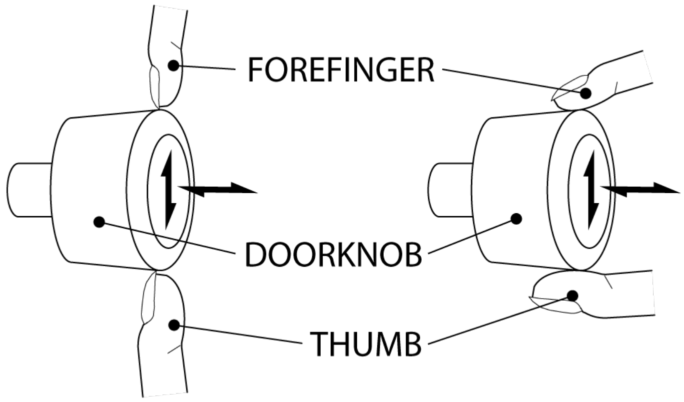

Figure 2-2   Demonstration B

Birznieks et al. (2009) investigated the response of SA-IInail (*SA-2-nail*) afferents surrounding the fingernail walls, finding these nerve fibers not only detect forces applied to the fingertip, but also resolve vectorial force direction. Furthermore, Birznieks et al. (2009) reported that the SA-IInail afferents were less impacted by tactile features of the contacted surface than afferents in the volar skin which contacted the objects, and therefore the signals of the SA-IInail afferents contained less noise. As regards handling objects using the finger pads, this means that the presence of the fingernail is important to accurately sensing holding force magnitude and direction.

Another study, by Seah et al. (2013), compared nailbed sensitivity for comparable static and mobile forces applied to the dorsal surface of the fingernail and to the finger pad. They found that the two were comparable in force detection, and that the finger pad was more sensitive to transient load.

Though neither Birznieks et al. (2009) or Seah et al. (2013) addressed the sensitivities of the nailbed or nail wall afferents for loads applied to the tip of the fingernail, an extrapolation of this higher-quality signal from the afferents in the nail walls, as compared with those from the finger pad, would suggest that direct application of forces to the nail tip would provide markedly improved signal quality than would be experienced by contact of the finger pad.

Blanchard et al. (2011) found that for small, slow hand motions, tactile information may equal or override the movement perceptions of muscle proprioceptive information. Revisiting Demonstration A, described previously, you will notice that if you gently drag a finger pad from a single sheet of paper to the underlying table surface, then do the same with a forward stroke of the nail edge of the same finger, the fingernail will register a transition that seems more immediate and of greater magnitude than that experienced by the finger pad.

Biomimicry of Haptic Response for Robotics

Where industrial robots once toiled independently within set-parameters, and within their own controlled workspace, cobots (collaborative robots) with machine-learning now complete tasks with varying inputs while engaging directly with humans as coworkers in a shared workspace. To do this safely and effectively, predictive AI (artificial intelligence) must integrate multiple input sources to maintain awareness of its own current and predictive working envelope, the inputs and outputs of its work, as well as every other element proximal to its workspace. In particular, haptic and visio-haptic inputs are being researched. To address the industrial need for robotics that can replicate human force-relevant movements, Gao et al. (2019) describe an approach for teaching force-relevant skills to robots based on motion and force analysis of human demonstrations. This article is typical of an evolving focus on developing learning models for robotics so that they can mimic human actions that must adapt in the context of differences and inconsistencies in force application resulting from component and assembly inconsistencies.

Ye et al. (2007) exemplify another focus on haptic research, the replication of the human finger's haptic capacity to detect specific surface aspects, including roughness and texture.

Zhang (2010) discusses the improvement in micro-fabricated strain gauge sensitivity when artificial epidermal ridges are applied.

Working with macroscale surface roughness samples produced by additive manufacturing, Sahil et al. (2020) studied visio-haptic perceptions of microscale surface roughness using the eye and the pad of the fingertip. They found that tactile perception of similarities was dominated by microscale roughness rather than visual resemblance. Per Sahil et al. (2020), higher surface roughness results in greater friction perception as the fingertip skin ridges engage on the surface asperities, allowing each individual to correlate the haptic sensation to a surface roughness. This corresponds to one technique that I employ using surface roughness comparison standards (e.g., Fowler #52-720-000) as a basis for estimating surface roughnesses. Though measured in microns, surface roughnesses are a maximum averaged sampling over a given area, rather than discrete steps as are anticipated in tolerances. Unfortunately, in their work Sahil et al. (2020) did not conduct a comparable evaluation using the end of the fingernail, another technique used with the roughness standard comparators, and the technique that I use for estimating linear distances at microscale.

Mechanical engineers that are "hands-on" tend to automatically correlate what their eyes see with what their hands feel as they work. As noted by Yang et al. (2016), "Humans typically combine visual predictions and feedback from physical interactions to accurately predict haptic properties and interact with the world" (p536). To allow robotics to anticipate the "feel" of objects before actual contact, Yang et al. (2016) explored both purely visual predictive analytical classification models, and purely haptic analytical models for haptic classification. They established that the two inputs were complementary and that their combination improves performance over both individually.

Bolopion et al. (2011) describe the tele-manipulation of objects below 10µm in size through a combination of virtual representation of the object accompanied by haptic feedback determined from vision algorithms which estimate respective positions for tools and objects being manipulated. Such systems require both the optical image and the haptic sensations to be magnified significantly to present appreciable magnitudes to the operator. While this is a logical approach to ensuring that micron-scale parameters are met, the fleshy pads of fingers are not effective at registering minor differences in distance and therefore this research is not reflective of an actual-scale visio-haptic response.

Collectively, these studies support the preferred use of the leading dorsal edge of the fingernail in conjunction with optical input for detecting micron-scale changes in surface topologies of a sample.

Use of Artifacts in Mechanical Engineering Design Education

Artifacts are well established in teaching and learning from infancy onward. We repeatedly point to an object and name it so that the child will correlate the name and the object over time. As the level of education increases, as in mechanical engineering design education, artifacts may be more specific to a particular lesson.

Use of Visual Artifacts in GD&T Instruction

Paige and Fu (2017) indicate that spatial reasoning is a particular challenge in teaching GD&T and describe a set of experiential learning tools to assist its development. The simple demonstration pieces, fabricated from common materials such as clear plastic tubing and plastic sheets, provide an exaggerated three-dimensional manifestation of tolerance zones that students can apply to sample workpieces. While this is a visual aid to understanding the principles of GD&T, it does not aid in cognizance of Fit-Classifications nor actual-scale geometric tolerances.

Design and Use of Artifacts in Mechanical Engineering Education

I return to my earlier definition of an artifact as pertains to the discussion of mechanical engineering education: *an artifact as an item or assembly, whether of incidental historical production or by intentional manufacture for instruction, made by skill and used as a teaching exemplar*. By this definition, virtually any physical object can be used as an artifact. Wood et al. (2001) and Sheppard (S. D. Sheppard 1996) espouse reverse engineering, or dissecting, mechanical systems to see how they work, while Akin and Pedgley (2014) recommended the creation of material (textile) libraries as artifacts. However, objects that have been repurposed for instructional use will likely have many features that are not relevant to the specific topic being instructed and, as Kroes & Meijers (2006) suggest, therefore may add more confusion or distraction than value in their use. Perhaps, then, purpose-driven artifacts, focused on specific learning content, should be considered where possible.

Artifacts as Instructional Aids in Mechanical Engineering Education

For this thesis, I have restricted the scope of design to the ideation and communication of a physical solution to a mechanical engineering question. Though the natural sciences contribute foundational knowledge, it is the act and art of the application that knowledge, which is to say the act of designing, that is the hallmark of mechanical design engineering. As Hodge and Steele (1995) qualified, "Despite the varied definitions ... virtually everyone acknowledges the unique nature of "designing" and agrees that "design, above all else, defines the difference between an engineering education and a science education". Wood et al. (2001) add that design is the bridge from theory to reality, and that design*ing* distinguishes engineers. Further, they (Wood, et al. 2001) describe students' perception of instruction of design methods; "many students report that design methods are typically taught at a high-level and in a compartmentalized fashion" (p1). This is an important recognition and commentary on the students' experiences in conventional design classes, with Wood et al. further commenting that students also don't often have incremental experiential opportunities with the design methods, nor opportunities for observation and reflection on the design methods in physical application. The implication is that, for many students, conventional design courses may be introduced too late in the curricula and with insufficient experiential context to cement the design theory into practice. Wood et al. (2001) propose the use of reverse-engineering as the basis of learning design techniques, the underlying concept being that when students physically handle, examine, disassemble and reimagine artifacts as they reflect on particular aspects of design engineering, they will get a robust correlation of design theories and physical manifestations. In other words, they are recommending the use of repurposed items as artifacts for design education.

Sheri Sheppard is a mechanical engineering professor who had already established a robust academic *curriculum vitae* in her field before turning her scholarship to the field of engineering education. She is a long-time advocate of reintroducing traditional practical skillsets and knowledge into the undergraduate engineering curriculum. One approach Sheppard (1996) espoused in the early 1990s was an early introduction of mechanical dissection of engineering artifacts to learn how others solved "a particular problem" (p1). Through this experience, students develop an understanding of historical design precedents and gain exposure to the vocabulary of mechanical engineering, establishing a foundation for subsequent courses. Since then, reverse-engineering and mechanical dissection-based courses were frequently described in the literature, some using common, everyday artifacts and others using artifacts of a more technical-historical nature.

The idea of learning design through reverse-engineering is supported by the five stages of a constructivist learning model (CLM) (Parcover and McCuen 1995); engage, explore, expand, extend, and evaluate. In the CLM, the gained knowledge and value of each learner’s experience is unique as they experience a new artifact, evaluate it in context of their existing knowledge, adapt their knowledge to reflect new ideas, and formulate ways to use this new information going forward. Parcover and McCuen (1995) wrote, “The basic assumption of constructivism is that learners receive sensory input, compare it with their pre-existing ideas, make modifications, and shape explanations that make sense to them” (p241).

Both approaches, reverse engineering and CLM, espouse the use of artifacts as a source of experiential design learning.

Artifacts are diverse in nature and common across a broad cross-section of engineering education disciplines, including industrial design, and the idea of a collection of standardized artifacts that can be drawn upon as instructional aids has been discussed in the literature. Akin and Pedgley[xii] (2014) note that, "[m]aterial libraries provide designers with a hands-on resource to understand material and related properties beyond what is possible through datasheets, catalogues and online resources" (p1207). This fosters the notion that, beyond the personal collections held by individual faculty members, engineering faculties should maintain libraries of physical artifacts, with content of common interest and focused on the institution's unique regional needs.

Considerations for the Design of Artifacts for Mechanical Engineering Education

It has been observed (Rugarcia, et al. 2000, Smith, et al. 2013) that little has changed in the delivery of engineering education between the 1940s and early 2000s; an instructor reading aloud while writing on the board, students passively copying notes if they are even that engaged in the class, the odd *pro forma* instructor question and student answer, and the class culminating in an assignment. Rugarcia et al. (2000) noted that most findings of engineering education research were not being integrated into engineering education practice: "little evidence of anything that has appeared in articles and conferences on engineering education in

[xii] While the authors reference textile / fabric libraries, the same holds for mechanical engineering artifacts where visual and tactile characteristics are often critical.

the past half-century can be found in most of our classrooms and textbooks" (p11). Notwithstanding the evidence of bulk stagnation, the authors (Rugarcia, et al. 2000) recognized that, increasingly, instructors have started to partake of education literature, conferences and workshops, and adopt new approaches in their teaching. More recent literature does not paint a picture of significant adoption. Borrego et al. (2010) reported significant awareness (87%), but mediocre adoption rates (47%): "Despite decades of effort focused on improvement of engineering education, many recent advances have not resulted in systemic change" (p185). A systemic review of research, conducted by Karabulut-Ilgu et al. (2018), found a rise in research on the topic of the flipped classroom starting after 2012, but did not report on correlation to adoption. Bjorkqvist and Roslof (2020) discuss initiatives introduced by some instructors in the Department of Information Technologies at Åbo Akademi University (ÅAU), Sweden, and noted that these initiatives are often critically discussed by some in the faculty. Riley et al. (2021) consider the influencing of pedagogical change in engineering education to be along a spectrum from dissemination to propagation, and note, "[w]hile innovations continue to be developed, tested, and published at an overwhelming rate, instructors often struggle to incorporate these new methods into their classrooms" (p1).

Rugarcia et al. (2000) recognize that changes in industry have meant increasingly specialized knowledge and skillsets in its workers, which, because of the significant number of specialties, cannot all be taught as core or even elective courses at institutions. They therefore propose a shift away from training in increasing numbers of specializations, instead focusing on developing a core set of engineering fundamentals courses. Rather than maintaining the status quo theory-centric education format, engineering education needs to focus on the integration and application of engineering knowledge. As noted by Rugarcia et al. (2000), "the focus in engineering education must shift away from the simple presentation of knowledge and towards integration of knowledge and the development of critical skills needed to make appropriate use of it" (p6). The *integration of knowledge and development of critical skills needed to make appropriate use of it* does not happen from an understanding of theory alone; it requires an understanding of the physical manifestation, and that physical understanding requires the use of human sensory skills, frequently vision and touch, and sometimes audio, olfactory and others.

In *The Dual Nature of Technical* Artifacts, Kroes and Meijers (2006) propose that there is value not just in studying the natural sciences, but also in studying the nature of technological sciences; that is, 'produced' articles (i.e. artifacts) designed intentionally for a particular function. Here, 'produced' has a dual meaning; first, to be fabricated rather than naturally occurring, and second, that they may only be considered technical artifacts through intentional designation as such. This latter meaning of ‘produced’ suggests some degree of deliberation on fitness, and perhaps value, for educational purpose is required before classifying it as a technical artifact. This contrasts with an object arbitrarily selected and forcefully interjected as an instruction artifact. Kroes and Meijers (2006) meaningfully use the term *teleological* to describe that the intentional, not the incidental, design and use of these technological artifacts is the differentiator from mere physical objects. Thus, the crux of Kroes' and Meijer's (2006) dual nature of technical artifacts is that technical artifacts are not just human made, but also designed for a specific functionality. On this intentionality of design, they (Kroes and Meijers 2006) suggest that "the realization of [technical artifacts'] function crucially depends on their physical structure" (p1). However, per Kroes and Meijers (2006), the understanding of technical artifacts as a conceptual framework combining the elements of physical characteristics and intended functionalities (the form and function) is inadequate. The question in essence is if the form of the artifact defines a universal functionality, how does the mind recognize or realize these elements? Alternatively, if functionality is perceived primarily as patterns of mental cognitions subject to an individual's mental processes, how is function universally conveyed by form? In response, Kroes and Meijers (2006) propose that "[p]robably the best way to conceive of functions and artifacts, then, is to regard the notion of a function as a bridging concept that relates the physical and intentional domain" (p2). In practical terms, as relates to considerations in the design of artifacts of design esoterica, the intended functionalities of the artifact must somehow be made explicit.

Wikberg-Nilsson and Getta (2017) argue that for artifacts to be of value, instructors must first perceive a value to the students in their use, and subsequently they must be fabricated and used in instruction. Furthermore, they argue that any features incorporated into the artifact must be meaningful in their use, otherwise they should be excluded from the artifact. Citing Trowler (2008), Wikberg-Nilsson and Getta (2017) add that in extended engagement with the artifacts, students' performance with the artifact improves regardless of whether students' overall abilities are directly changed. Artifacts, and their use in instruction, therefore, should be designed to be extended from the particular context into additional practical uses. Regarding the use of artifacts, Wikberg-Nilsson and Getta (2017) noted, "a central part in the design of an artifact is to create connections, so-called alignments, which support a specific intended use, but also opens up completely new ways of thinking and acting" (p3). This suggests that, in designing an artifact, the design should not be so restrictive as to limit its value beyond what is expected of it; instead, the artifact should allow, if not foster, tangential thinking that may allow the student to grow beyond the limits of the specific lesson.

Considerations for Use of Physical Artifacts in Instructing Mechanical Design Esoterica

Another source provides some guidance on the design and use of artifacts in engineering design. In his dissertation, Ben McGarry (2005) considers the artifacts, that is, the things we think *with*, in conducting design engineering. As artifacts, McGarry (2005) considers *the tools with which we think*: pencil and paper, whiteboard, textbooks, catalogs, software, and the like.

Initially seemingly different in nature from the artifacts considered in my writing (McGarry's artifacts are not described as fabricated in a reproduceable structure that demonstrates design esoterica for learning purposes), they are similar in that they provide reference elements of visual and haptic stimuli to the designer and affect considerations in the design process.

McGarry's study (2005) had several aims, the primary being "to better understand interactions with artifacts in engineering design" (p10). He observes that, in considering design as a thought process, the contribution of the design tools used are ignored; "To date, studies of the use of representations in engineering have paid little attention to the materiality and physicality of those representations, focusing instead on design as essentially an 'internal' cognitive process" (p10). To correct this shortfall, McGarry sought to investigate design practice in a professional environment, focusing on the use of design tools (artifacts per his definition) in situ. Further, McGarry (2005) recognizes that design of new technologies, that is artifacts, is rooted in understanding of the strengths and deficiencies of its predecessors. This recalls a simple maxim of field service engineering practice: understand it before you *fix* it. McGarry (2005, p130) positions artifacts in a duality of representing an aspect of the design, while also participating in the design process. McGarry comments, "The artifact is part of an evolving 'design space'. The engineer can 'see through' the artifact to the design they're working on, and by interacting with … the artifact, can deepen their understanding of the design space" (p132). This positions an artifact of design esoterica as a foundation element from which deeper insight can be gained or from which scaffolding can stretch. He further adds that artifacts may be transparent or opaque; transparent in that the content or attributes of the artifact may be immediately meaningful in a certain context, and opaque in that their meaning may be unclear in a different context. This may be an important consideration in the design of the artifact itself; will the functional intent of all elements of the artifact be immediately discernable or will some be confusing or distracting to the user? In the realm of mechanical design engineering, there are inevitably design features included for fixturing, handling, safety, weight reduction, or myriad other reasons not relevant to the intended functionality of the artifact. The question thus arises, is it reasonable to ignore in the design and/or documentation, such elements that are not relevant to the intended functionality? Conversely, should such features be included in both the design and the documentation so that the artifact may be of broader value as a design tool? Citing Bertelsen and Bodker (2002), McGarry (2005) offers that artifacts may be used in ways other than anticipated. A portion of McGarry's list of artifact attributes is paraphrased to relate to artifacts in my context of design esoterica: (p178)

- Esoterica design artifacts may find common use across different design contexts.

- Multiple artifacts may individually or collectively represent the same esoterica.
- The insights gained from one artifact may be the starting perspective for considering another artifact.
- Chains of artifacts may be formed to convey esoterica.
- Chains of esoterica may be reformed by substitution of artifacts to convey the same or alternate esoterica.

McGarry derives a list of understandings of interactions with artifacts in design:

- "Design artifacts do not just represent the design world, but they participate in the interactions that make that world meaningful." (p234)
  - In my context, artifacts of design esoterica represent specific design elements while also representing specific design functionalities.
- "Artifacts are not used as static pictures of the design, but rather they present dynamic perspectives and are actively engaged by the engineers to support their designing." (p234)
- Artifacts of design esoterica provide not only a visual manifestation of the design element, but also a tactile one, granting the user a visio-haptic appreciation of form and aesthetics as well as functionality.
- "The meaning of a design artifact is negotiated and renegotiated in situ." (p234)
- In the viewing and handling of artifacts of design esoterica, the user's perspective and understanding of the various elements of esoterica are evolved as they engage with the artifact.

- "Engineering design is based on collaborative, constructive criticism around artifacts, enabled by participation in a community and by access to a shared physical context." (p234)
    - As regards artifacts of design esoterica, users must apply a critical evaluation of merits and concerns about the elements demonstrated. Furthermore, such artifacts provide a tangible focal point for discussion within groups.
- "Artifacts, and the relationships between them, evolve unpredictably through design activity, and engineers must continually negotiate webs of meaning through a 'constellation' of artifacts." (p235)
    - Core design elements are intertwined in ways that are not always immediately apparent, and that may necessitate changes in other elements to attain acceptable results. The same is true for design esoterica where elements that are not directly related, such as Fit-Class and surface finish which, nonetheless impact each other.
- "Artifacts' material qualities shape interaction styles and, where possible, artifacts and environments are physically reconfigured to better support activity." (p236)
    - The design of artifacts of design esoterica, must address the environment in which they will be used. Geometric considerations including size, weight and balance, as well as the legibility of any markings, lighting and environmental factors of temperature and humidity may be considered.

These criteria were used to establish a set of general design queries (see **Appendix A**) for use in evaluating design completeness and robustness of each artifact.

McGarry's perspective, that the means of design inherently impacts and therefore is part of the design, parallels Marshall McLuhan's (1964) noted phrase, *medium is the message*, meaning that the medium of delivery of the message inherently becomes part of the message itself. McGarry (2005) summarized, "Design artifacts were seen to do more than 'represent' the design - they were engaged by engineers as participants in designing. This suggests that improving the design artifacts that engineers use is one route towards better supporting design practice" (p241). While McGarry's artifacts were meta-scale cognitive tools rather than the physical, representational artifacts considered in my thesis, a direct parallel can be drawn for this statement between macro-level cognitive artifacts and micro-level design esoterica artifacts. Notably, there is an absence of literature supporting any conjecture that design esoterica are effectively instructed in the undergraduate mechanical engineering curriculum. Indeed, implicit in much of the literature that I reviewed (Case 2016, Lamancusa 2006, S. D. Sheppard 1996, Issapour and Sheppard 2015, Symonds and Britton 2012, Frederik, Sonneveld and de Vries 2011) is a notion that practical aspects of mechanical design are not widely understood by faculty professors. Therefore guidance, in the form of physical artifacts of design esoterica is warranted as a tool for understanding their meaning and application.

Frederik et al. (2011) posit that everyday objects that surround us in daily life are technology artifacts, reflecting "a body of knowledge, that technology entails designing and producing" (p278), and therefore appropriately used in technology education. However, such artifacts are too numerous to become familiar with them all, and as new artifacts reflecting technologies are introduced, they make earlier artifacts technologically outdated. Frederik et al. (2011) therefore argue that artifacts presented in education should be introduced "such that pupils learn to recognize characteristics of the artifact that are not specific for one specific artifact, but that relate to the very nature of all technical artifacts" (p278). That is, the underlying technical concept is more important than the details of the *particular* artifact. The authors indicate that instructors must have knowledge of the nature of technical artifacts; presumably, that means the relevant technologies or aspects thereof to be explored in the artifact. However, they also note that little research had been done on how instructors and students think about the artifacts. Briefly exploring *The Dual Nature of Artifacts* (Kroes and Meijers 2006), Frederik et al. (2011) distinguish the duality of a technical artifact as a physical object with a function, and elucidate that an understanding of a technical object can only be gained by describing both its designed functionalities and its physical structure. Frederik et al. (2011) studied instructors' understanding of the dual nature of technical artifacts, determining that instructors, unfamiliar with the artifacts, typically focused heavily on the physical characteristics with little attention to the functionalities. Extending this to technical artifact usage by students, it becomes apparent that superfluous characteristics must be minimized or, conversely, critical and non-critical physical characteristics of the artifact must be distinguished from each other so that only the relevant aspects are focused upon.

Based on McGarry's thesis (2005), a collated list of considerations *for the design and use of artifacts of design esoterica in mechanical engineering education* is provided in Appendix A. The collated considerations will be reformatted as a series of design queries to be used in guiding and/or validating the design of the artifacts for this thesis.

The Presence of My Lived Experience

My lived experience as a mechanical design engineer and instructor is the magnetic north of my knowledge and my engineering truth, and it is present as I review literature and interpret its relevance and validity for the contexts with which I am intimately familiar.

A literature review is intended to explore what has been investigated so that knowledge may be explored, but also to identify gaps in the knowledge of a subject.

The challenge, when looking at something in an unconventional way, or at a different level by aggregating or individuating things (i.e. macro or micro level), is that the specific area of interest may not have been explored in the way now considered. Questions may arise, then, as to why it was not previously considered, or if it was considered but discarded because it deals with a sensitive topic that may make some future reviewer or potential consumer of the information uncomfortable. In researching the fields relevant to my thesis, I found that, again and again, authors did not make the provocative statement that might be perceived as laying down the proverbial gauntlet of challenge. I found no explicit declaration that the practical design knowledge of most instructors of core design courses is robust, limited, or somewhere on the spectrum in between, nor even what may determine or characterize robustness of practical design knowledge, and therefore lack thereof. Indeed, I found no definition for, or enumeration of practical design knowledge. It cannot be unexpected, therefore, that I found no evidence that mechanical engineering design esoterica had been studied for the purpose of cataloguing or for the purpose of studying the knowledge thereof held by core mechanical design instructors. And that is where my lived experience comes in as a comparator for design knowledge.

Repeating my earlier assertion, I believe there is adequate evidence that mechanical engineering education's focus on instructing engineering theory has had the result, over time, that the practice of engineering design is generally not within the repertoire of research-centric professors now teaching core mechanical design courses. As a result, most of today's mechanical engineers enter industry with little more than engineering design theory. I did not find any research on the specific design knowledge that is missing from the curriculum, or from graduates' design knowledge.

From experience, I recognize that some of the absent design knowledge may be what I have termed design esoterica. In my experience as a mechanical design engineer, consideration of design esoterica *during* the design process is critical to reducing design iterations and to producing a functional, manufacturable component or system design. By extension, the absence of such specific design knowledge may be costing industry, though again I found no research that considers this.

I assert that one of the most critical constituents of design esoterica is the determination of design tolerances based on functional interactions, or Fit-Classes. Two elements of tolerancing are physical understanding of Fit-Class interaction characteristics, and the physical magnitude of tolerances. However, I found no research addressing student cognizance of the physical fit and magnitude of micron-scale tolerances. Because Fit-Class tolerances are micron-scale, and therefore difficult to appreciate their magnitude, I proposed a design study for three tolerance demonstration artifacts: one providing an entirely visual comparison of items at micron-scale, one providing an essentially haptic demonstration of Fit-Classes, and another providing visio-haptic demonstrations of micron-scale.

A Discussion of Qualitative Study Methodologies

Research methodology represents the structure under which the study will investigate the research question. In this case, the purpose of this study is to convey, through a combination of introspection and conventional academic description, an exploration of my approach to the development of three artifacts that may be used to improve learner perceptions of micron-scale dimensional tolerancing. Under the umbrella of qualitative studies in educational research, Creswell and Guetterman (2019) indicate three baseline qualitative research designs: grounded theory, narrative, and ethnographic, and provide action research as a mixed method (i.e., often combining qualitative and quantitative aspects). Based on the descriptions provided by Creswell and Guetterman (2019), the study designs are discussed briefly.

Grounded theory research design seeks to develop a theory out of the experiences of individuals. This approach would be appropriate if I were to investigate engineering graduates' thoughts on their goals and outcomes for the education, and propose a theory based on these data, rather than fitting the data to an *a priori* chosen theory. Informally, and unknowingly, this is the general approach that I applied in my various conversations throughout my career, from which I found recurring themes reflecting how mechanical design engineers felt about their education.

Narrative research design draws out and interprets the stories of individuals with inherent rich description of their lives and experiences independent of any group (Poulos 2021). Hamilton et al. (2008) build on this, indicating that narrative research can be a story of self. Further, Hamilton et al. (2008) indicate that there may be "layers of ambiguity that could lead the reader to identify it [the study] as a narrative or an auto-ethnography. … The blurred boundaries … afford us the opportunity to consider elements from each methodology" (p17). Implicit in this statement is the idea that a researcher may selectively adopt or incorporate elements or ideas of multiple research methodologies to optimally suit the study's general intent and specific topic.

Ethnographic research design observes, in situ, the common culture within a group in a particular setting in time and place. At first glance, this seems inappropriate because I am studying myself, not a group. However, Poulos (2021) describes a sub-design, autoethnography (alternatively auto/ethnography, (auto)ethnography), which evolved from conventional ethnography to inject the researcher's lived experience and insight into the study of a social or cultural environment. Poulos provides that autoethnography is an autobiographical examination of the researcher's life, grounded in active consideration of how the researcher's past impacts their interactions with the research environment and their interpretation thereof. This approach (Poulos 2021) uses the writing process itself as the research practice drives the inquiry, rather than simply documenting it after the fact. Poulos notes that, "autoethnography is a method that attempts to recenter the researcher's experience as vital in and to the research process" (p4). Together, the elements of active self-reflexivity (i.e. engaged in the development rather than in the post-study analysis alone) and recentering on the vitality of life experience in the research process seem appropriate to my study as the artifact designs and the ongoing critiques thereof during their evolution, are entirely rooted in my design experiences. Poulos (2021) provides a list of data sources conventionally used in qualitative research and applicable to autoethnography: "participant observation, interviews, conversational engagement, focus groups, narrative analysis, artifact analysis archival research, journaling, field notes, thematic analysis, description, context, interpretation and storytelling" (p5). My study, however, is based largely on memories of informal engagements, communications and observations throughout my career. These data sources are aligned with qualitive inquiry and enable exploration of questions of interest that are not answerable through quantitative methods. Therefore, my approach of relying on personal memories as the basis of the research, and presenting that history through the Design Companion's voice, though unconventional in traditional quantitative and experimental engineering research, may be seen as appropriate to autoethnographic research.

Creswell and Guetterman (2019) indicate action research as a mixed method (i.e., *often* combining qualitative and quantitative aspects) research methodology. They indicate the intent of action research designs, "In some action research designs, you seek to address and solve local, practical problems … In other studies, your objective might be to empower, transform, and emancipate individuals in educational settings" (p22). If my focus were on cognizance of micron-scale magnitudes in general, it could arguably be seen as a universal problem. However, cognizance of micron-scale magnitudes in the context of understanding dimensional tolerancing is a problem specific to mechanical design engineering education and practice, and action research may be appropriate.

Hamilton et al. (2008) highlight three research methodologies: "*narrative* (a look at a story of self), *auto-ethnography* (a look at self within a larger context), and *self-study* (a look at self in action, usually within educational contexts)" (p17). Autoethnography is focused on the perceptual changes in one's own thinking over time and within the context of a given environment (including a situational environment). Whereas self-study is heavily rooted in autoethnography, it has the goal of examining and changing a practice or way of doing something. In the context of engineering education, an autoethnography would explore how and why I arrived at my thoughts on mechanical engineering design education, or perhaps a specific focus within that large domain, but would stop there. The exploration of the evolution of that ultimate perception would be the purpose of the autoethnographic study. Though that is a legitimate endeavor in and of itself, my interest lies in improving engineering education in practical ways. Narrative inquiry is substantially similar to autoethnography, except that narrative study focuses on driving external change without directing how to make the change. Self-study would essentially integrate that autoethnographic analysis along with addressing a gap that I perceive in the practice of education of mechanical design engineering, and attempt to remedy through the development of instructional artifacts. Simplified, self-study research is an inward-focusing form of action research which focuses on improvement of the *researcher's own* teaching practices. This allows my research to consider a self-study methodology in that it seeks to develop instructional artifacts that may improve the teaching of dimensional tolerancing practices.

This literature review has explored themes of tolerance as esoterica, visio-haptic perception of magnitudes, and the role of artifacts in design education. A shift to science-based curriculum in engineering education was shown to reduce practical knowledge about tolerancing in mechanical engineering education. Finally, insights into how magnitude is instructed for conventional magnitudes, was provided as a precursor to addressing research into micron-scale visual, haptic, and visio-haptic perceptions.

Chapter 3 Methodology

This thesis combines two methodologies: an engineering design study and a self-study. The first, an engineering design study, will be considered from a mixture of conventional engineered design and qualitative research approach, reflecting a somewhat unconventional approach to typical engineering design research. The latter will reflect a separate qualitative research approach. As follows, I will outline each, and their supporting epistemological, axiological, and ontological assumptions.

Artifact Design Methodology

The mechanical engineering aspect of my thesis is the design of three artifacts that may be used in undergraduate mechanical engineering design courses, or in a stand-alone educational unit such as an independent micro-course (IµC) (Sykes 2020) or individual micro credential. The purpose of the artifacts is to provide experiential learning opportunities for students to gain the use of visual and haptic inputs as elements of understanding tolerance selections. As such, I am using a design methodology with six elements:

- Description of design intent.
- Research of human visio- and visio-haptic capabilities.
- Development of design considerations.
- Iterative ideation and evaluation for completeness based on design considerations.
- Final design and detailing.
- Discussion.

Of these five, statement of intent and research into specific elements that are anticipated to be incorporated into the design are typical first steps in a design process, and are provided in the introduction and literature review. The third step, development of design considerations differs slightly from conventional representations of design requirements. *Requirements* suggest an absolute inclusion or exclusion of something in the final design, which I have found to focus or limit ideation on strict resolution of those conditions. In contrast, the approach of developing design considerations may require more supporting research in advance, thereby providing guidance to the designer without limiting their ideation and creativity. I have also found that the process of developing design considerations simultaneously develops a “big picture” perspective. The fourth step, the iterative ideation and evaluation of concepts, is informal in my application, though it can be formalized as needed. As an experienced mechanical design engineer, I generally retain the design considerations in my active memory to maintain a macro-view of the design while engaged in the design process. As a result, my ideation typically respects the design considerations as an inherent presence.

Engineering Design Study Epistemological, Axiological, and Ontological Assumptions

I employ a pragmatic interpretive framework for the engineering design study aspect of this thesis. Consistent with this pragmatic framework (Creswell and Poth 2018), it is inconsequential whether I perceive or have evidence that we have reached a condition in mechanical engineering design education where artifacts for instruction of elements of design esoterica are largely absent; what matters is the remedying of that condition by the introduction, or re-introduction of artifacts demonstrating design esoterica into the curriculum. Artifacts which I design in this study are anticipated to be adequate to meet my instructional needs of today, and may require changes in the future. Furthermore, the use of graphical depictions of concepts in conjunction with the invocation of a Design Companion voice used in describing the ideation and design process, represents multiple data sources, is appropriate within a pragmatic framework.

Epistemology considers how the researcher understands knowledge. Creswell and Poth (2018) ask the questions: "What counts as knowledge? How are knowledge claims justified? What is the relationship between the researcher and that being researched?" (p.20). Distinguishing between knowledge and opinion is a challenge of self-reflection. As regards lived experience, the questions are no easier to answer because the truths of my lived experiences are based in both first- and second-hand experiences. First-hand experiences are easily understood as those that I have personally encountered; the veracity of that knowledge is subject only to my personal recollections and interpretations thereof. However, my experiences include engagements with others, and particularly as a recipient of their thoughts and commentaries on various subjects. Judiciously, I do not take their commentary as absolute truths, but rather take the aggregate of many commentaries as truthful and therefore valid knowledge.

Axiology considers the researcher's values and biases present in their role as researcher (Creswell and Poth 2018). I bring my lived experience and knowledge in the fields of mechanical engineering design, mechanical engineering design esoterica, and the teaching of both, as valid and rich sources of information. I recognize that I am biased toward engineering application over engineering theory, while simultaneously recognizing the value and importance of engineering theory as a foundation for engineering application. I recognize that I am biased toward action and implementation over theorization or postulation of change.

Ontology reflects that reality is subject to perspective (Creswell and Poth 2018). I recognize that the way that I perceive and engage in design, as an activity, affects design as an end product. The considerations that I generate for the design of the artifacts are subjective, and based in my experience and knowledge. Another designer, with unique experiences, may generate different designs.

Self-Study Methodology

Upon consideration of the earlier discussion of qualitative research methodologies, I will apply a research methodology based in self-reflection study, and using the voice of my inner Design Companion to convey my self-reflection.

Hamilton et al. (2008) indicate that narrative, auto-ethnographic and self-study methodologies “privilege self into the research design” (p17), meaning that the researcher is an integral part of the system that they are studying, and therefore their participation in the research is an essential contribution to our understanding of the system. They describe a self-study methodology as “a look at self in action, usually within educational contexts” (p17), and that it “may be *insider* research or it may include biographical elements” (p18), and emphasize the power of lived experience and voice in self-study. LaBoskey (2004) provides the five elements of self-study:

- Self-study research is self-initiated and self-focused.
- Self-study is aimed at the improvement of the researcher’s own practice.

- Self-study is interactive, incorporating self-reflection.
- Multiple, mainly qualitative methods are incorporated.
- Validity is based in trustworthiness.

As follows, I will address these elements, outlined by LaBoskey (2004) and considered in Hamilton et al. (2008). The need for artifacts to teach micron-scale fits and tolerances is rooted in my experiences as a mechanical design engineer and as an industrial and university instructor. My immediate focus for these artifacts is to improve my own teaching of these subjects, with the potential benefit to provide other instructors and learners artifacts to completed designs from which they may fabricate their own artifacts. My inclusion of a qualitative research methodology is intended to establish how my thoughts on mechanical engineering design emerged and then evolved into an approach to design coaching that I now refer to as the Voice of my Design Companion. Self-reflection and anecdotes, expressed through invocation of my Design Companion voice, are my research instruments. I provide my self-reflection and anecdotes as genuine and truthful reflections and memories, because it is my nature to be open and honest with myself.

Self-Reflective Study Epistemological, Axiological, and Ontological Assumptions

I employ a transformative framework for the self-study aspect of this thesis. Through my self-reflection, I consider the roots and evolution of my self-perception, and recognize how this has affected me personally and professionally. In so doing, the transformative framework is anticipated to liberate the study subject, myself, from irrational self-perceptions that have been detrimental to my self-development and self-determination.

Regarding epistemological considerations, I am the subject of the self-reflective study. I commit to truthful and adequate self-reflection in order to explore my self-perception and its impacts.

Axiologically, I recognize and accept that the value in my self-reflection is in identifying the way that I am, and why I am that way. I recognize that I have difficulty perceiving myself in a positive light, while I am biased toward viewing others in a positive light. I recognize that in sharing my self-reflection, that it may provide insights to others as to themselves and their way of being.

My ontological perspective is that I view metaphysical reality as a cognitive construct that as transitory, continuously changing with context and reflection. Within the self-reflection, I recognize that inclusion or exclusion of any part of a memory, or the alteration of any details within an anecdote, changes the interpreted reality of that moment. Therefore, I recognize that by the decisions of inclusion, exclusion, and alteration, that I have made, I have constructed the reality of the self-reflection, and therefore have impacted the self-study.

Collectively, this discussion of my research paradigm and its constituent elements set a reasonable foundation upon which my unconventional study methodology is constructed.

Theoretical Sensitivity

Researchers conceptualize and formulate theories as they emerge from the data. This requires what Glaser and Strauss (1967) termed *theoretical sensitivity*, which is an evolving awareness of, and openness to, various sociological theories. Glaser and Strauss indicate two other characteristics of theoretical sensitivity of sociologists: “First, it involves his personal and temperamental bent. Second, it involves the sociologist's ability to have theoretical insight into his area of research, combined with an ability to make something of his insights" (p.46). Further, they caution a lack of theoretical sensitivity wherein the researcher attempts to fit the data to specific pre-conceived theories that they favor. As regards the self-reflective study element of this thesis, I recognized from the outset that my reflections must adequately encompass my lived experiences so that my self-perceptions are not unduly skewed toward the negative or the positive to suit a particular narrative. Furthermore, my long-established habit of iterative introspection consistently holds that I reconsider past analyses and add new perspectives to future analyses as a matter of course. In these regards, I make a conscious effort to be theoretically sensitive.

Positionality

Through an introspective look at my lived experiences from childhood education through conventional employment, self-employment, and academic employment, I explore how my self-perception has been shaped, and how my communication with colleagues and students has evolved. This leads to an explanation of the evolution of *the Voice of a Design Companion* as a tool to convey both self-reflection and my design thoughts. Collectively, these contribute to my positionality.

I know, Aubrey, that you've caught me staring off into the abyss when I'm recalling something, or deliberating on a response to your question. I think *deliberating* is the perfect word for that because I *try* to be *deliberate* and focused in my answer, though my anecdotes do ramble. When I'm deliberating, I'm turning inward, looking for a personal truth that I can share with you. You see, introspection is simultaneously a simple task, and a difficult task. To informally examine my innermost thoughts and emotions seems, at first blush, a simple application of baseline questions: who, what, when, where, why and how. But, it requires brutal honesty in providing the answers, at a depth of personal criticality that typically makes people uncomfortable. To me, it seems that personal ownership, *once people are uncomfortable*, is the difficulty of the task. Right now, I'm deliberating on what to share with you about the evolution of *the Voice of the Design Companion.* It's a longer story arc, bridged with a number of personal anecdotes.

This next bit may make you feel uncomfortable, Aubrey, but I think it will help you get a better idea how I approach things. You're from a different generation, Aubrey. Your parents are likely from my generation, or slightly younger, and things were different when I was growing up in the '70s and '80s. In my family, punishment for dishonesty of any kind was swift and physical in nature. That was pretty consistent with what I witnessed around me, so I didn't think of it as abusive. And it wasn't just acknowledging our acts that was required of our atonement, it was *ownership* of our role in the infraction. I think that's the origins of my continuous inner dialog that re-examines my personal and professional interactions, and my every activity. This dialog iterates until I understand the nature and roots of my transgressions; until I *own* them. Through that dialog, I determine whether my actions were appropriate to my knowledge, morality and ethics in that particular context and whether I would knowingly repeat them while reasonably anticipating the same outcomes. This is an endless process, melding current and previous experiences and analyses into my evolving knowledge, ethics, morality and behaviour. My upbringing probably seems horrific by today's standards of parenting, but that's how it was. Don't feel bad for me, or pity me; I don't. All of this background is to explain that I live a life of introspection, and I have become comfortable with my evolving knowledge of self that has come of it. I *own* my truth. That's why I'm always telling your class to own your mistakes and move on.

Because I own my behaviour, I don't regret my decisions or actions. These are things of my past, and I can't change them; I can only acknowledge my past and decide whether to repeat it. I bare the physical and emotional scars of my choices as a constant reminder of those decisions, of who I was, and why I am, today, as I am. Though I don't believe in regrets, I have a significant sense of guilt that accompanies ownership of my actions. In my perpetual cycle of analysis, I have come to search for how I have impacted others, to their benefit and to their detriment. Though I have long pondered the role of spirituality, organized or individual, in my motivations, actions and outcomes, I am comfortable that it is my impact on others that determines my sense of guilt. I try to live by the creed, *do unto others as you would have done to you.* Where I have elevated the existence of others, I am grateful that I was able to be of service to them. I don't track these instances, but I do collect some of them as anecdotes that I call upon when they may help others, including you, Aubrey. Or, when they may help lift my own spirits. Where I have harmed the psyche of others, I feel a guilt that is always at the edge of my thoughts. These, too, I collect as anecdotes that I use to help others, or to keep my own ego in check.

I know, at both practical and philosophical levels, that everyone impacts others both positively and negatively, but I default to seeing the positive in those around me and typically I see the negative only after significant exposure to such behaviours. Whereas I default to seeing the good in others, I dwell on the negative in my own history. The result, in my self-perception, is that others are inherently morally superior to me. This, in turn, perpetuates my feeling of inferiority.

A single incident, occupying only a brief moment in one's existence, can set a foundation stone of one's life. It can skew how one sees themself, and how one sees their place in the world around them. It can set a perception of self-worth which, in turn, can become a barrier that halts progress or sets a challenge to overcome. It can determine whether one's character sees barriers as imposing limitations, unexplored opportunities, or another thing to work through. It can set one on a course of rigid adherence or thoughtful unconventionality. In my case, it was an incident of abuse by a teacher, when I was around age eight, that gradually established how I have perceived myself, the world of mechanical engineering design, and my place in that world That was the impetus for the unconventional way that I approach new situations, including design and even this thesis' methodology.

I can trace the roots of my inner Design Companion, this voice, the voice that continuously challenges all that I know and believe, to that incident. I'll tell you about that incident in a moment, Aubrey. First, though, I want to tell you about something that always gnawing at my confidence.

Unconventionality. *Unintentionally*, unconventionality has become something of a *modis operandi* in my thinking, my life, my professional work as a mechanical design engineer and as an instructor. I've been accused of arrogance and having a feeling of superiority over my peers. Though I haven't shared this widely, the truth is quite the opposite; I have always suffered from a sense of inferiority when compared to those around me. This sense was so overwhelming in my early career that I became frustrated at what I perceived as lackluster effort from my colleagues. That was detrimental to some of my early professional relationships.

Time for another anecdote inside an anecdote. This is probably a good point to talk about my early education and engineering career, Aubrey. In class and in my office, you've heard snippets about my career, but nothing about my childhood. To now, there's only been a handful of close friends that know that I have a feeling of inferiority; it's a difficult topic for someone my age, or with my experience. Some people have thought that my sense inferiority is disingenuous, maybe even seeing my anecdotes as a humble brag. I can't dissuade anyone from these thoughts. What I can offer is that, while I now recognize my successes, and that I am largely responsible for them, I still have a sense of inferiority that makes it difficult for me to gain satisfaction from my successes. And, probably worse, it still drives me push others, like you, to achieve what I see in you.

Self-Perception – The Incident

In grade three, I had a teacher who used derogatory terms of the day to express her belief that I was a troublemaker, and that I had a low IQ. I was struggling in mathematics but had no history of getting into trouble at school, other than a snowball fight … with the principal! And he's the one that busted me! Anyway, not unusual for the mid-1970s, where corporal punishment was still generally an accepted practice in public schools in Canada, my teacher was physically and verbally abusive to me in front of my classmates. Of course, I believed her; I was around eight years old, and she was a teacher and an adult, both of which I had been taught to respect. Plus, she terrified me! Up to that point, I knew that my broken family structure and poverty marked me as different from some classmates, but not from others from my neighborhood with similar backgrounds. Until then, I hadn't yet felt terribly different from my classmates. Looking back now, I recall being singled out by the same teacher for debasement on earlier occasions. That maybe should have foreshadowed "the incident," but I didn't even know that word at that point. On that particular day, I remember going home with visible evidence of the teacher's abuse. That is my earliest recollection of feeling an inherent inferiority to my peers. The abuse was addressed with the school and the Board of Education, and otherwise my parents' solution was to double-down on my mathematics work for the two grades that I was in her class. That was the start of my feelings of inferiority.

Self-Perception Grows - Academics

The extra math homework seemed to pay off. In middle school, I showed an unexpected strength in mathematics and was encouraged to do extracurricular math quizzes organized by the University of Waterloo. On the other hand, my handwriting was, and as you have witnessed, continues to be illegible to most people, and I again recall being publicly ridiculed in various classes, and once by the Principal. I found it hard to keep up as teachers wrote on the chalkboard, so I developed a personal shorthand that helped me, but made my notes even less legible to others. Even I couldn't read my notes sometimes, but I recognized that I was processing my shorthand somewhat as graphic reminders of the dialog that the teacher had spoken while writing; as I re-read my shorthand notes, I could hear the teacher's full dialogue. I think it was a mental compensation that I developed, and it has served me well throughout my education and career. At that time, however, I saw it as just a way to survive. It was also during middle-school that I *recognized* that I was processing the day's lessons overnight as I slept, that I was reconciling the information with what I already knew, and that I was applying these new understandings to see where I had made mistakes in my work. Before entering secondary school, I scored in the 98th percentile in a standardized mathematics test across Canada. That seemed to impress others, but in my mind, I couldn't understand how this could have happened; why had all these students, whom I knew to be much smarter than me, not done better than me? In secondary school, I had strong grades in advanced mathematics and computer science courses. I don't remember ever having top grades in any of those courses. I attributed any academic success that I had to luck and the generosity of teachers. I remember being amazed by the intelligence of classmates that competed for the top grades. I never considered myself anywhere near their calibre. Even then, I recognized that I was in conflict between what I was achieving and my sense of inferiority, so I reconciled any successes to luck.

In my undergraduate engineering program at Carleton University, I was awestruck, again, by the incredible intelligence that surrounded me. You and your classmates remind me of them, Aubrey. I am in awe of what you all do, seemingly without effort. I never felt equal to my classmates, much less superior to anyone's evident intelligence and skillsets. Now, as a licensed professional engineer, I believe in being open about my past in discussions with clients, colleagues, and students like you. You've heard me refer to myself as a "C" student. I may have been slightly stronger than that, but I felt like a "C", and I still refer to myself that way. I did poorly in my early engineering foundational courses (statics, dynamics, stress, calculus, and so on), and I gave serious consideration to dropping out of engineering entirely before proceeding into and throughout my third (junior) year courses. Instead of giving up, I recognized that I could never be a "good" design engineer, and I added a concentration in management studies as my fallback option. Still, I found unexpected success in engineering courses that some of my classmates found more challenging: thermodynamics, heat transfer, feedback and control systems, and materials. I attributed those successes to lucky exam preparation and "riding the curve"; that's what we called the practice of adjusting grades to a normal distribution.

Self-Perception Evolves - Industry

People evolve as they face new experiences. It seems incongruous that a personal evolution can be both positive and negative at the same time.

Later in your life, Aubrey, as you look back, you'll recognize the significance of the COVID-19 pandemic as the radical disruptor it has been. The social and economic upheaval of the pandemic lockdowns may not be settled for years to come, but I am hopeful that such a radical disruptor will bring your generation radical opportunities as well. I graduated during the 1993 recession. By the time my cohort sat for our final examinations, some of my classmates had decided to proceed directly into graduate engineering programs. I remember two of them commenting to me that they weren't as brave as me. As top students, they were afraid to face the failure of not finding immediate, well-paid employment in industry. Apparently, I was lucky to have already faced failure and to have low expectations. So, instead of facing potential rejection, they had decided to pursue graduate studies. Their comments stung, but I could feel the validity in their argument; they were way more intelligent and creative than me and had exciting careers in their futures. I didn't expect much from my engineering career other than to have to work hard to achieve at a baseline level. My job search was depressing. After more than 200 applications and rejections, I found employment as an entry level mold designer. The pay was about a third to a half of what my newly employed former classmates were earning, but it was a start and I thought it was about what I merited compared to others. What I found in that first design job was that I took quickly to the practicalities of mechanical design. I had the benefit of a

Master Mold Maker taking me under his wing and introducing me to the practical aspects of metal-removal manufacturing processes. He facilitated my understanding of what tolerances, and their magnitudes, meant.

You and your classmates have asked me many times if the core mechanical engineering courses that you take will be of use. I think so, Aubrey. At least they were to me. As I worked on engineering designs to reduce mold cycle times, I was frustrated to find that heat transfer and materials textbooks were nowhere close to the geometries and conditions that I was experiencing. But that frustration led me to rely on the general ideas in those textbooks, rather than specific calculations. For one project, the client wanted us to shave a couple seconds off a thirty-eight second molding cycle. I suggested a complex mold component design that would be costly to produce, but I believed would reduce the cooling cycle by several seconds. Everyone laughed at the complexity of the design, but the operations manager allowed me to run with the idea, expecting that I would learn from my expensive mistake. The resulting cycle was around sixteen seconds, and we were contracted to provide replacement components for a hundred existing molds for the same product. At that time in the early 1990s, computational fluid dynamics analyses were prohibitively difficult and expensive, so there was no way to quantify the potential gain before physical production. However, the principles of heat transfer, fluids and metallurgy justified the *direction* of my solution. That was the first time that I saw value in the theoretical aspects of my undergraduate engineering degree. It was also the first time that I experienced the value of unconventional thinking. Hopefully you will have those "aha" moments early in your career, Aubrey. Despite the significant economic value that my employer gained from that unconventional design choice, I only felt relief that nobody had asked me to prove mathematically that it would work. As I approached eighteen months with that employer, I developed CAD model and drawing templates that reduced typical mold design by 66-84% to fifty-five hours. Though I felt a sense of achievement, I felt more strongly that coworkers could have achieved the same, if they were as afraid of failure as I was. Throughout my first engineering job, I pushed myself because I was afraid that others would recognize the inferiority that I knew in myself, and in seeing it, I would be fired.

Experiential learning is not restricted to formal education and apprenticeship in the trades. Each new assignment or project in early-career mechanical engineering design jobs provides scaffolding to new levels of knowledge and skill.

The first four or five years of my career were a bit of a blur, Aubrey. Fifty-five hour weeks were the starting point, and sixty-five hours became normal; passing 80 hours happened enough times. Eighteen months after graduating, I started my second job, as an entry-level mold design engineer in a large global corporation. For some reason, I bypassed the required "new designer" postings in the print room and in the shop. Those temporary postings were mandatory even for newly hired but *experienced* design engineers, so that they could get a feel for the company's processes. Instead, I was placed immediately into production mold design engineering. I didn't know that was unusual at the time; I was just worried that I wouldn't measure up to the experienced designers in my business unit. Within twelve months, I unknowingly set a new benchmark for mold design engineering speed and accuracy. There was no intention behind this. I was just *afraid of failing to have adequate productivity or quality of workmanship. The funniest thing, Aubrey, is that I didn't even know this became a benchmark until several years later when a friend and colleague of mine surpassed my productivity benchmark. In our business group, his achievement was thought to be so significant that an engineering manager made it a point to track me down and tell me that my "record" had been broken. That's the first time I heard that I had set the benchmark. I was so excited for my colleague that I sought him out, shook his hand and literally patted him on the back. Later, he told me that my recognition of his achievement was a career milestone for* him. *You've seen how excited I get for you and your classmates when I hear that note of realization in your voices as you explain a creative GD&T solution on your assignments. I am always excited when I see that someone has achieved something challenging, even more so when they surpass what I have done. Anyway, I eventually came to understand that I cast a large shadow among those around me, and that it is particularly valued by some when* I *recognize their efforts, contributions, and successes. I appreciate the respect that you and your peers grant me, Aubrey, and I see the glint of pride in your eyes when you impress me. It is a great generosity that you and others hold me in such esteem as to value my recognition of you. Because of that, I make more of an effort to try to recognize others whenever I can.*

Goals may guide your intentions, but the perceptions of your intentions by others can impact the pursuit of your goals. That can be a difficult early-career lesson, but it can also create opportunities to formally identify and communicate your intentions. This can be particularly important when your role evolves in ways that could not be foreseen.

When students, like you, ask me about my career, I like to start by asking about their career goals. From there, I figure out which anecdotes to share with you that may help solidify your goals into intentions. We've had that conversation already, Aubrey. It may surprise you that I have never had the goal of being the best in mechanical engineering design, GD&T, or in anything else for that matter. I'm damned good at some things, but I don't believe that I am the best at anything. My early-career goal was simply to remain employed, and my intention was to do that by not attracting attention. I was always afraid that I would not measure up to those around me, so I pushed myself. With my feelings of inferiority, fear of failure was my constant companion and personal motivator. I still feel insecure in an environment of intelligent and creative design engineers, and it has frequently coloured my expectations of them. My underlying thought was, and generally remains, "If I can do this, anyone can do it." Though I didn't know it in the early days of my career, some saw my design efforts as an intent to prove everyone else wrong or inadequate by comparison.

Within eighteen months of starting that second engineering job, a series of promotions elevated me two levels to a Senior Designer designation. By then, the company was entrusting me with its reputation. I represented the company in international trade groups and in direct customer relations, and I had developed the technologies needed for a new client-centric product development business unit. My underlying thought, always, "Don't screw this up." When I was put in charge of that product development unit, I even had a manager tell me "*The job is yours to lose, Jim.*" I interpreted that to mean that management was already expecting me to fail. I rationalized the promotions as necessary to the new roles and responsibilities that I was assigned. It was a year or two later, as I assisted in overhauling engineering job titles and work descriptions for the global corporation, that I became aware that the normal progression to Senior Designer took twelve to eighteen years and required hitting of milestones of patents, publications, conference presentations, and mastery of an array of technologies. Before I became aware of this, I attributed my promotions to external factors like the opportunities that I had been given and the support of colleagues within and outside the company. In my mind, my promotions had no basis in my accomplishments. I didn't see that I was given the opportunities because of my ongoing successes, attributing them, instead, to my inability to say "no" to an assignment for fear of failure.

I think it's easy for someone to say they feel inferior when actually they just feel a bit insecure. But that wasn't me, Aubrey; I felt the fear in my gut. My self-perception of inferiority was reinforced by another former engineering classmate, who started as an entry level design engineer months after my promotion to Senior Designer. He was one of the top students in our graduating class of mechanical engineers, completed a master's degree in mechanical engineering, and subsequently worked in the design group of a company recognized for their innovative design engineering. I was excited to see him join our engineering group. My role at that time had both significant responsibility and independence within the business unit, and this former classmate commented to me and others in our engineering department that because I had progressed to Senior Designer in so short a time, he would surely do it in less time. While his comments stung, my sense of inferiority as a design engineer left me thinking that he was probably right. Unfortunately, he had issues with absence of the autonomy that I had; he left within weeks. I could have felt smug, or vindicated by his departure, but I didn't. I was just disappointed.

Devil's Advocacy: A Forerunner to a Design Companion

I recognize that I don't make changes to how I do things until I am made aware that there is a problem. Facing those problems may not be easy, but in so doing I am given an opportunity to evolve professionally and personally.

One day my engineering manager came to speak to me about some grumblings regarding my behaviour. Coworkers, junior and more senior in the company than I was, felt that I was challenging them in design reviews because I wanted my design ideas to be chosen over theirs. This was jarring to me; *how could anyone think that I could compete with them?* I never cared who the ideas came from, just that all design options were considered, and the best agreed upon. My manager asked me why I pushed people so hard, and my response was surprising to him. *I felt inadequate compared to my colleagues' education and demonstrated design skills.* I told him that if I could ask probing questions of their designs, then they *must* have already considered them, and all I wanted to do was understand their design rationale. With some humor in his voice, my manager said, "*You don't see it, do you?*" A long conversation followed, but the core of his message was that I was one of the strongest design engineers he had worked with. My thought, paraphrased here for appropriate language, was, *this is nonsense*. I have to tell you, Aubrey; I knew most of the design engineers that my manager had worked with, and that had worked for him, and they were incredibly talented and skilled. It took him a while to lay out his argument for this discomfiting revelation. Though I reluctantly accepted his points, I still had to reconcile his perception of me with my perception. To this day, this fellow is a friend and mentor that I respect deeply, and who continues to demonstrate his respect for me. I have no reason to doubt his, but I still struggle with this at times, some twenty-five years later. There were two functional outcomes of that conversation. First, I had to recognize and acknowledge that I was a capable and valued mechanical design engineer. The second was a recognition that I had to change how I interacted with others. I needed them to see me as collaborative rather than competitive. I developed a persona that I would introduce at the start of any meeting where people sought my input; I was there as the *Devil's Advocate*, and I didn't have a *pony in the race*. I made it clear that my role was to understand and validate their design rationale and, in so doing, help them arrive at *their* best engineering design. Not everyone trusted this approach, but my participation, in the guise of the Devil's Advocate *persona*, was sought across multiple business units internationally, and by external customers and industry groups. From *my* perspective, my participation in design meetings was an opportunity for me to learn more about design as both individual elements and a system, as a collaboration, and as a process. I was asked to participate in ideation sessions, design reviews, and service issue resolutions for technologies that I had no knowledge of. I came to an understanding that my Devil's Advocacy approach, and my accumulated design knowledge, were *valued. Still, to me, I was only helping others to pull out what they already knew better than I did, but which they had not fully communicated.*

Devil's Advocacy, as I try to practice it, is a repeated questioning of why and how until an anchor can be established in fundamental academic elements, or in validated empirical knowledge. I used Devil's Advocacy before I named it and normalized it as my approach to collaborative design *reviews*. I apply it retroactively to discussions that I've had, sometimes returning to them again over years to seek new perspectives based on something new that I've learned. I still practice it actively in some discussions with others.

I've heard you and your closest teammates going at it more than once, Aubrey, so you might relate to this. My wife chastised me for always arguing with other engineers when we got together. What she heard was each of us trying to prove our perspective was the correct one. She said our voices were raised and we were visibly agitated. "They're not going to be your friends for long if you keep arguing with them," she said. That observation bothered me because I never experienced them as negative interactions. I always thought they were fun! I found myself asking other engineers how they felt about our "arguments". I don't recall any of us feeling that we were "arguing"; rather we felt we were debating, point and counterpoint, ***passionately*** *trying to* ***understand*** *each other's perspective. I was trying to find fault in my own thoughts, not trying to prove the correctness of my thoughts.*

More recently, my participation is increasingly sought for my perspective as an elder-engineer. Though I still ask questions to seek an understanding of the design at hand, I tend to couch guidance in the form of anecdotes and metaphors; I act as a Design Companion for their work.

The Voice of a Design Companion

Where Devil's Advocacy was essentially a design validation tool, the Design Companion started to emerge as a distinguishable voice when I began leading design teams involved with technologies that were new to them. As the person ultimately responsible for the design work of others with no knowledge or understanding of the technologies involved, I had to shift from design validator to design coach. The emergence of the Design Companion persona was not immediate. It likely began when one of my designers started asking me "why", mirroring my own Devil's Advocacy practice. It was either a realization or a reminder that I had to elevate the knowledge and skills of other designers as a determined and consistent practice.

There is not a prescribed process in being a Design Companion. I do whatever it takes to introduce, scaffold, and cement new ideas for design engineers. I introduce reference materials and samples (artifacts) that are unfamiliar to the designers as discussion points to guide the design thinking that I wanted to see in them. I find anecdotes an effective way to simultaneously scaffold and validate new design ideas, so I add them as appropriate. I understand that design decisions can be contextual, so I intentionally "lead designers down the garden path" on a trail of thought that could be supported by relevant principles of engineering and design. After following that path to its terminus, I lead them to see the limitations of that trail of thought in that context. Before they become frustrated with my seeming deception, I show them how to step back and follow another fork in the trail. I pose "what if" scenarios as design alternatives, and have them explain how they would proceed, pointing out any concerns and nudging in another direction as needed. When a designer is overwhelmed, either failing to see the trees for the forest, or the forest for the trees, I re-center them outside of the design issue and ask them questions to gain the converse perspective so that they simultaneously see both the macro system and the micro elements of the system. Perhaps most important, I allow the designer to feel comfortable with not knowing something at this early stage. I achieve this through a mix of humour (often self-deprecating, sarcastic, and witty as appropriate to the designer's personality), and reflections on my own and others' design mistakes. Perhaps the most important aspect of the Design Companion persona is the celebration of the designer's understanding and eventual mastery of their new knowledge.

The *voice* of the Design Companion is a separate and distinct manifestation of *my* Design Companion persona; a persona that I have employed in practice to guide the evolution of other design engineers. By making my inner reflective voice, my Design Companion, a unique entity in its own right, it is liberated from my solitary practice to become an abstract presence. The intent of that presence is to convey, to the reader of this thesis, insights into the impact of my experiences in design processes and design considerations on my own evolution as a design engineer. In so doing, it is hoped that other instructors and learners of mechanical engineering design may recognize that, and how, their lived experiences affect their own evolution as a mechanical design engineer.

To be clear, Aubrey, I don't hear a disembodied voice debating my design decisions, or more correctly, my dialogues are perceived within my consciousness to be in my own voice. I generally try very hard *not to let the dialogue out where other people can hear it, though I occasionally slip, to the amusement of some. Of course, you've witnessed my internal design "debates" firsthand, Aubrey. You've heard me intentionally demonstrating my Design Companion's approach: I verbalize my internal dialogue's voice, simultaneously the proponent, inquisitor, and coach's thoughts, as something of an oral stream-of-consciousness where the voices comingle without oral distinction, as if arguing with myself. Distinction, to those witnessing this exchange, is communicated by means of exaggerated body language, as if I am initially an actor portraying both roles and then the two roles becoming one toward the reconciliation of the final design.*

Because a Design Companion dialogue is central to my engineering design practice, my goal in this thesis is to use the Voice of the Design Companion as a means of communicating design development. The issue with this approach is that I have, to date, only demonstrated my Design Companion persona in oral form, with no practice in written form. How, then, to distinguish a Design Companion dialogue from academic-style writing?

One aspect of my thesis is the design of three instructional artifacts which may be used to improve the teaching and learning of the physical meaning of dimensional tolerancing. While the final designs of those artifacts should be of value in the improvement of practice for teaching and learning on the specific topic, they are simultaneously instruments to share my design thinking. The sharing of my design thinking is the underlying focus of this thesis. By sharing my design thinking, and its evolution, through a self-reflective study, I hope to motivate other learners and instructors to consider their own lived experience and its impact on their mechanical engineering designs.

The development of teaching artifacts would normally be addressed as a design methodology study. Improvement of teaching methods is addressed by qualitative methodological approaches. The integration of both aspects into a single study is unconventional for a mechanical engineering design thesis. A typical mechanical engineering design thesis approach would be rooted in academic mechanical engineering design theory. There is, however, no mechanical engineering design theory that addresses the *cognizance* of magnitude of scale, much less at micron-scale where my instructional concerns reside. Instead, I must rely on my personal experiences and supporting research in tangential fields to develop these artifacts. However, it seems inappropriate to communicate my personal and professional experience in a typical academic voice, and yet that experience is appropriately included in engineering design. An alternative voice is needed to convey my lived experience as a core element of my designs. Qualitative methodological approaches allow representation of study findings in ways that are unconventional in engineering design studies but may be effective in sociological studies. My thesis must reflect both conventional academic content and an unconventional conveyance of my design thinking, which is rooted in experience and resides in the realm of qualitative study. As expressed previously, unconventionality is my domain of operation.

As I explored my writing style, I was pointed in the direction of Shawn Wilson, an Indigenous scholar. I reference his work with permission. As a critical element of his doctoral thesis and subsequent book, *Research Is Ceremony – Indigenous Research Methods* (2008), Wilson sought a way to distinguish between conventional academic writing and a narrative style that would incorporate the relational accountability of Indigenous oral communication traditions. This resulted in two critical stylistic departures from conventional academic writing. First, he determined that the use of a different typeface provided a visual distinction between the two communication styles in his writing. Second, he determined that addressing his narrative content to specific people, specifically to his sons, would provide the relational accountability that reflected traditional Indigenous oral storytelling.

Wilson's approach (2008) provided insights into how I might resolve the combination of elements that I identified for my thesis. My Design Companion approach can be seen to invoke a separate voice, distinct in that it conveys my lived experiences, both personal and professional. To distinguish and visually emphasize the informality of this voice from conventional academic writing, a *stylized typeface* is used. In addressing his narrative content to his sons, Wilson also used language that was more conversational and less academic. As mentioned in the introduction, I have chosen to address the Voice of the Design Companion to Aubrey, an embodiment of the students and early-career design engineers that I have taught and with whom I have enjoyed the privilege of far-reaching conversations. In the context of my thesis, and considering that my Voice of the Design Companion is addressing a former AGC student, it would feel inauthentic for the Voice of the Design Companion to exclude language and terminologies that are not above a conversational level. To reinforce the notion that our discussions were centered in the profession of engineering, such conversations were informal as is my practice in engineering meetings, but intentionally invoked professional, technical, and sometimes academic, language as appropriate.

This rhetorical voice, the Voice of my Design Companion, is at times an anecdotalist, used to convey my self-reflexivity, recounting anecdotes from my past. At other times, this voice exemplifies my thoughts on the evolution of the three artifact designs. To demonstrate the voice of my Design Companion, I offer the following:

Hello Aubrey. As I was considering this idea of a rhetorical voice representing my design processes and my lived experiences, I wasn't sure that this idea would be taken seriously in academia. I wasn't confident that I could effectively distinguish it within the text of a thesis. But, I realized that most of us employ our inner personae without conscious thought. We talk, behave, and respond differently when we are with our families, our friends, or our colleagues, or … public authorities such as the police. And, sometimes, we intentionally act as a separate and distinguishable persona.

I remember sitting in my calculus class one summer, waiting for the instructor. In walked this disheveled old man. He wore beat-up work boots with orange-and-white striped socks to his knees. Cut-off denim farmer-john bib-overalls, with a soiled t-shirt underneath it. His facial and body hair were all long, white and grown wild. He had a vivid orange longshoreman's cap with an orange pom-pom, on top of his head. A beat-up canvas backpack over one shoulder. I had no idea why he was there, but he sure didn't look like he belonged there. As he walked toward the front of the class, he introduced himself in a scratchy, slightly pitchy New England accent; "Hello, I'm Professor Schneider." He disliked textbooks and suggested that any engineers in the class should track down an old copy of *Professor Schneider's Quick & Dirty Calculus* handwritten notes which he had first circulated to engineering students in the 1960s or '70s. The title, as we were advised, was based on the fact that he cut out all the derivations that he felt were useless to engineers, and he had annotated the text with … illustrations … that were not appropriate in the 1990s. He made it clear that he would help students at any hour of the day or night, anywhere the student wanted to work, and preferably in one of the campus bars. He urged us to take him up on his offer of assistance because otherwise we would meet *Dr Bastard.* As he introduced his second persona, his voice shifted to a gravely bass. It was a brilliant bit of theatre which made clear what to expect.

Upon recalling that anecdote, I was comfortable that the idea of outwardly representing an inner voice *could* be accepted by others, if it is made distinct from the academic voice.

Anyway, Aubrey, when I started teaching as an EiR, I recalled Professor Schneider, and adopted a similar approaching in introducing the duality of my presence. I made myself available anytime, and some of you would drop in, sometimes at 1 a.m., to ask a question, or to chat. I told you, Aubrey, and your classmates, that I would push you all harder than you may have been pushed before, and that I would be harsh when students don't engage with the content. It terrorized some students until they realized it was a tactic that I used to get students to ask for help before falling irrecoverably behind. I have to thank you, Aubrey, because, year after year, you and your classmates fostered the course's reputation of being challenging but rewarding, *even advising friends to ride out the first couple extremely heavy weeks. Because of that reputation, some of my best students registered specifically* for *the challenge.*

As the reader now understands, I use this voice as a self-reflection of my experiences, providing glimpses into my past and how it shaped me as a person, and subsequently as a mechanical design engineer and even as an instructor, and I use this voice to reflect my design thoughts throughout the design evolution of the three artifacts.

Chapter 4 Artifact Design

Having identified the need for artifacts to be designed to aid in the teaching of micron-scale dimensional tolerancing, I proposed three artifacts:

1. A visual comparison graphic of items that are both identifiable and relatable in the size range of 1µm to 1000µm (0.01mm to 1mm).
2. A primarily haptic demonstrator of the five clearance-Fit-Classes based on ASME B4.2 Preferred Fits; loose running, free running, close running, and sliding. The transition and interference fits included in the ASME B4.2 standard represent static engagement of components and provide no sensory distinction or value in the development of perception of magnitude.
3. A visio-haptic demonstrator of micron-scale magnitudes from 1µm to 1000µm.

The artifacts are meant to demonstrate dimensional tolerance ranges that are common in moderate to high precision material-removal manufacturing processes, and which are typical within Fit-Class clearance tolerances. Furthermore, these tolerances generally have sub-millimetre and typically micron-level values, which are difficult to distinguish with unaided vision. Some justification for the stated limitations of these three artifacts is warranted.

Justification of Artifact Limitations

Regarding the **first artifact**, the graphical comparison chart, the range of 1-1000µm represents a range from loose tolerance of high-precision, non-visible magnitude to easily visible magnitude. For reference, the visibility threshold for unaided human vision is 26-40µm

(0.026-0.04mm at 15cm from your eye) (Wong 2010, Deering 1998). This range includes clearance Fit-Class tolerances and is therefore appropriate for consideration in this context.

Regarding the **second artifact**, the primarily haptic demonstrator of clearance-fit classes represents five of the ten Fit-Classes. Five Fit-Classes defined within ASME B4.2 (ASME 1978) as loose running, free running, close running, sliding fit and locational clearance, provide varying clearances between the mating male and female components of the same cross-sectional geometry, typically cylindrical. These fit classes ensure that the parts will allow relative motion between one another, which means that they *might* be experienced visually but specifically *can* be experienced haptically. The other five fit classes defined within ASME B4.2 (two classes of locational transition, locational interference, medium drive, and force fit) all allow that either there *might not* or *cannot* be clearance between the components. If included in a fitment demonstrator, these last five classes would not show any visible clearance between the components and would not allow any haptic response because there would be no relative motion between the components.

The **third artifact**, a visio-haptic demonstrator of micron-scale magnitudes from 0.01 to 1mm, is intended to provide the user with a basis for visually and haptically appreciating various sub-millimetre magnitudes. It is expected this may establish a foundation for estimating magnitudes in this range, which is typical of moderate-precision manufacturing capabilities.

I consider these as the starting points in the design considerations for the three proposed artifacts.

On the Topic of Design Considerations

I've noticed, Aubrey, that you and your classmates use several tools to help guide your ideation; that is, your brainstorming. I was taught a different approach. I remember that my third-year mechanical design instructor, Professor Geza Kardos, at Carleton University in the early 1990s, focused on introducing ideation methods and developing design goals. As I recall, qualification of a design against requirements was largely a qualitative evaluation against loosely defined design goals. I remember my classmates and I were bothered by this because we believed that engineering design was all about the application of math and science. Professor Kardos was an experienced mechanical design engineer, and he seemed to reject that perspective. Instead, he focused on creativity in engineering design and using engineering principles as design tools. What I remember most about his classes was him just sitting on the corner of his desk, telling us about his approach tom the design of his biggest projects, and answering our questions. He was one of the few professors that talked with us about life as a mechanical design engineer. About twenty-five years later, just after I started teaching at the university, I contacted him and thanked him for his insights. He appreciated that I'd remembered him and his anecdotes after so long.

Over my career, I have observed that industrial-sector mechanical design engineering is often rooted in design history and individual creativity, supported by engineering principles and theory. In 2016, I re-entered an academic environment with the Price Faculty of Engineering, University of Manitoba, as an Engineer-in-Residence. My experiences advising capstone project teams, cocurricular engineering teams, and engineering-related case competitions brought me into regular contact with engineering students from around the globe. Through those interactions, students communicate their observations that mechanical engineering design process courses seem to focus increasingly on pre-determination and quantification of design criteria as the basis of mechanical design ideation and decision making. This is an understandable starting practice for new mechanical designers; it is even somewhat closer to what I had expected in my undergraduate engineering degree. As a designer and consultant in industry and as an advisor of capstone projects, I have repeatedly observed new mechanical design engineers focused on meeting the criteria as *the goal* of ideation and, as a result, I have found that the formality of a structured set of design requirements often stifles creativity and may preclude elegant alternatives, the outside-the-box ideas. My usual ideation process coarsely postulates general, and undocumented, considerations as starting points, often in the form of queries rather than criteria or rules. I then *qualitatively* assess design changes and ideas against the queries as the design progresses. This allows me freedom to add, remove, escalate or subside any given consideration as a design evolves. I have found that this results in a flexibility to diverge from a *logical* or *expedient* solution, often establishing a more elegant design in practice.

We never had a reason to go over this in AGC or the MDSW, Aubrey. Design elegance. It's not so much a designation as it is a coveted status, highly valued and respected by experienced *design engineers. What makes a design elegant will differ by engineering field, but generally suggests an evident clarity or cleanliness of the design beyond what a typical practitioner would derive. Design elegance often reflects a* *simplified solution that addresses the core requirements with an element of flair that elevates the design stylistically or aesthetically above mere functionality. I feel that a rigorous set of design requirements is antithetical to design elegance.*

I view generalized design considerations as a distillation of the design's statement of need into its root elements. To some, the vagueness of general considerations rather than absolute functional requirements may imply that mechanical engineering design is a solitary endeavor undertaken by an all-knowing engineer. That is far from reality. Engineers use the term *clean sheet design* to mean *starting with no legacy design on which to base the new work*. Engineers experienced in clean sheet design will have encountered the dynamism and unpredictability of a fluid and evolving design project; if they are fortunate, they will have encountered the limits of their contemporaneous knowledge and gained new knowledge that they could not have foreseen. Copernicus (n.d.) wrote, "*To know that we know what we know, and to know that we do not know what we do not know, that is true knowledge*". New mechanical design engineers have a burgeoning start on the first component; their formal academic and design courses constitute *that which they know that they know*. This is the grounding that they trust and rely upon. From experience, I recognize that junior designers also do not realize *all* that they know; they often give little credence to what they have learned from experiences outside of academia. Experienced designers, however, build upon their foundational engineering knowledge with tangential knowledge that they have garnered from other designers and other sources, formal and casual, but which they have not yet proven for themselves a validity beyond trust in the source. In this way, design is not a solitary endeavor;

those that contributed to any knowledge that the designer draws upon in their design are indirect participants in your final design.

The second part of Copernicus' thought, however, is a constant burden to new designers. Accepting that ignorance is the opposite of knowledge, I suspect the Copernicus quotation is the genesis of the aphorism, "*Ignorance is not knowing what you don't know,"* (unknown source). In terms of mechanical engineering design, the relevance is that a new designer may not be aware of any predecessor designs or technologies that have been developed to solve the same, similar, or constituent problem, and therefore, by extension, cannot be expected to consider it in undertaking their design work.

You made me think, Aubrey, when you asked me how to search for something that you don't know exists. I think it's easier now; you google a few key words and start looking through the images that come up, then follow rabbit holes until you find something useful. Search engines weren't very advanced in the '90s, and the internet wasn't much use in engineering searches. I was working on a consumer product safety issue, and I had to design a fixture to hold workpieces for inspection of their precise and intricate features. When I finished, I submitted the design for process planning. A former machinist visited me with a fixturing catalog in hand. He estimated the fabrication cost for my design would approach twenty thousand dollars. From the catalog he showed me a fixture that could provide the core functionalities that I needed but would require modification and a few new parts. The estimated cost of the proposed alternative would be perhaps three thousand dollars. Until then, I hadn't thought of fixtures as commodity items. Since then, I make it a habit to *review technical catalogs and historical design texts on mechanical mechanisms for ideas that might be relevant to a future design.*

The relevance herein to the idea of design considerations is twofold. First, because a designer does not know the final design until it is complete, they cannot anticipate *all* the design considerations that will emerge during the design evolution. Second, to evolve their design knowledge, a mechanical design engineer must actively indulge a sense of curiosity beyond their current experiences. Collectively, these two thoughts represent that a list of design considerations or criteria cannot be fully developed in advance of the design process, but rather will evolve with it. In my experience, design is a fluid and iterative process that necessitates an evolving design criteria, as well as a broad knowledge base.

Development of Design Considerations

A few times now, you've heard me mention that my career has been unconventional, and that I had developed a reputation for unconventional solutions. But I don't think I've ever mentioned what made my solutions unconventional. First, I should explain what a conventional solution entailed. Almost none of the design engineers that I worked with were provided significant freedom in their designs; instead, they were typically provided with a set of functional requirements, design practices, and standardized manufacturing processes that they weren't allowed to deviate from without approval. In a large global corporation with a couple hundred design engineers, it was important to standardize. That was the design engineer's world of convention. Most of the time, designers could work within those constraints. Sometimes, however, they couldn't find a workable solution. Other times, a workable solution was later found to have a significant flaw that other designers couldn't overcome. As they say, timing is everything, but a robust knowledge of engineering design and manufacturing, and friends that are machinists help. In my memories, it always seems that the issues came to me mid-Friday. It wasn't *always*, but it felt like it. Anyway, I would have to produce a complete set of engineering drawings, released and ready for process-planning by the time that team arrived on Monday morning. That's the timing element … there were no managers and few designers around on weekends, so no one interfered with my design. Those weekends could top forty hours of overtime. Anyway, I'd usually quickly exhaust conventional design options, then I'd rethink the original issue, and start a clean-sheet design. I would consider *all* of our shop's machining capabilities, not just the conventional setups and fixtures. I would consider non-standard tooling sizes, and geometries that would normally be too complex and too expensive to use. In the worst cases, I'd rethink the problem that was put to me and consider whether I needed to go up a couple levels in the design to resolve the issue by preventing it from ever occurring. In my early design days, managers would sometimes have a more senior designer try to oversee my work on an issue resolution, but those designers would try to restrict me to the conventional. They were stuck inside a proverbial *box of conventionality*, regardless of the circumstances. My managers quickly recognized my abilities and left me alone once a special issue was assigned. Over time, word spread within the company, and it wasn't unusual for me to pass by a meeting room in another business unit, only to be stopped and called in for a quick brainstorming session or to discuss a design for some technology that I had no *knowledge of. By then, I had introduced my Devil's Advocate persona. Eventually, my manager let other managers know that I was being distracted from my own work to help others with their issues, so those impromptu meetings decreased. Then he started getting requests for me to work on another business operation's issue. My manager was pretty judicious with my time. When he accepted an outside request for my help, he would warn them that, while they would get a solution, it might not be to the problem that they thought they had. My reputation of design unconventionality had preceded me.*

From my review of McGarry's thesis (2005), general considerations for the design and use of esoterica artifacts were extracted and used to generate the structured collection of general artifact design considerations structured as queries in Table 4.A. For tracking purposes, each consideration query is given a consideration number (C#).

Still, the list of extracted general considerations is inadequate in that it does not include size and mass, materials, durability, surface finishes, handling, marking methods, and the like, as applicable to each of the three artifacts. The next challenge was to contemplate considerations specifically applicable to tolerance demonstration artifacts. This resulted in Table 4.B.

Design considerations C21 through C32, and their subordinate elements, represent aspects that I commonly consider in design projects, but is intentionally not exhaustive. I have found that it is not possible to foresee all design considerations before the design is complete.

Upon developing this *preliminary* collection of considerations, *I still do not yet know what I do not know of this design*. Just as a complete list of design considerations can only flow from a completed design, so too must it be understood that not all design considerations will be relevant to each artifact design, and therefore may not be discussed in the context of any of the three artifact designs. The use of the accumulated design considerations is demonstrated in Appendix A.

Table 4.A General artifact considerations

C#	Consideration Query
C1	What are the instructional goals for the artifact? What are the learning goals for the artifact?
C2	Are all features incorporated into the artifact meaningful in their use? If not, can they be excluded from the artifact?
C3	Are there other existing artifacts, individually or collectively, representing the same concepts? If so, explain why this new artifact design is needed.
C4	Is the artifact design rooted in a predecessor? If so, identify predecessor and describe insights (strengths and deficiencies) carried over to the new artifact.
C5	How is the artifact broadly useful? If not, identify specific limitations (sizes, conditions, etc.).
C6	How has the artifact been designed to be extended in use from the particular context to additional practical uses?
C7	How is the underlying technical concept clear and distinguishable from the physical details of the artifact?
C8	What are the specific design elements and functionalities represented by the artifact?
C9	What elements of the artifact design are intertwined in ways that are not immediately apparent? Explain any changes to the artifact that are necessary.
C10	How are critical and non-critical physical characteristics of the artifact differentiated?
C11	What is the anticipated usage environment (lighting, temperature, hygiene, other)?
C12	What sensory inputs are anticipated in the artifact's use? Visual / Olfactory / Haptic / Auditory / Taste / Other
C13	How are intended functionalities of artifact made explicit?
C14	What other artifacts should / must be chained with this artifact to convey the core concept?
C15	What other chain of artifacts may this artifact be added into or substituted to convey a core concept?
C16	Will the artifact be produced physically? How will the artifact be incorporated into teaching?
C17	What are the limitations of useability based on location, disability, capability, or capacity?
C18	How does the artifact design encourage a critical evaluation of merits and concerns about the elements demonstrated? How may the artifact be used in group discussion?
C19	How do you anticipate the user's perspective and understanding of the various elements to evolve as they engage with the artifact?
C20	Is the technical nature of the artifact effectively documented and communicated such that instructors can readily understand and use the artifact?

Table 4.B Tolerance artifact design considerations

C#	Consideration
C21	Safety
	Injuries - Significant Potential
	Injuries - Moderate Potential
	Injuries - Low Potential
C22	Ergonomics
	Vision
	Finger size
	Weight Limit
	Size Limits
C23	Operating / Usage
	Lubrication
	Hygiene
	Static / Dynamic
C24	Assembly
	Complexity
	Features
	Techniques
C25	Design Complexity
C26	Aesthetics and Handling
	Colours
	Chamfer / Radius / Sharp Edges
	Surface Reflectivity
	Text Format

C#	Consideration
C27	Communications - instructions
	Pack/ Unpack
	Handling
	Use / Operation
	Learning Goals
	Maintenance
C28	Material
	Durability
	Corrosion
	Lubrication
C29	Manufacturing
	Design Complexity
	Processes
	Tolerance Requirement
	Surface Finish
	Markings
C30	Shipping
	Method
	Packaging Type
	Size
C31	Design Rules of Thumb
C32	Reference Artifacts

Design Development

A Non-Linear Approach to Ideation and Design Evolution

I perceive my thought processes, specifically as relate to ideation, design evolution, and decision making to be rooted in managed chaos. My thoughts typically run multiple steps ahead of the design stage that I am working on, creating thought-branches like the naked canopy of a tree. Each primary branch represents design considerations. Each secondary branch represents design options that will fulfill each consideration. Tertiary branches represent limitations or concerns related to each option, and each stubby twig represents a potential resolution to each limitation or concern. Some branches grow more substantially than others. Some branches are pruned as I recognize that an investigated design consideration is not a valid consideration after all. As a thought process, the canopy continues to develop, iteratively and interminably, long after I have released the final design. I perceive it as chaotic because I jump between branch levels, twigs, and prunings as ideas and concerns come to me. I recognize that many people have had concerns about how I resolve design issues, and yet I developed a reputation for effective, though unorthodox, solutions.

Just as you have asked me how I come up with answers and anecdotes so quickly, a colleague once asked me why I made what he thought were rash decisions, without enough information and without much thought. It wasn't the first time that I'd been asked similar questions, and I had already given it some consideration. As a thought exercise, I asked him how he decided what he was going to have for dinner that evening. He stopped his work, thought about it, then answered as I worked away on a design project. He said that on the way home from work, he stops at a large grocery store and walks through the meat department to see what appealed to him at the moment. From there, he would backtrack through the produce section to see what he wanted to go with it, and then walk the various aisles to see what side dish ideas appealed to him. He said that grocery shopping regularly took up to an hour per day. Then he would go home and make his meal. He didn't indicate any preferred food type or recipe that would be included in his decisions. I found his thought process was extremely linear and time consuming. He asked how I would decide on my meal for the evening. As I continued to work, I described the fresh ingredients and leftovers in my refrigerator and freezer, the ingredients in my cupboards, and my collection of spices. As I added each new item to the running *inventory, I commented on which items would go well together, what dishes I could make, and any ingredients that were missing and would have to be purchased on the way home. At the end, I told him what I had decided on for that evening's meal, and what I would probably make for the next few days as well. My colleague was stymied that I had processed all of that so quickly while maintaining productivity and conversation at the same time. He commented that my process must be mentally exhausting. I explained, that's just how my mind works, all the time. Looping back to his original comment, I explained that what he perceived as a rash decision was actually an unknowable number of branches of inquiries, resolutions and evaluations that included unstated criteria and considerations that my mind had worst-cased into the fray in the absence of full information. In practice, my managed chaos was highly effective for me and, when one of my problem resolutions eventually failed, I was able to pivot, change resolutions and implement again before some designers determined their first resolution. If you think about it, Aubrey, that's how I walk you through GD&T application options in class or at my desk, just slowed down a lot.*

This is not just my decision making process, it is also my thought process, and my design process. Putting voice to my Design Companion is an effort to organize the chaos and express my thoughts on each artifact concept.

Design of a Visual Comparator Graphic – Artifact #1

The idea for a visual comparison graphic of dimensional magnitudes surfaced before I started my graduate studies; I was advised by students in my 2016 Advanced Graphical Communications course that they had no basis of understanding for sub-millimetre tolerances, much less at the micron-level. As I renewed my search for practical physical samples to demonstrate the magnitudes involved, I confirmed that there was nothing commercially available. As design of physical samples can be time consuming and manufacturing of precision workpieces can be costly, I reconsidered my approach. I had already been instructing students to use common, readily available items to approximate some magnitudes for comparison. I had several small metal rulers, 150mm long and approximately 0.5mm thick, and some students acquired the same. I had mechanical pencils with 0.5 and 0.7mm leads. The metal ferrule that supported the 0.5mm lead was 1mm diameter. I introduced other artifacts, but none were adequate to demonstrate low micron-scale magnitudes.

It is common for industrial parts suppliers to produce graphics showing differences between related items as aids to recognizing size, configuration, and other similarities and differences between objects. In the domain of mechanical design engineering, these are common for metal extrusion profiles, fastener types, fittings, etc. The idea of graphics depicting the size comparison of known objects had merit in my context.

The next step was to determine a list of comprehensible items in the sub-millimetre range. From the comparison values that I incorporated into the graphic used in my AGC course, Table 4.C includes comparisons from 2500µm to 0.5µm (2.5mm to 0.0005mm). The larger values, 1 and 2.5mm, were included as a visual calibrator for users of the graphic because both sizes were easily distinguishable on a standard metric ruler which typically has minimum increments of 0.5mm marked.

To this point, I have focused any discussion on SI metric units. While most countries work primarily in SI metric units, I recognize that Canadian industry, and therefore Canadian mechanical engineering programs, often work in both SI metric and US customary units. To provide the greatest value to students in my AGC course, US customary inch-units were included in the AGC graphic for several of the comparators; see Figure 4-1.

Table 4.C Scale comparator values used in AGC course

Comparator Description	Size
None provided	2500 µm (2.5 mm)
None provided	1000 µm (1 mm)
None provided	250 µm (0.25 mm)
None provided	100 µm (0.1 mm)
Human hair	50 – 90 µm (0.05 - 0.09 mm)
Table salt	60 µm (0.06 mm)
Visibility threshold	30 – 40 µm (0.03 – 0.04 mm)
White blood cell	25 µm (0.025 mm)
Dust mite feces	10 µm (0.01 mm)
Red blood cell	8 µm (0.008 mm)
None provided	2.5 µm (0.0025 mm)
None provided	1 µm (0.001 mm)
None provided	0.5 µm (0.0005 mm)

Stylistically, several design factors needed to be considered:

- whether to distinguish each magnitude-representation element as a single line, or as geometric shape representing a zone
- layout of magnitude-representation elements to optimize visual comparison of sizes
- whether each magnitude-representation element would be made distinct by a solid colour fill or by differentiating the lines representing the elements
- line style(s)
- colour selection
- how to label magnitude values for each element.

A collection of individual linear lines in close proximity does not imply mating geometries, which are the purpose of ASME B4.2 fit-basis tolerances. Reflecting on the historic nature of fit-basis tolerancing, the B4.2 tolerance values were likely based on the most common precision-fitted geometry, the circle. In practical terms, I have observed that mating or engaging systems such as hydraulic and pneumatic cylinders, telescoping and nesting elements and other applications are typically based on nominally cylindrical geometries. Though modern manufacturing processes facilitate the production of high-precision geometries of any shape, the predominant machine shop tool of high precision would, historically, have been the metal-cutting lathe. Lathes are used to remove material from a block of material (such as metal or plastic), and create geometries of circular cross-section and flat surfaces perpendicular to the axis of the lathe. Based on the nature of the lathe, turned features (i.e., features machined on a metal-cutting lathe) that can provide an engagement with other turned features would be limited to cylindrical, conical, and spherical geometries, all of which are based on circular cross-sections.

On the first day of AGC, I explained to you and the class that I use "pins" and "holes" to generically simplify male and female mating geometries. Somewhere along the line, I failed to explain this effectively, and recently I had a training client ask me what to do with all the other features on a part. It took me a minute to realize that they thought I was talking exclusively about literal pins and holes. I had not made the connection that "pins" and "holes", respectively, are representative of any features that protrude from or *intrude into the nominal workpiece. For example, a boss, tab, key, or flange is a pin, whereas a slot, keyway, cavity, bore, or any shape of cutout would be a hole.*

In this light, it seems reasonable to use a circular line (or lines), or enclosed circular geometries, to represent each magnitude value or range of values.

The next question of representation relates to the layout of magnitude-representation circles to optimize visual comparison of sizes. Laying them out randomly would not allow an easy correlation of magnitudes, while a Venn diagram layout would be too chaotic to gain any comparison and would imply an interrelation between some of the circles, but not others. The evident interrelationship is that each circle would be entirely nested within the next-largest circle element. That leaves me two options: (1) All circles laid concentric on the same point; (2) All circles contacting on their tangency at the same point. Laying the magnitude-circles concentrically may reinforce the idea that they represent the *ideal* engagement relationship between mating components. However, in reality the mating elements do not locate concentrically, but rather they predominantly engage at a tangency established when one of the elements shifts into contact with the other mating element. This suggests that the second option, the circles contacting on their tangency at the same point, is the more realistic scenario. As this study is rooted in practice rather than theory, this is the preferred option.

The question of whether to represent each magnitude-circle with a distinct solid colour fill or by differentiating the lines representing the elements initially seems a matter of preference. *Historically*, mechanical engineering education included a series of courses in drafting and emphasized the differentiation of line styles and line weights. The ASME Y14.2-2014(R2020) standard indicates line styles appropriate to mechanical engineering drawings.

Together, these guide me to use solid-colour filled elements where possible, with minimal use of distinct line type for differentiation.

Extending the preceding thoughts, solid lines of consistent line width will be of primary use, with a long-dash line used where further distinction is needed, as in the representation of the size of table salt in Figure 4-2, which is within the range of width of human hair. Line thickness should be minimal, perhaps 1 – 5 points (on a full-size print) for drawing hygiene. Colours should be opaque and adequately bold to contrast with adjoining colours.

If you think I'm fussy about your drafting, Aubrey, you should have met my *drafting instructor. Before CAD software, we drafted by hand, on boards or tables, in black pencil. Earlier versions of that course required drafting in black ink! Either way, a draftsperson was judged by the hygiene of their drawings. In the 1990s, CAD (Computer Aided Design) software gradually replaced board drafting in industry, and engineering schools followed. I could draft geometries, but my instructor made it absolutely clear to me that my drawing hygiene was … poor, which contributed to my belief that I could never be a good mechanical design engineer. Fortunately for me, this shift from manual to CAD drafting was accelerating as I entered the regular workforce. Unfortunately for industry, this shift also ended conventional drafting courses in engineering programs and the understanding of appropriate use of line types and weights. As a result, I have noticed that most senior mechanical engineering undergrads have no understanding of line types on* *engineering drawings. I was surprised that you and your classmates were challenged to recognize subtle-to-moderate differences in drawings before I taught you all to check drawings. Well, I shouldn't have been surprised, really. I've noticed that designers that are just a few years younger than me, have trouble checking drawings. Because of this loss of skillset, I think it would be unreasonable to expect future users of a graphic to distinguish between subtleties of line representation; I need to make differences bold and noticeable.*

Where not possible to clearly place text within the respective magnitude-circle, text should be superimposed on a coloured background consistent with the magnitude-circle being labelled. For a consistent appearance, and wherever possible, text and leaders shall be black. Where black text visibility is inadequate on a given background colour, white text will be substituted.

The resulting graphic, shown in Figure 4-1 and magnified for detail in Figure 4-2, was incorporated into AGC course materials and circulated freely to my industrial clients.

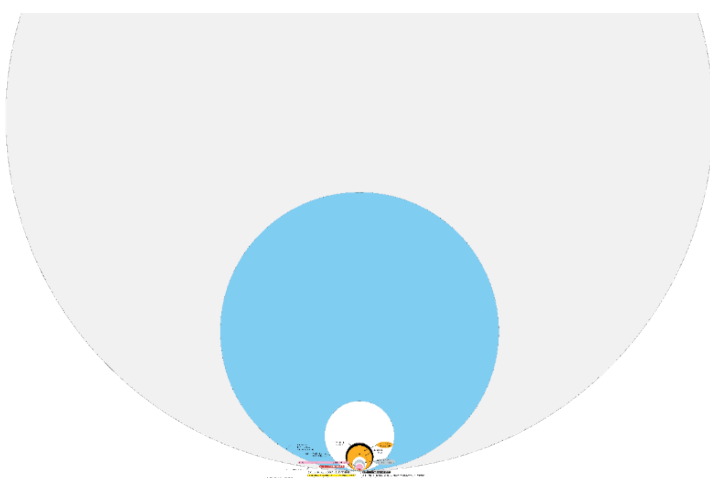

Figure 4-1 AGC Unit scale comparator (intended for large-format printing)

As I review the detail view (Figure 4-2) of the unit scale comparator graphic for the similar but slightly different context of a design artifact, I believe that the graphic was effective for its original purpose but includes a 2.5mm magnitude-circle that is not needed. The graphic includes magnitude-circles for several values for which, due to their extreme size, I did not consider a physical object as comparison counterpart.

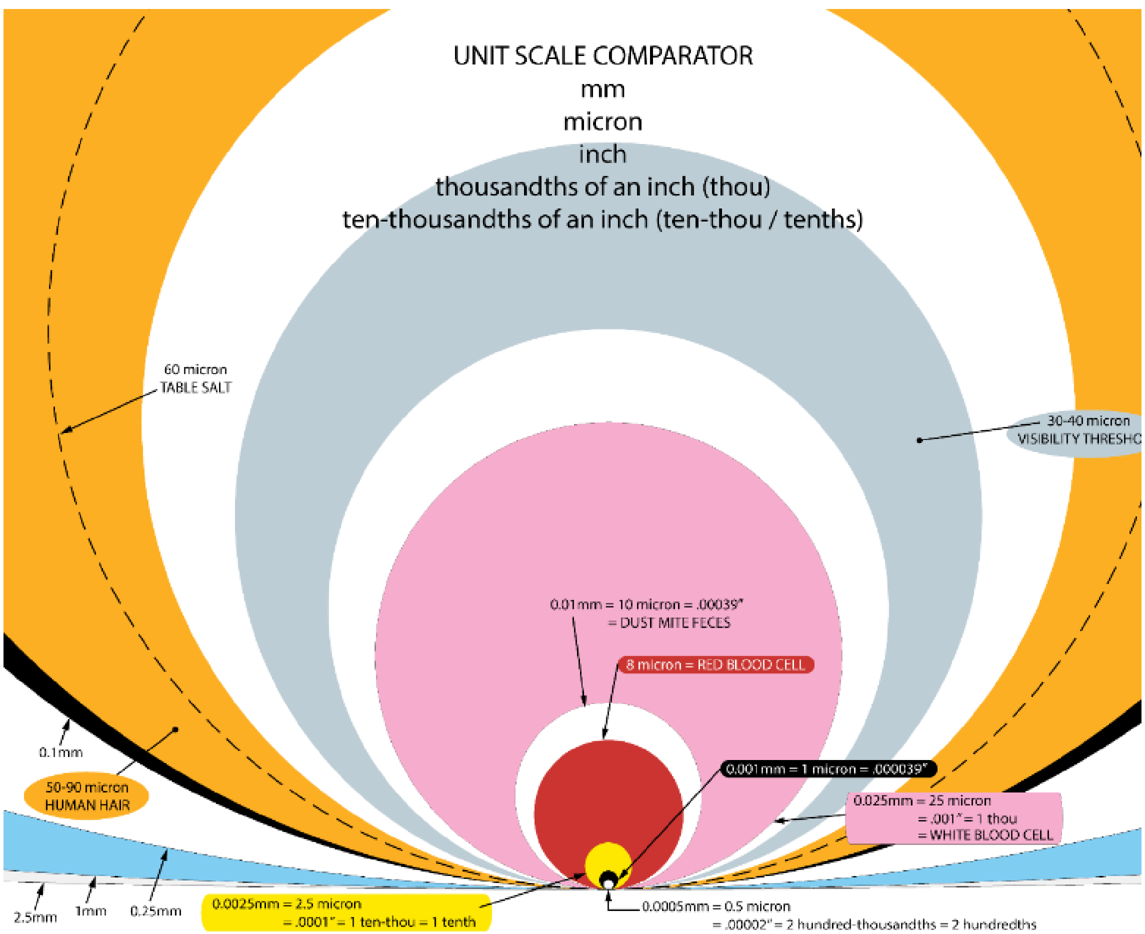

Figure 4-2 AGC Unit scale comparator – detail view

Of the remaining magnitudes for which physical object counterparts were not provided, the following are now identified:

- 1000µm (1mm): thickness of a Canadian dime
- 250µm (0.25mm): 30 AWG (American Wire Gauge)
- 100µm (0.1mm): 28 AWG
- 25µm (0.025mm): 50 AWG.

AWG (American Wire Gauge) initially seems like a strange basis of comparison for these extreme sizes because they are used in data cables, which are typically not in the design purview of mechanical design engineers. However, I realized that most engineering students have experience with, or access to extremely fine wire as found in data cables including USB,

HDMI, coaxial, and similar, and therefore they may be relatable. Specific cable types (e.g. USB-C) are not provided in the graphic because cable types may, in the future, be removed from regular use, and therefore the graphic would become outdated. Instead, users of the graphic can search for current cable technologies that use the indicated AWG size. The remaining magnitude circles, (2.5µm, 1µm, 0.5µm) reflect extremely precise manufacturing capabilities and do not have readily identifiable physical object counterparts; they will be left as numbers only.

As discussed previously for the AGC graphic, inch-equivalent values will be included in the new artifact.

The final design for Artifact #1 is provided in Figure 4-3, and in larger scale in Figure A.1.

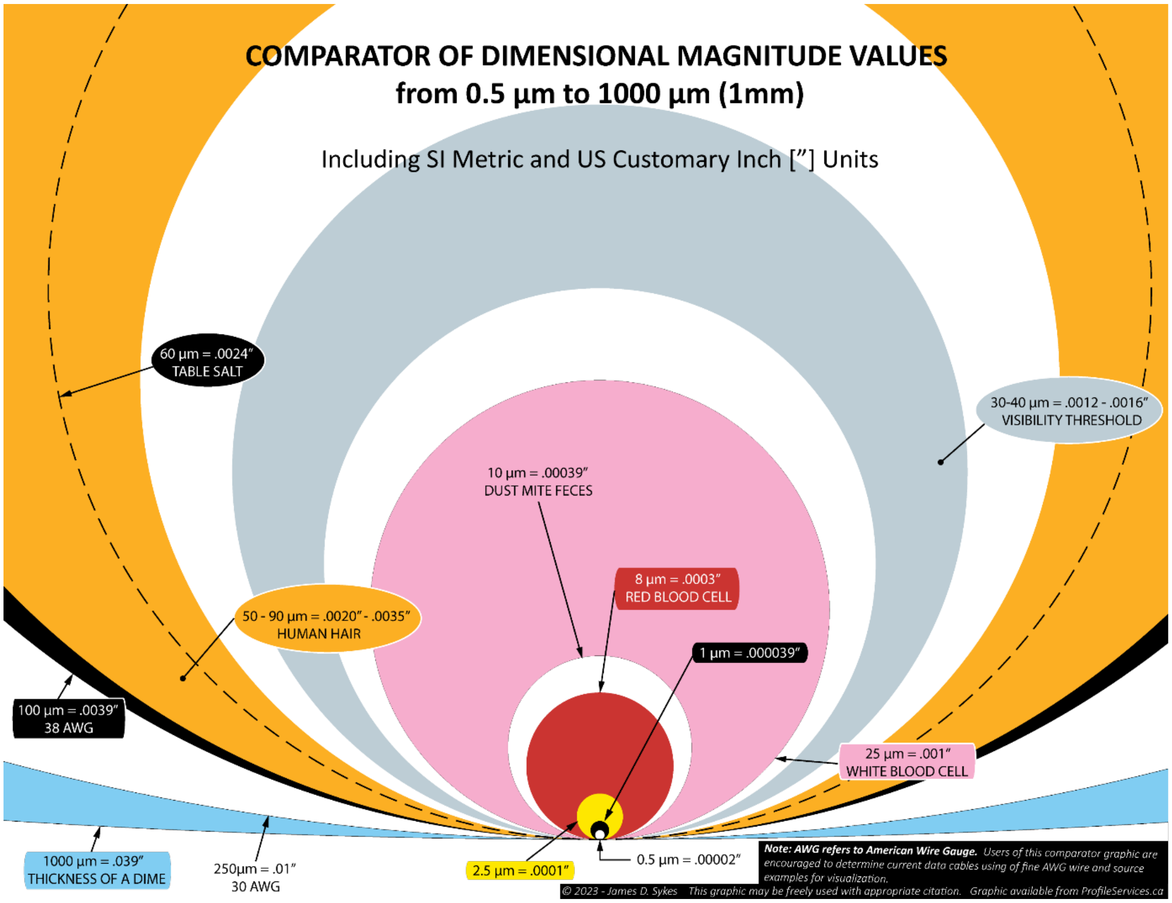

Figure 4-3 Artifact #1 – Comparator of dimensional magnitude values 0.5 µm - 1000 µm

Design of a Haptic Demonstrator of Five Clearance Fit-Classes – Artifact #2

I recall, in my two freshman drafting courses, learning of the different ways to represent tolerances on a drawing (limit-based, equal bilateral, unequal bilateral, unilateral, and Fit-Class designations), and that we were told not to worry about where the numbers came from for the time being.

It turned out that "the time being" meant the duration of my engineering studies, Aubrey. I graduated knowing nothing more about the source of tolerances than I did before I started my undergraduate mechanical engineering degree. I can't even estimate the number of engineers that I've talked with, but I've never heard anyone say that they learned tolerance determination in an undergraduate engineering program. Even worse, most engineers that I have encountered have no physical awareness of the magnitude of small tolerances.

As I said earlier, Aubrey, my first job after graduation became an unofficial apprenticeship of sorts for me when a master moldmaker took me under his tutelage and educated me on the meaning of tolerances, and more specifically the magnitude of the tolerances. That first job involved me duplicating tolerances from previous projects for application on new projects. I was fortunate that one of the senior designers was a trained professional draftsperson and had been in practice for years before shifting to design roles. He was aware of how tolerances were typically selected from tables of information, but it was not relevant to my job there. Eventually, I recognized that copying old tolerances was a common practice in industry, one that had been in use for so long that I never met a designer who knew the origins of those copied tolerances. My second job was essentially the same for regular production designs; CAD drawing templates with established tolerances were developed as the starting point for every new CAD drawing. My role with that company evolved and shifted to product development and field service engineering in the late 1990s, and I was developing new technologies and designs, and I had to establish tolerances had and adjust them for thermal effects. There were no internal resources to advise me on how the template tolerances had been determined. That might have been the first time that I had to tolerance from scratch.

In my earlier design engineering roles, I had worked extensively with manual and CNC (computer numeric control) machinists, and they had shown me a variety of fits-based tolerancing standards from around the world, where they had been completed their apprenticeships. Most discussed were the ASME (American Society of Mechanical Engineers) B4.1 [inch] and B4.2 [metric] standards, and they were typically sourced from old copies of *Machinery's Handbook* which included chapters on mathematics, statics and dynamics, tooling, all manner of design and manufacturing esoterica such as surface finishes, tolerances, and material grades, and much more. *Machinery's Handbook* has been a resource for machinists and mechanical design engineers since its first edition in 1914. It was from my copy of Machinery's Handbook 25 (1996) that I developed my understanding of fits-basis tolerance selections.

Sometimes I need to be reminded of lessons from my past, Aubrey. For the first two years of AGC, I provided tolerance values to apply to the components they were creating engineering drawings for. As you know firsthand, I share information on my engineering education and design history with the class; I've found that people pay more attention when they see that you have experiences to share with them. Anyway, your fellow AGC alumni pointed out that I was doing to them as had been done to me. I gave tolerances without explaining where they came from. By the third AGC course, I developed training content for fits-based tolerancing. Still, the next class identified that ... one, they wanted more practice selecting Fit-classes and determining tolerances, and ... two, they didn't understand how to select Fits-based tolerances was not the same as understanding what the Fit-classifications meant...physically. That was backed up with the Fit-

classes they selected in their next assignment… oh, they were bad! I could remedy the first issue fairly quickly. I've always been fascinated with historic steam devices, and I had already been working on a series of CAD assembly and component models for a vertical steam regulator design (Figure 4-4) that I wanted to incorporate into new training material.

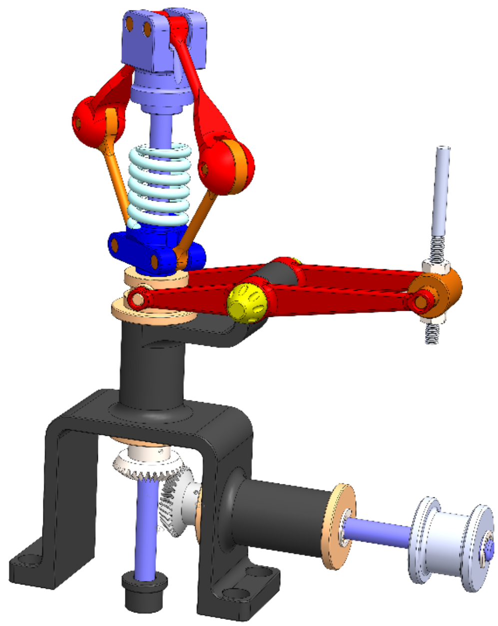

Figure 4-4   Vertical steam regulator design used for AGC tolerancing exercises

That was just as the COVID-19 restrictions started. I finished the new content for a Mechanical Design Skills Workshop that Summer. Feedback was really strong, and I was satisfied that I finally had effective content for selecting appropriate Fit-Classes and completing the calculations. I used that content again in AGC's final session in 2021. One issue popped up every time we worked on Fit selection; students couldn't perceive, physically, the differences between the various fits-classes. It bothered me that I didn't have a solution for that.

From personal experience, I had connected the theoretical understanding of the fits with a proximal feel for the clearance classes. In the injection molding industry, with multi-cavitation molds and large-capacity machines on which I worked, precise engagements and functionalities between components is critical to everything from assembly through to wear characteristics. As a result, I had experience working with component mating sizes from a few millimetres to over a metre diameter, but these components were not available for engineering students to gain the same experiences. I recognized that something smaller would be needed to demonstrate the *feel* of the Fit-Classes to students. The question of where and how the students would use the demonstrator were initial concerns.

My initial thoughts were that a fits demonstrator could be used in classroom settings and in off-campus locations when incorporated into independent micro courses and similar. As the Fit-Classes determine the relative freedom of movement between components, both longitudinally and transversally, a simple sliding mechanism was envisioned. The next question was what to actually demonstrate?

ASME B4.2 describes Hole-Basis and Shaft-Basis fits for ten Fit-Classifications, for twenty-eight nominal (basic) sizes from 1mm to 500mm; sizes between nominal values can be interpolated from the tables. There are 560 specific sets of size limits for mating parts. Because five fit classes represent intentional interference fits between the components, meaning there could be no relative motion between them, only clearance fits have the potential to show relative motion. Artifact development will therefore focus on clearance fits. Clearly the maximum size and overall range of sizes described above, would be impractical to demonstrate. Though selection of *a single nominal size* would not be accurately representative of the fits *for* *all nominal sizes*, it would give a reasonable demonstration of relative motion prescribed by the limits of sizes. I decided to focus on a single nominal size between 10 and 50 mm. This range is of adequate size to be easily handled by artifact users, while limiting the weight somewhat.

I recognized that ASME B4.2 provides a maximum and a minimum size for the shaft and the hole sizes, which establish the fit (i.e. maximum and minimum clearance) between the mating components. To show both values for each fit type would mean using the maximum and the minimum *pin* (shaft) diameters with the minimum and maximum slider *hole* (bore) diameters, respectively; that is, two pins and two holes for each fit type.

It seems inevitable, Aubrey, that inexperienced designers working on a large project will come to a point that shows them having one of two perspectives; they can't see the trees for the forest, or they can't see the forest for the trees. In mechanical design, the first perspective has the students so focused on the sheer magnitude of the overall project, that they can't see where to start. You and your team were so busy negotiating the interfaces between your parts that you fell into the "*forest for the trees*" group; you lost track of the overall system and the importance of non-mating features. That's not a criticism; it afflicts us all at times. After working on Concept #3, I found myself in the trees again. I realized that, practically speaking, the maximum and minimum clearances for each individual fit would be *visually and haptically indistinguishable* from each other. That revelation was actually liberating; I decided to represent only the *maximum* clearance for each fit. That would provide adequate relative movement between the components to exemplify the Fit-Classification. The combination of minimum shaft size and maximum hole size provided in

B4.2 for each fit type would be used as the design sizes. Manufacturing would have to hold sub-micron size tolerances, but that's achievable with hard turning or cylindrical grinding. This was a big step, Aubrey.

As I use the term, *ideation* is coming up with a plurality of distinct or unique core design *ideas* to address a design question. *Concepting*, then, is the conceiving of variants based on each core design idea that bears merit. *Final design* takes the rough or incomplete graphic manifestations that are the concepts, and determines all remaining design considerations, resulting in a complete product definition. That product definition will be a graphic representation, whether illustration, CAD model, or technical drawing, as appropriate. This may falsely imply that ideation and concepting are separate, sequential steps in the design process. They may be, or the process may jump chaotically between them in whatever sequence fits the designer's personal process.

As follows, nine *concepts* expand on two core *ideas*. This is not exhaustive of all concepts that were considered for this artifact. These concepts were selected, and shown in the sequence indicated, to illustrate how ideation and concepting can be initially chaotic, and how preferred concepts are evolved to the point where one is selected for final design.

Concept 1

The initial concept, represented in Figure 4-5, has a slotted base plate with a key[xiii] sliding longitudinally within each slot. I selected a shaft-basis 15mm nominal size because the

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[xiii] In mechanical engineering, a key is a machine component which, when engaged in mating keyways or slots, is used to restrict or guide relative motion between components. As used in this artifact, a key is a machine component that may actuate along a specified pathway.

keys would be large enough to handle easily and be somewhat damage resistant in typical moderately-rough handling. Though ASME B4.2 describes all sizes as diameters, the fits work equally well with other geometries, such as rectangles, ellipses, hexagons, etc.

Here's what I was thinking, Aubrey. Manufacturing of precise slots and rectangular keys can be less expensive than producing cylindrical features, so I chose to start concepting with slots and keys. In this concept, each key and slot would be individually sized as calculated based on the ASME B4.2 tables. To allow sliding without binding, I would typically set an engagement depth (that is, mating surface engagement depth of slot and key) of 1-1.5 times the width of a key. For more stability, I chose a depth of 1.25 times the nominal width. It's bad design practice, even for low loads, to have steel-on-steel movement; both pieces inevitably wear, and you end up having to replace both parts.

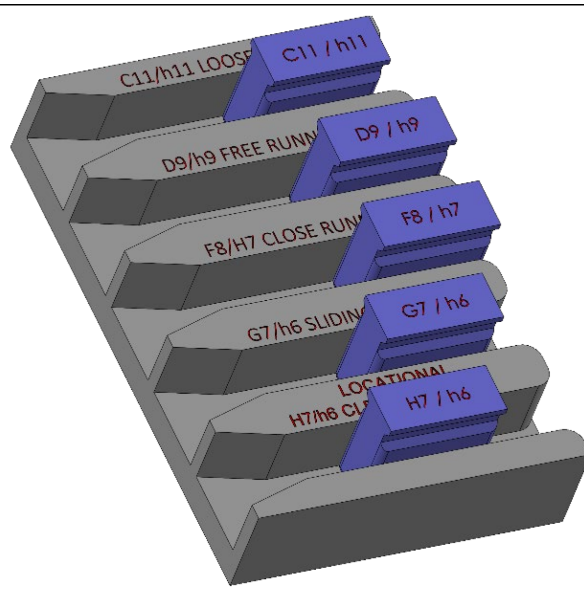


Figure 4-5 Fits Demonstrator – Concept 1

We might not have gone over this in AGC, but preferred practice is to make the more complex, and therefore expensive, of the mating pieces out of steel, which typically has a high hardness value. The less expensive part will typically be made from a softer material so that it becomes the *sacrificial* element in the mating. I have a successful history using aluminum-bronze in high-wear applications, I decided on that for the keys. This metal is extremely abrasion and wear resistant, easily surviving millions of cycles with hundreds of pounds of load normal to the direction of movement. Unlike common brasses and bronzes, aluminum-bronze doesn't tarnish significantly, so it doesn't need a protective coating, and it won't need a lubricant for this application. For aesthetics and corrosion resistance, I'd use stainless steel for the plate.

It sounds random, Aubrey, but when I'm designing relatively compact items, I try to design for a footprint up to 150 mm x 150 mm (6" x 6"). Really, 150 mm is just a length easily visualized using a compact ruler, so I find it convenient. Have you noticed that most of the surface finish comparators and other samples and demonstration pieces that I have brought to class are within this limit of size. I think that *this* fits demonstrator artifact could be physically smaller, but someone once told me that small pieces are easily forgotten in someone's pocket. In other words, I have to design with security of the artifact in mind, too.

I modelled the base channels with an acute lead-in angle and a radiused back edge to minimize risk of damage during key ingress and egress, but either geometry could be used for both ends. I considered using T-slots in the table with T-flanges on the keys to retain the keys in their slots, but this would require end plates to hold the keys in place. Still, I didn't like the idea of the keys being able to slide in their slots during shipping, so that idea was rejected.

Yes, Aubrey, I pushed the concept to near-completion before moving on. It forces me to think a couple steps beyond the point where I get comfortable with a design. It allows me to see if there are other options that I should have considered. You and your classmates, and most people that I work with for that matter, see me as confident when I'm talking about design, but I'm still insecure about my design abilities. I'm always concerned that I've missed something in my concept, something that will make the design not function as expected, or maybe not even be manufacturable. Concepting is relatively inexpensive as it is just *trying* ideas and seeing what looks like it will work, or won't work, and doesn't need to have all the little finishing details, the design esoterica, worked out. When a concept is evolving into a final design, that's where the value is added to the design, and it becomes an investment in the design. If I get to the late stages of the final design and realizes that something was missed in the concept, making the concept invalid, the investment in *that* final design is wasted. I don't recall that happening to me in a significant way until I was self-employed, but it did happen. A company contracted me to design an injection mold based on the molds that I had designed earlier in my career. I hadn't designed a mold from scratch in at least five years, but the client was comfortable that I would remember the majority of the mold design and that I could figure out any remaining parts. I submitted the final drawings despite a nagging concern that I had missed something. It turned out I had … I'd forgotten the holes used to fasten the mold shoe to the machine platen. I felt like an *idiot, that I could miss something so fundamental. I corrected the design and resubmitted it. Fortunately, the omission was caught before the $25-$30000 plate was manufactured. It wouldn't have been salvageable. It didn't cost the client anything. Outwardly, it cost me one day's work, and more than a little embarrassment. Inwardly ... well, old insecurities were reinforced.*

Concept 2

The second concept that I explored (Figure 4-6) centers around sets of cylindrical rods with two sliders engaging axially on each rod. The rod/sliders sets are removably mounted on a base.

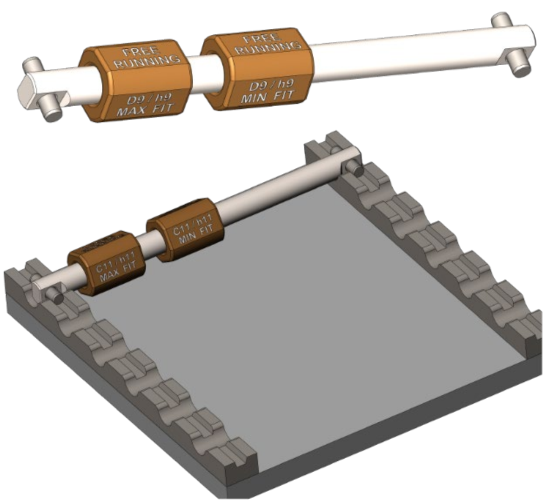


Figure 4-6 Fits demonstrator – Concept 2

For each rod, a pair of parallel holes will be drilled through the rod, one at each end, and a parallel dowel pin or other pin will be press-fit into these holes to ensure the sliders do not disengage from the rod.

The holes in each pair of sliders will be precision-bored (sub-micron tolerances) to provide the maximum and minimum clearance for each fit classification.

The base is a simple design of a relatively compact plate with two contoured rails to support the rod/sliders sub-assemblies. This arrangement allows the student to take each sub-assembly directly in hand, or to leave it on the base while comparing relative motions of slider on rod. The key limitation to this base design is that the five sub-assemblies are not restrained on the rails, and therefore may be unintentionally disengaged from the rails during storage or shipping, which may result in damage to the components.

Let's look at Concept 2, Aubrey. I have experience with commercial stainless steel rod stock with extremely tight, that is sub-micron, tolerances on diameter, and with extreme straightness along its length, particularly over relatively short lengths up to 200 or 300 mm [8–12"]. This rod stock is often case-hardened before final grinding, making it super wear resistant. I arbitrarily chose a diameter of 10 mm to provide reasonable stiffness for the 150 mm unsupported length that I selected.

The sliders will be machined from aluminum-bronze rod stock; same reasons as before. From experience, because the bore diameter is relatively small, an engagement length to diameter ratio of 1:1 to 3:2 seems inadequate. I set a ratio of 5:2 instead, yielding a slider length of 25 mm. I have found that for small diameters, a short engagement length allows yaw motion between the rod and the slider, but this is minimized by increasing the engagement length. Unless yaw is intended, experienced designers will eliminate or minimize it. Less experienced designers generally don't consider or address any relative motions other than the more obvious axial translation and radial shift.

Because the rod stock size is an industry standard size, I chose to use Shaft-Basis Fits in the design. The clearance Fit-Classification and designation, like C11/h11 for a Shaft-Basis Loose Running Fit, and an indication of maximum or minimum fit will be engraved on each slider. Despite a common belief that certain brands of ink markers and paints are permanent, there are few that bond with most metals, and none that cannot be worn off over time. Ideally, markings are laser engraved (fast, clean, durable) to a depth of 0.1 – 0.2 mm, and then have a contrasting, material-compatible paint or non-bake enamel applied to the engraving to make it more visible in use. I typically make engraving red or white in my CAD models so that they show up effectively on graphics, but any colour that contrasts with the actual base metal colour is effective in application.

Concept 3

The third concept, Figure 4-7 , is a minor evolution of Concept 2, involving changes to the two rails of the base. This redesign replaces each single-part rail with a two-part rail. The bottom part of each rail provides a means of both seating the rod of each sub-assembly and preventing its rotation. The top part of each rail, held to the bottom part of each rail by strong magnets, provides additional anti-rotation constraint of each sub-assembly as well as encapsulating the end of each sub-assembly between the top and bottom rails.

The concept graphic (Figure 4-7) includes engraving details depicting identification and usage instructions, which would also be applicable to Concept 2 (Figure 4-6).

Though this new rail design ensures that the sub-assemblies will be better protected during storage, handling and shipping, the sliders may still translate along the rods, potentially being damaged. That's not a deal-breaker, but something to consider going forward.

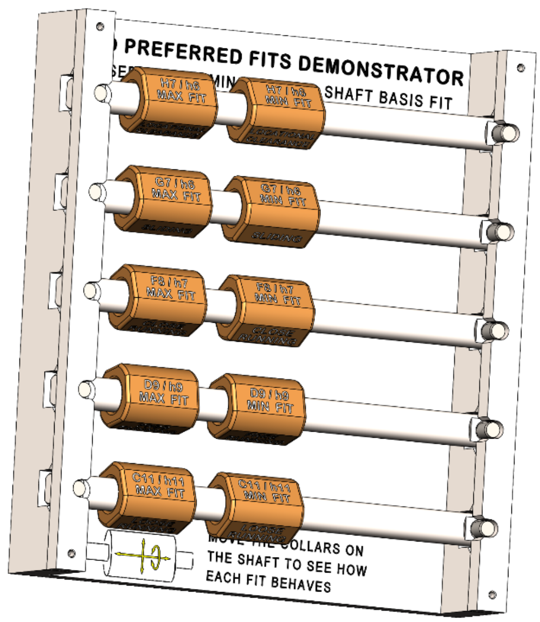


Figure 4-7   Fits Demonstrator – Concept 3

Concept 4

Though Concept #3 (Figure 4-7) was a rough concept, I recognized an issue with the sizing of each rod and slider sub-assembly. As noted, ASME B4.2 provides a maximum and a minimum fit (i.e., clearance) between the mating components. To show both values would mean using the maximum and the minimum rod diameters with the minimum and maximum slider bore diameters, respectively; that is, two rods and two sliders.

So, this was another a-ha moment, Aubrey. It hit me that the maximum and minimum clearances for each fit were indistinguishable, so I decided to represent only the maximum clearance for each fit, providing the greatest likelihood of the user being able to feel the clearances.

At this point, I had a palm-to-forehead revelation about my underlying rationalization regarding representation of just the maximum clearance for each fit by using the minimum shaft size in conjunction with the maximum hole size. My realization is incomplete. Though the series of five fit classes was based on the same *nominal* shaft diameter, each shaft minimum size was *different*. This meant that the five shafts would, in fact, be slightly different sizes. Instead, a *single* shaft size could be used unilaterally for all five clearance fit classes, and each hole size could be calculated to achieve the maximum clearance in conjunction with the single shaft size.

The revelation that I could use a single shaft size for all fits prompted me to return to Concept 1 and revise it so that the keys were all the same thickness. Using a single key size should reduce manufacturing costs for the keys by machining one longer piece of stock to a constant size, then cutting segments from it to produce the keys. Because each slot width is manufactured independently, a simple change of toolpath will establish the width of the slot, without increasing the manufacturing cost. Tolerance on the key thickness would need to be sub-micron, achievable with a bed grinder. To accommodate the single key width, each slot width now had to be calculated to establish the maximum clearance for each fit. Tolerance on the width of each slot would be sub-micron so that collectively, the tolerances on the keyway and the slot would not significantly change the maximum clearance for each fit. The resulting Concept 4 is shown in Figure 4-8.

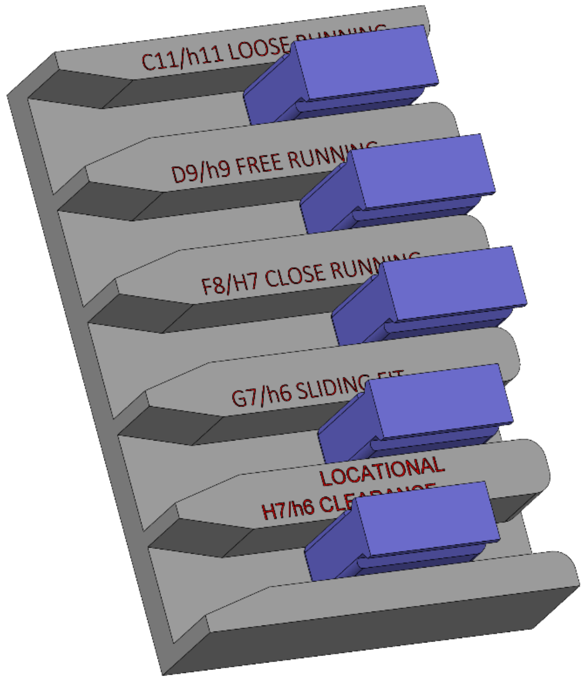


Figure 4-8 Fits Demonstrator – Concept 4

Step Away and Return With an Open Mind

Design is a creative process, Aubrey, and it may come in a burst or a trickle over time. Sometimes creative blocks happen, and sometimes the designer is too focused on the trees to see the forest. I've found that perspective often requires stepping away from the issue and clearing any thoughts of the issue from my mind. When I realize that I'm no longer thinking about the design, it's time to return to it.

When concepting something new, or considering its evolution, I tend to work in brief, intense periods, then let the concepts stew for a while before actively reconsidering them. I do a significant amount of development thinking when I intentionally don't focus on it; I call it back-channel processing though it's apparently a normal cognitive function and likely has a longer, more technical name. Regardless, sometimes, as happened with Artifact 3, that passive rumination may last years. For some other projects, ideation happens in a flurry of creativity and the first results exceed requirements. More often, however, I try to let things simmer for a few days or weeks before I actively return to the work with an open mind to see things in new ways. Then I proceed with fleshing out the initial idea, overhauling it, scrapping it altogether, or exploring a new approach using some element of the initial concept. In this case, weeks passed before I returned to concepting for Artifact 2.

The time away from the artifact design made me recognize what I dislike most about the four concepts so far. They could be made functional, but they are awkward. There is no design elegance in the solution; it feels like it was a just brute force solution. I can do better.

Those first four concepts are ugly, aren't they, Aubrey? Still, I recognize several elements that I can carry forward:

- Only the *maximum* clearance between the two components needs to be represented for each of the five clearance fits.

- I can use a single size for the shaft (pin) **or** the hole for all five fits, and calculate the size of the counterpart element (i.e. the hole or the shaft (pin), respectively) for an equivalent clearance gap that ASME B4.2 provides for each fit.
- Using a rod and a ring to represent the shaft and hole sizes will maintain a tangible link to the B4.2 tables.
- I want to minimize the number of components in the artifact. This should reduce manufacturing costs, reduce the risk of damage or loss of pieces, and could simplify the design and usage.
- While I had been focusing on shaft-basis fits, which would allow a single shaft diameter to be used, this would mean multiple rings, increasing the number of components. Alternatively, by shifting to a hole-basis, a single ring could be used in conjunction with a single stepped shaft with five different diameters representing the five clearance fits.
- Retaining a single ring on a stepped shaft would minimize the risk of lost components.

Concept 5

Collectively, these elements generated Concept 5 (Figure 4-9).

The slide ring has a nominal Ø16mm hole with an outer diameter of 24mm, and has four flat faces equidistant from the axis of the bore, establishing 23mm across flats (23mm A/F). This will allow the ring to be machined from Ø25mm aluminum-bronze rod stock. The ring will be 12mm long. Though this is only a 3:4 ratio to the bore diameter, which may allow “chatter” of the ring on the shaft segments, it should be minor because of diameters involved.

The stepped shaft has a 150mm overall length, with 25mm long stepped segments. This allows the ring to move 13mm along each segment. One end of the shaft terminates in an integral Ø25mm shoulder, from Ø25mm bar stock. The other end of the shaft terminates in a short, reduced diameter section. Each segment of stepped shaft is shown engraved with the fit classification.

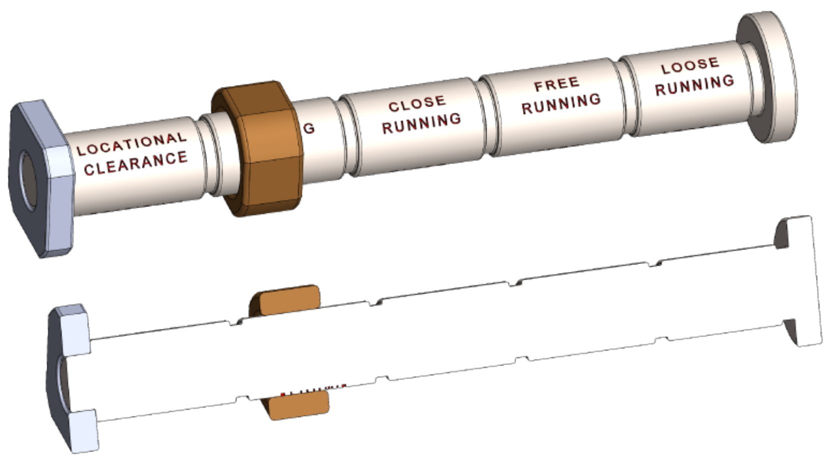


Figure 4-9 Fits Demonstrator – Concept 5

A square flange is thermal-press-fit onto the reduced diameter end of the shaft. The press-fit flange is squared so that the assembly cannot roll.

The shoulder and flange are the same effective size, allowing the shaft to lay parallel to a tabletop, and are adequately sized to allow the ring to be minimally offset from the tabletop if the assembly is so placed.

This concept reflects the preceding six considerations, but in hindsight, I don't like the use of a thermal press-fit in this application. The tight tolerances of a thermal press-fit increases machining costs, which isn't justified by its functionality in this application. I can foresee artifact users letting the mass slide from the shoulder end to the flange end. I've seen similar setups where, over time, the repeated impact of a sliding mass caused the flange to be dislodged, damaging the shaft itself.

I recognize that a stepped shaft would require a centered hard-turning or centered grinding process to ensure coaxiality of all cylindrical segments, but the reduction of components more than offsets any extra costs. This design will allow the user to hold the same ring to compare fits on adjoining steps of the shaft … yeah, that's the right approach for a comparison, rather than having to move their hand between separate rings.

Concept 6

Concept 6 (Figure 4-10) is derived from Concept 5. The ring is unchanged. The length of the stepped segments and the shoulder at the end of the shaft are unchanged. At the end opposite the shoulder, the reduced diameter is removed. Both ends have a conical tooling center and an internal thread added. The tooling centers and threads are primarily for manufacturing purposes., though they will also reduce weight slightly. The collar is thickened and provided with a counterbore which will allow it to be fastened to the shaft using a socket-head cap machine screw.

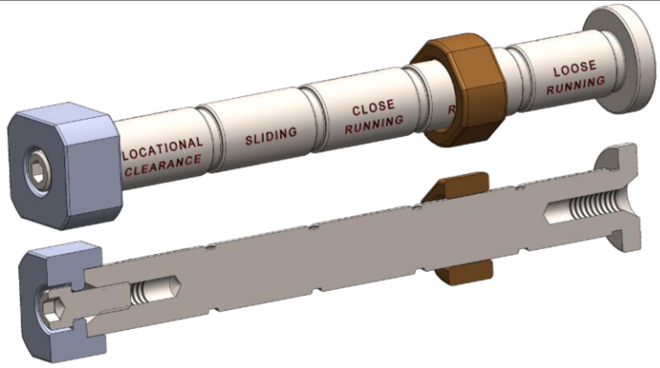


Figure 4-10 Fits Demonstrator – Concept 6

You've heard me use the terms *experience*, *observation*, and *recollection* to reflect empirical knowledge that I have gained over time. I've found that the designers tend to accept these terms when referring to mechanical engineering design, but are generally uncomfortable trusting design guidance based on subconscious recognitions labelled gut feel, intuition, instinct, common sense, or a sixth sense. I find it funny because it's just different words meaning the same thing. These subconscious recognitions are neither naturally occurring nor magically imbued in a mechanical design engineer. They are every bit as legitimate as experience, observation and recollection because they are learned reactions to repeated stimuli or experiences, and they reflect knowledge rooted in direct or anecdotal failures and boundary-pushing successes. These accrue over time, and they are a "cheat code" that design engineers rely upon rather than returning to textbooks, reference materials and theory for a same or similar situation.

At this point, Aubrey, I step back for a period of reflection on Concept 6. I'm generally satisfied with the concept. But, at a nominal Ø 16 mm shaft size, my gut feel is that Concepts 5 and 6 are undersized. So, I *learned that many people, me included, will subconsciously and without any purpose, test the flexibility and torsional stiffness of small shafts when handling them. Some people flex them to the point of inflicting damage, and I've watched people "tapping" shafts against harder surfaces, damaging them due to lack of robustness. I also feel that the shaft size and ring across-flats dimension may be uncomfortably small for moderate to large hand sizes. Design is an iterative process, which means I tinker with it until I am satisfied, which is often well after bare functionality is achieved.*

Concept 7

Concept 7, shown in Figure 4-11, is an evolution of Concept 6. The shaft nominal diameter is increased to 30mm, and the length of each shaft segment is increased to 27mm. Instead of a machined-in shoulder at one end, two flanges will be threaded into the ends of the shaft: one flange is circular, and the other is nominally square. Both flanges have male threads to engage with female threads in the shaft. The end flange pieces are sized to ensure that the slide ring will not contact a tabletop when set down.

I don't generally like to use custom-cut male threads to engage in a custom-cut female thread because they can be finicky to cut and to use. In this application, though, it would eliminate the use of two fasteners which could be easily lost.

For a comfortable feel when handling the ring, four flats (50mm across-flats) are machined on the ring, which is made from Ø60mm aluminum-bronze rod stock. Because the length of each of the shaft's segments has been increased, the ring length can be increased slightly, from

10mm to 15mm. Though the engagement length of the ring on the shaft is less than I would want for a functioning mechanical assembly, it may be adequate to minimize the risk of chatter because the diametral clearances are so small.

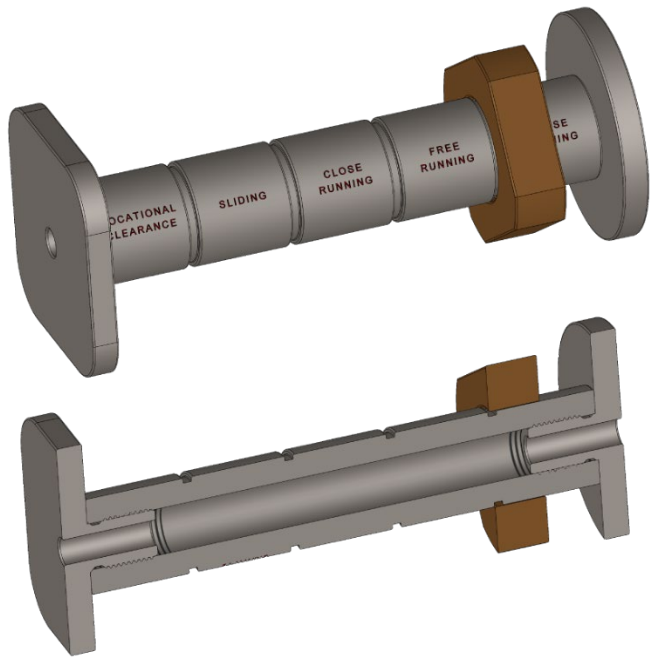


Figure 4-11 Fits Demonstrator – Concept 7 (including section view)

To offset the additional weight that results from bulking-up of the design, and which will make it harder to handle and more costly if shipped to end-users as part of a remote-learning course, a bore is added through the full length of the shaft. The shaft wall thickness will remain adequate for both bending and torsional stiffness and will not promote damage if mishandled.

Overall, I like this concept, Aubrey. It seems robust and hits my functional considerations. Aesthetically, I don't like the size of the end flanges. They look like they will interfere with a user's hand moving the slide ring over the segment at each end of the stepped shaft. There was no evident concern about shoulder and collar sizes when I completed Concept 6, so I reconsidered this aspect of Concept 7. The end shoulder and the squared end collar were larger than the slide ring diameter so that the assembly could be set down on a tabletop and the slider moved longitudinally and radially along each segment to establish a "feel" for the fit that the clearances established.

I'm reconsidering this aspect of functionality in Concept 7: Would a user be able to comfortably move the slider longitudinally and radially when the assembly is not held in their other hand? My feeling is that the clearance between the slide ring and the tabletop would have to be adequate for the users' fingers to fit comfortably and with clearance in that gap. Based on my own hand, over 20mm clearance will be required; this means that the flanges will have to be at least 40mm larger than the slide ring. This will increase the weight substantially and make it awkward and possibly unstable to hold the assembly in one hand while using the other to engage the slide ring.

After considering a reduction in the collar sizes, another functionality to consider is the flats on the collar which prevent the assembly from rolling off a tabletop. If the shoulder sizes are reduced to not interfere with the actuation of the slide ring, they may not be large enough to ensure the flats seat on the tabletop, which would compromise stability of the assembly.

Concept 8

The next iteration of this fits-demonstrator adopts the shaft characteristics of Concept 7 but integrates a shoulder at one end. See Figure 4-12. At the other end of the shaft, a cylindrical end collar will be held in place with a machine screw. To reduce mass, the shaft will have a

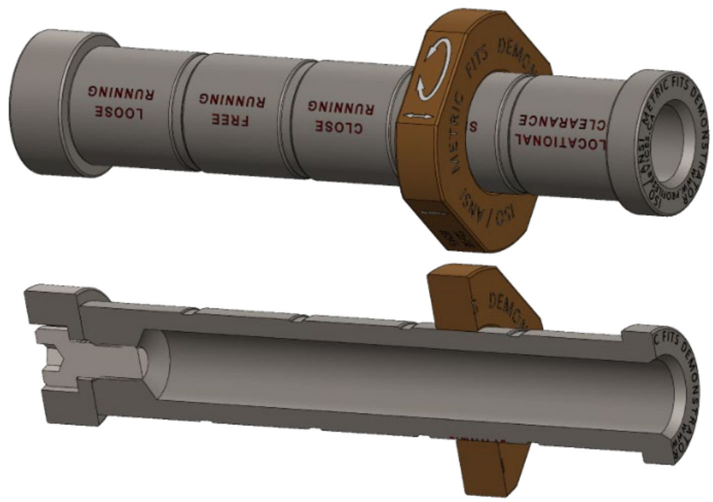


Figure 4-12 Fits Demonstrator – Concept 8 (including section view)

large-diameter bore that will terminate in proximity to the collared end, and a threaded hole will be included for the machine screw. To assist manufacturing, tooling centers will be included in the bores at both ends of the shaft.

The shoulder and the collar will both be cylindrical and have a diameter slightly larger than the largest step diameter in the shaft so that the slide ring will be retained.

The slide ring will be made from Ø50mm aluminum-bronze rod stock, with four flats (45mm across-flats) machined. The flats on the slide ring, along with being grip surfaces, will ensure that the assembly does not roll when placed on a tabletop.

Identification and artifact usage instructions are engraved into the components.

I think I'm getting close now, Aubrey. Overall, this design appears usable and robust. Something is bothering my subconscious, but it is not something obvious, so I let it sit for a while. Upon returning to the design, I visualize how this artifact will be assembled, handled, used, and stored.

I have minimized the number of components, and therefore the amount of assembly required. The collar that mounts to the one end of the stepped shaft is held in place with a single M8 socket head cap screw (SHCS), used exclusively in tension. A drop of thread adhesive will prevent it from backing out over time. I did some calculations years ago; a single, high grade (Class 12.9), M8 SHCS can hold a typical city bus without failing in tension[xiv,xv], so I'm not concerned with fastener failure.

As I visualize this assembly step, I recognize that flats will be needed on the stepped shaft to grip with a wrench and apply adequate torque to the M8 SHCS. Unless I put a flat on the stepped segment closest to the collar, the flats will have to be on the shoulder at the far end. That will require more significant changes to the stepped shaft component, increasing weight. This will also increase the risk of injury and damage as the wrench will be significantly away from the location of torque application on the SHCS and therefore inherently unstable. Instead of putting flats at the far end of the shaft, I will change the interface between the collar and the end of the stepped shaft so that they will mechanically interlock.

[xiv] The threaded portion of threaded fasteners is designed to take load in tension (i.e., axially) only. Failure in tension is typically in the form of a sudden spiral failure of the metal, or in a progressive necking. Unfortunately, inappropriate design may also introduce a shear (i.e., transverse) load in the threaded region. Such shear-mode thread failures are deemed catastrophic.

[xv] M6 and ¼-20 UNC/UNF (1/4" = 6.35 mm) fasteners are easily mixed-up, and will bind (lock up) on engagement, potentially failing in assembly. As a result, I avoid either as a general practice.

Concept 9

Based on Concept 8 (Figure 4-12), Concept 9 shows two variations: one with a single slot cut from the shaft (Figure 4-13), the other with two flats cut from the shaft (Figure 4-14). In the first case, the collar has two mating flats cut from it, and in the latter, the collar has a mating slot cut into it. Functionally, Concept 9-A will be safer in use than 9-B because the edges of the

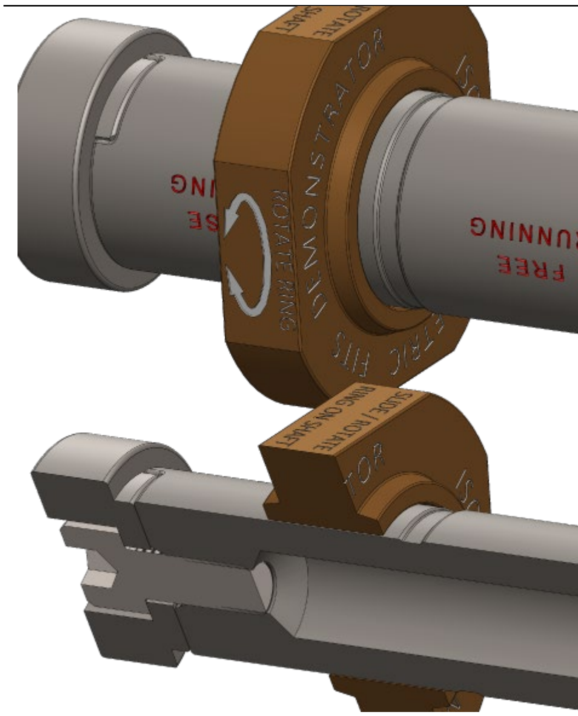


Figure 4-13 Fits demonstrator – Concept 9-A including tapered ring extension

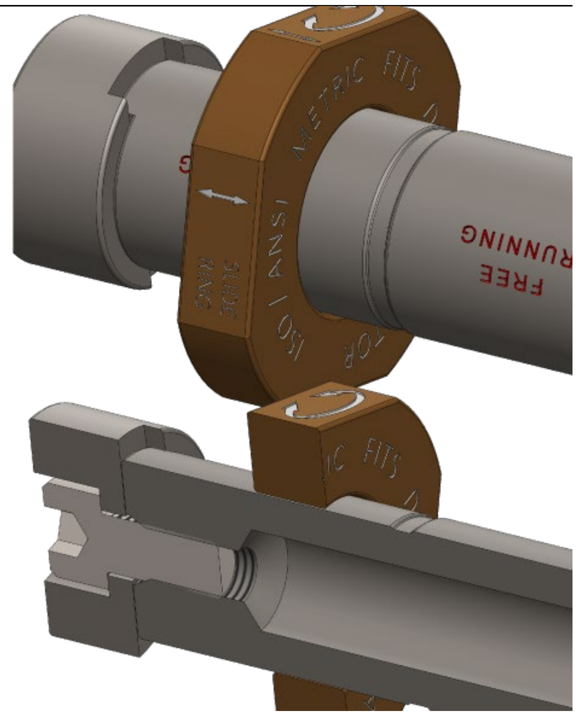


Figure 4-14 Fits demonstrator – Concept 9-B

slot cut into the collar may get caught on the user's hands. The shoulder diameter on the collar in alternative A is reduced slightly from the diameter of the shaft at that location. From a manufacturing perspective, the configuration with the slot cut into the shaft is preferable as it will reduce machine set-ups, cutting time, and risk of scrapping a complex workpiece. A pair of opposed flats is added to the collar diameter to grip with an adjustable wrench. By having the flats on the collar, near the hex-wrench that would apply torque to the fastener, the risk of slippage, injury, and damage, is decreased significantly.

To address how the artifact will be held in use, users will hold the artifact in one hand, likely gripping it on the stepped shaft section near the shaft segment(s) representing the fit-types that they are considering. Ideally, handling or grip surfaces have a rough surface finish or texture that would facilitate grip. However, in this application, the shaft segment surfaces need to be significantly smooth, though not mirror finish. Using a Surface Roughness Standards comparator[xvi], a surface roughness specification of 0.2μm Ra is selected. From experience, this finish is adequate for dry grip but will not add significant friction to the movement of the ring, which would alter the haptic perception of the relative clearance between the two components. For increased grip on the shaft's shoulder and the collar at the other end, a multi-directional, brushed finish, with a surface roughness of 3.2 – 6.3μm Ra is indicated. That addresses how the user will hold the artifact in use.

In use, I anticipate the user's subordinate hand to hold the stepped shaft of the artifact while their dominant hand grips and moves the ring axially and perpendicular to the axis. The ring, therefore, should have some areas of enhanced surface roughness to optimize potential grip using just two fingers, as it is limited by the 10mm width of the ring. As the flats of the ring have engraved instructions, the radiused portions will have a multi-directional, brushed finish,

[xvi] Fowler Surface Roughness Standards – Code No. 52-720-000

with a surface roughness of 3.2 – 6.3μm Ra, consistent with the shoulder and collar of the assembly.

To address unresolved concerns about the limited 10mm of axial contact of the ring on each segment of the stepped shaft, I opted for a tapered 2.5 mm extension on each of the two main faces of the ring, as shown in Figure 4-13. This effectively increases the engagement by 50%, without significantly increasing the mass of the ring.

Final Design – Artifact 2 – Haptic Demonstrator of Five Clearance Fit-Classes

Concept 9-A (Figure 4-13) is selected as the final design for Artifact #2, shown in Figure 4-15. The final design consists of three machined components and a commercial fastener.

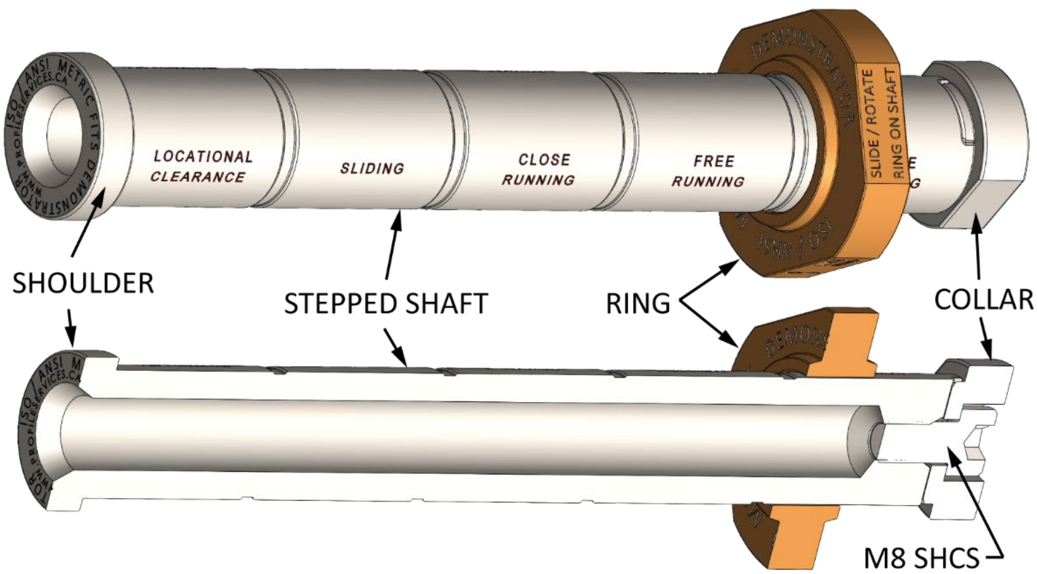


Figure 4-15 Artifact #2 – Haptic tolerance demonstrator

The stepped shaft, which includes the shoulder as an integral element, and the collar are fabricated from a durable yet easily machinable grade of stainless steel (AISI 416). Because the stepped shaft has multiple tightly-toleranced surfaces, compared to the ring with only one tightly-toleranced surface, the shaft will be the dominant part and the ring will be the submissive (also referred to as wear, or sacrificial) component. The ring is made of a significantly softer aluminum bronze material (AMPCO-18®), commonly used in linear bearings and bushings.

Identification of each clearance Fit-Class is engraved at three circumferential locations on the stepped shaft so that it can be readily visible regardless of how the assembly is being held. Engraving on the ring (Figure 4-16) includes identification, source, text and visual instructions for use of the artifact. The collar and stepped shaft positively engage so that only a single tool, a common hex-key is required for assembly of the artifact.

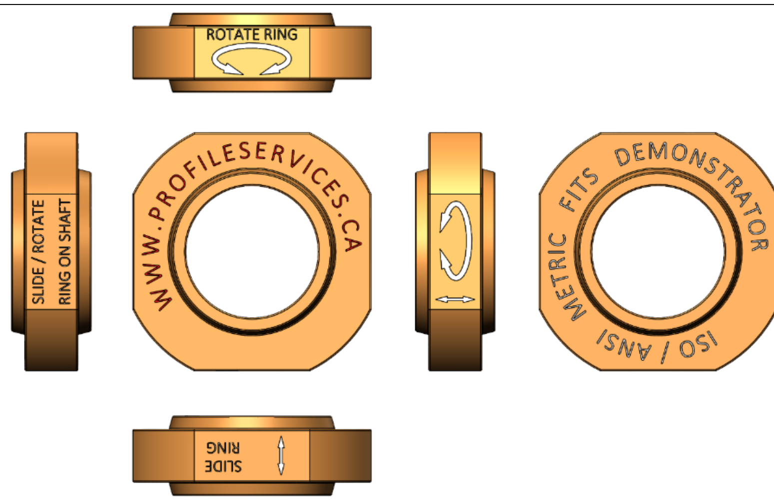


Figure 4-16 Engraving details for ring component of Artifact #2

Well, Aubrey, I am satisfied with the design of Artifact #2. The stepped shaft is approximately Ø25 [1"] x 200 mm [8"] long, with Ø30 mm [1.25"] shoulder and collar. At Ø50 mm [2"], the grip-surfaces of the ring should be comfortable in most hands. The engraved flats on the ring are approximately the same width as the bore diameter, which should be adequate for stability when the assembly is put on a horizontal surface. The overall weight of the assembly is about 680 grams [1.5 lb], which should be comfortable for most people to hold. Overall, this approach to demonstrating clearance Fit-Classifications seems intuitively usable, compact in form and weight, and aesthetically appealing. If another design engineer asked me to review this design as their own, I would compliment them on an achieving an elegant design. As it is my own design, I'm just satisfied that I have finally scratched this particular itch.

Design of a Visio-Haptic Demonstrator of Micron-Scale Magnitudes – Artifact #3

Humility is an important attribute when learning, or teaching. The learner must know that they do not know. I recognize that I have had a successful engineering design career so far, but I also recognize that, even in areas where I am considered a subject matter expert, there is always something new to learn. I have been teaching the same core GD&T course for almost twenty years. I mentor industrial personnel and mechanical engineering students alike, and globally I mentor other GD&T instructors. Still, I am humbled that I learn something new in every class that I teach, and in every mentoring opportunity. Sometimes it is something new about a particular industrial sector, and other times it is just hearing a new question or perspective that I have not addressed before. You kept me on my toes, Aubrey. Good questions.

I know you've heard this story again and again, but I can't overstate how that Master Mold Maker affected me. Reflecting on it now, the delivery of that lesson exemplified humility. My own by accepting what I didn't know. The moldmaker's by stepping back from a place of anger and frustration, and finding a meaningful way to instruct me. And perhaps in the sample itself; imprecise and with no aesthetic value, yet adequate to the task.

My second job in the mold industry had me working with tolerances of 0.0025 mm (2.5 microns), and sometimes tighter; tolerances that were at least an order of magnitude tighter than I had experience with. As I've mentioned, there were no commercial samples to get a feel for those magnitudes. Most design engineers that I worked with were comfortable not knowing about the physical magnitude of the tolerances they were working with; to them, the numbers were abstractions because they were so small. Some designers and, most interestingly, many of the undergraduate mechanical engineering students that I mentored, were interested in understanding, physically, the magnitude of the tolerances that we worked with. In my simultaneous roles of product development and service engineering, I usually had a collection of prototype and failed workpieces on my desk. Now that I think of it, those were probably the first artifacts that I used for teaching students. Occasionally one of the workpieces showed some irregularity in a machined surface, and I could use that to demonstrate dimensional magnitudes *above* the micron-scale. Unfortunately, availability of such pieces was inconsistent, and they were inevitably dispositioned and removed from being a training resource. The need for such a training aid was not consistent in my work, so I didn't dwell on it much at that time. Still, it remained in the back of my mind that mechanical engineering education would benefit from having something available that could demonstrate micron-scale magnitudes.

Pre-Study Concepts

For at least the last decade, I toyed with the idea of a tolerance magnitude demonstrator. For the most part, it was a mental exercise with a few hand sketches and a few CAD-modelled concepts. Those early ideas focused on two or more elements that could slide with respect to each other, either linearly or helically, to allow the visualization of any sub-millimetre tolerances. One of the earliest ideas was based on two rings; the inside ring threaded externally and the outer ring threaded internally, as shown in Figure 4-17. As the outer ring is rotated about its center axis, its thread will follow the helix of the inner ring's thread, resulting in a gap opening between the bottom of the outer ring and the base of the inner ring. The gap would be measured on an engraved scale on an outer relief of the inner ring.

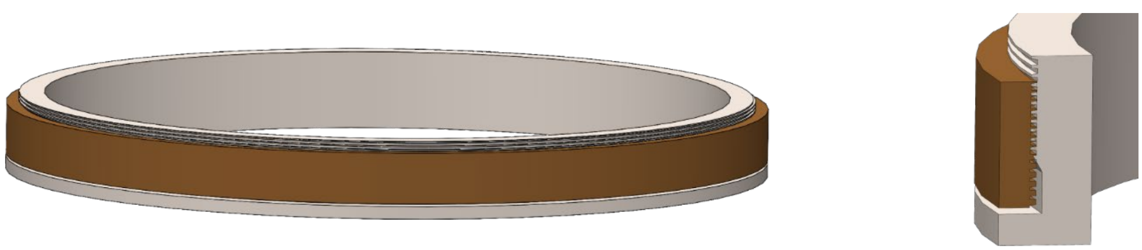


Figure 4-17 Pre-study Concept #1

including enlarged section detail of helical (threaded) engagement

This initially seemed like a potential solution, but the physical reality of threads raised concerns. Threads are extremely difficult to manufacture with high precision. The helix angle of the thread must be extremely small, which means that the threadform must be extremely small, and therefore the diameter of the rings must be very large to accommodate a slow increase in the gap between the rings. I explored variations of this arrangement (not shown), but the issues increased with the complexity of the design.

A second pre-study idea came from an adjustable parallel, a simple device that is based on two right-angled blocks that slide along their hypotenuses; a Brown and Sharpe adjustable parallel is shown in Figure 4-18. The tolerance demonstrator concept, based on parallel slides, is shown in Figure 4-19. In order to show a range of 0.01 to 1mm gap, a very shallow angle was required, which resulted in an overall length over 300mm [12”], which would make the demonstrator unwieldy in use, and subject to damage from handling or storage.

Figure 4-18 Brown & Sharpe adjustable parallel

Other concepts, not shown, envisioned worm gears and other mechanisms to set a gap between two moving components. Though creative, those ideas were immediately and visibly impractical for various reasons and were discarded.

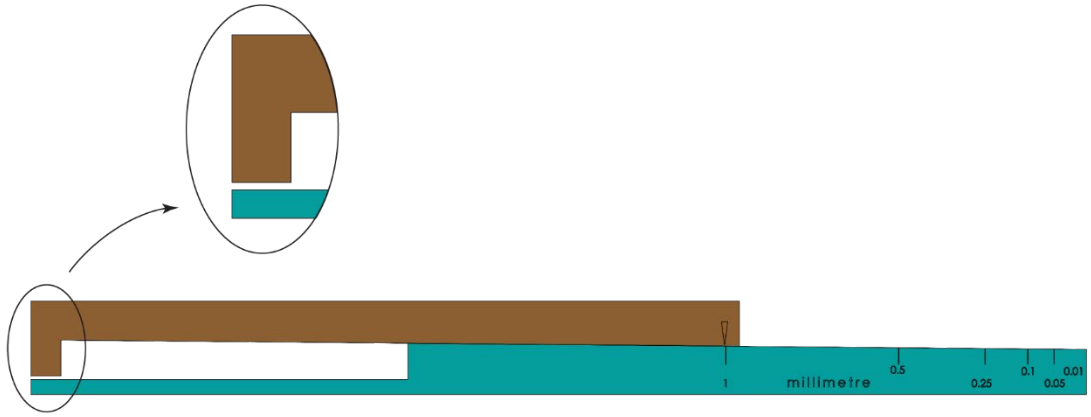


Figure 4-19 Pre-study concept: adjustable parallel with gap detail shown

Intuitively, I had concerns about using moving parts to demonstrate tolerance magnitudes. First, I understood that size would be an issue for any tolerance demonstrator that had moving parts, however the reality of the sizes required did not manifest itself until these crude concepts were modelled in CAD. Second, for parts to move with respect to each other, there must be at least a very small clearance between them. Those clearances are at exactly the scale that I am trying to demonstrate, and therefore would immediately introduce an error in the resulting gap. Finally, the manufacturing error on any feature is inconsistent over the feature's duration; this would add further doubt to the accuracy of the demonstrator.

Prior to this design study, I had been preoccupied with the visualization of fine-scale tolerances, and thought that being able to drag a fingernail across any gap would provide adequate tactile correlation. As the focus of my study developed, I came to realize that the visio-haptic understanding that I wanted would be made significantly more difficult if only one magnitude could be sampled at a time. Put more simply, you would lose any correlation from a first sample to a second sample if you had to change the demonstrator settings in between samplings. Instead, sequential visio-haptic sampling of static magnitude samples in close proximity would distinguish the differences and provide a more valuable learning opportunity.

This realization was frustrating, Aubrey, even discouraging! I had been focusing on an elegant solution, but I had completely forgotten the tolerance samples that had started me on my exploration of tolerances and my understanding of their physical magnitudes. While those crude samples were entirely tactile, they could all be experienced without changing the sample. I had lost the forest for the trees, and realizing what I had forgotten allowed me to refocus on the forest.

Concept 1

Focusing on the combined visio-haptic aspects of the artifact, I decided that the magnitudes would be manifested as progressively deeper machined surfaces relieved from a single, common surface. The relieved areas would be wide enough that, when sampled using the back of the index finger's nail, no part of the fingernail would engage the opposite side of the relief. I felt this was important so that the user wouldn't experience a second haptic sensation that may negate the primary sensation as the nail's leading edge drops from the common surface. Similarly, the spacing between the reliefs must be adequate so that the user does not accidentally engage more than one relieved segment while sampling.

The relieved segments also allow visual sampling by direct viewing from any angle, however the most effective visualization would come from looking along the length of the groove so that the walls and base of the relief can be seen. It is counterintuitive that excess light can negatively impact visualization. Specifically, light that indiscriminately reflects off the sides and bottom of the relief will make it difficult to accurately perceive the depth of the relief. This could be mitigated to some extent by texturing the surfaces to reduce reflection, however that may also distort the visual perception and the accuracy of the relief depth. Instead, I decided to use a shroud near the end of the relief where the light will enter.

The concept shown in Figure 4-20 indicates two relieved sample bars (one metric, one inch) engaged on a shared base. The bars are held in place by strong magnets which allow the bars to be turned relief-up for tactile sampling, or turned with the reliefs facing each other for visual sampling. In this second setup, the common surface of each sample bar is pressed against a central bar element in the base component. The base is relieved on the underside so that light may simultaneously enter all reliefs in each bar.

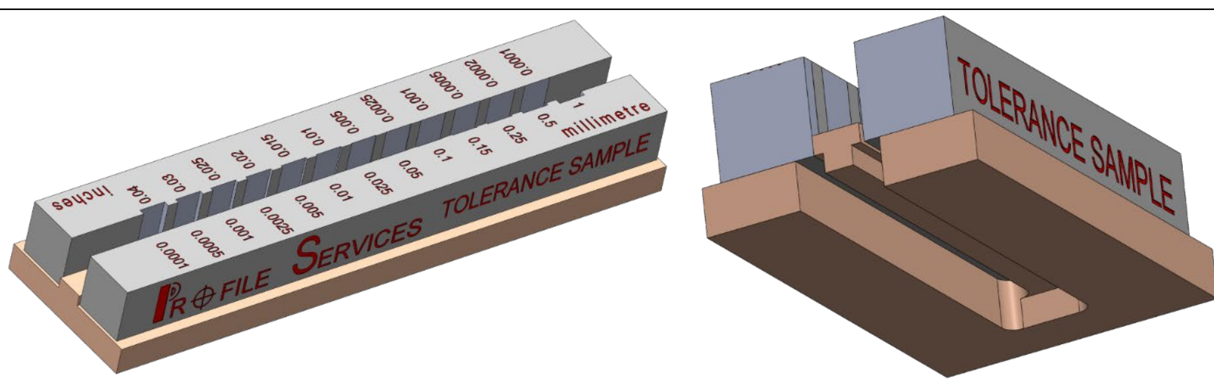


Figure 4-20 Tolerance demonstrator – Concept 1 (section view shown on right)

This is awful, Aubrey! There are several elements that I dislike in this concept. First, because there were so many magnitudes represented, the difference between consecutive groove depths was too small to be appreciable; a subset would be used going forward. This would also allow all components to be shortened. Second, the need to uncouple and rotate the bars makes the artifact cumbersome to use and will increase the risk of damage. Back to the drawing board… CAD software.

Concept 2

The core idea of the previous concept is carried forward. Shown in Figure 4-21, two relieved bars are connected to a third, central component, which acts as a shroud or light waveguide. In this case, the common faces are directed upward, and they engage under the lip of a central bar. The three components are connected with a pair of machine screws. The central bar is significantly relieved on the underside and acts as a waveguide for the light, which must now redirect by ninety degrees to enter the reliefs. The two sample bars are significantly relieved on the underside so that they, along with the center bar, maximize the amount of light entering the demonstrator.

This design would require that users hold the assembly in a way that the opening at the bottom must be turned toward a bright light source, which may make the tolerance demonstrator uncomfortable to use for visual sampling.

This is a cleaner concept than its predecessor but is bulky and likely uncomfortable to use. The elements to be carried forward to the next concept are the reliefs from a common surface and the use of a shroud or light waveguide. Also, locating the engraving to the common face will make the artifact more comfortable to use.

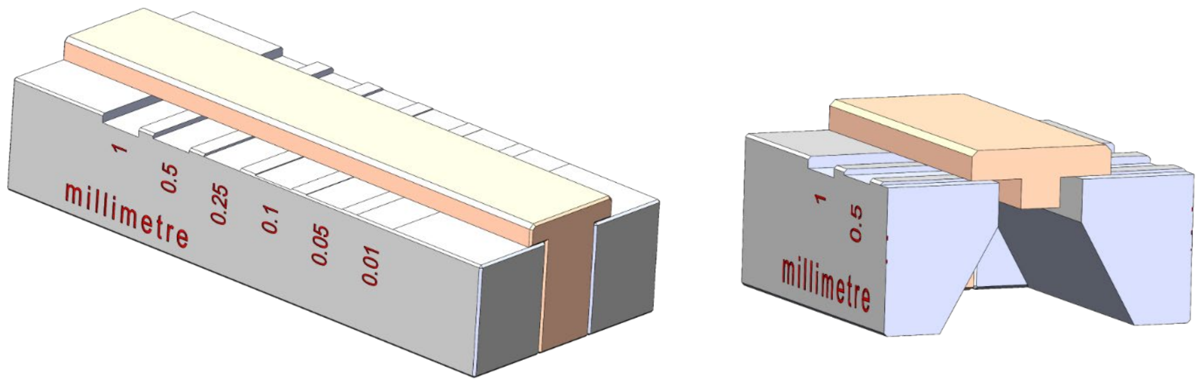


Figure 4-21 Tolerance demonstrator – Concept 2 (section view shown on right)

Concept 3

This concept, shown in Figure 4-22, provides a significantly smaller envelope that would make the artifact easier to hold and use. The relieved segments for both metric and inch values are machined directly into the same piece. In this iteration, light will enter from the top of the artifact rather than the underside. This single change facilitated the greatest reduction in bulk exhibited in earlier concepts. Two cross bars, acting as light guides, are mounted to the top of the base component and sit flush on the common surfaces, which are angled downward from the top surface. The cross bars are mounted at both ends. To protect them from accidental damage resulting in collapse, a support pad is included at the center of each cross bar. Grooves are included in the opposed longitudinal sides of the base piece. Longitudinal ribs inside the cover engage the grooves of the base, which makes the cover reversible. As shown in the pictogram, the cover also acts as rocker base that allows the compact artifact to be conveniently oriented with respect to the light source. The user instruction pictogram shown in Figure 4-22 may be engraved on either the inside or outside of the cover.

While this concept is aesthetically pleasing with a compact form factor, it would not be cost effective to manufacture. The compact size adds to manufacturing complexities and tooling challenges, particularly for the cross bars. The cover was conceived as an extrusion, which would provide some elastic clamping force to hold it securely to the artifact base. Machining the cover out of solid material would be expensive and would not exhibit the elasticity of an extruded cross-section. Arguably, the cover could be eliminated from the design, and the pictogram modified and engraved on the back face of the base. The small size, while making the artifact's use more convenient, will also facilitate accidental or intentional loss.

I spent a lot of time dwelling on this concept, Aubrey. I feel an attachment to it. It strikes me as an elegant design. Its functionality is evident. Its features are reduced to almost a minimalist aesthetic. It seems stylish, as if it would be something to be proudly shown for its aesthetics alone. I could have accepted this as the final design, but the artifact's purpose is pragmatic and that outweighs the high cost factor. Though deeply disappointed, I had to weigh my concerns against my aesthetic pleasure.

New elements to be carried forward to the next concept are the inclined faces, the cross bars, and the inclusion of a pictogram to convey artifact usage.

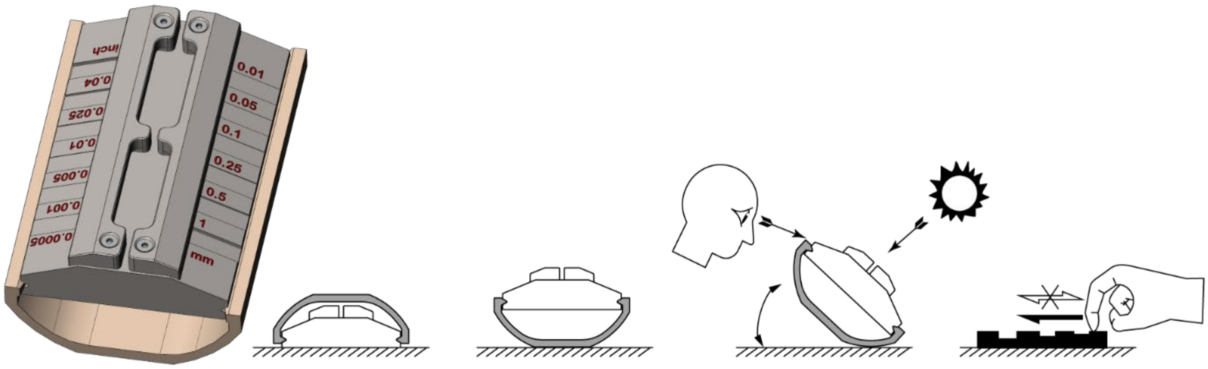


Figure 4-22 Tolerance demonstrator – Concept 3 including artifact usage pictogram

Concept 4

As shown in Figure 4-23, the size and bulk have been increased to help loss prevention and make the artifact a bit more rugged and durable in misuse and mishandling. Whereas the crossbars were mounted on the top surface of the base in Concept 3, they have now been moved near the opposite end of the inclined faces. This allows the user to set the artifact on any horizontal surface near a light source and look down along the inclined faces of the artifact to see light passing under the cross bar. Each component in this concept is simplified, and the base has a relieved underside to reduce artifact weight. A new pictogram depicts usage of this specific artifact.

It bothers me that there are no aesthetically pleasing elements in this design. It appears stark and coarse, almost vulgar in its aesthetic. However, you've seen my collection of surface finish and other comparator samples, Aubrey, and they exhibit the same starkness. This tolerance demonstrator would not seem out of place among them. The common factor between my collection of design artifacts is that they all suit their purpose; they're designed to work, not to look pretty.

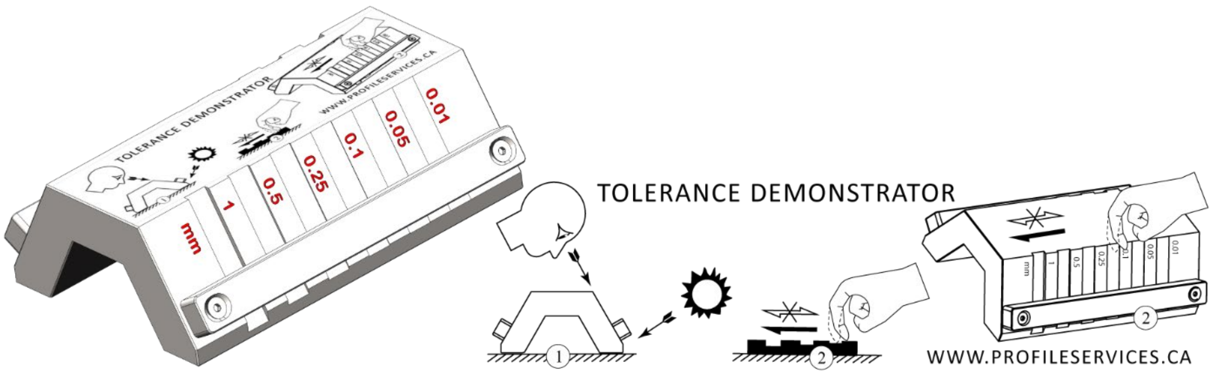


Figure 4-23 Tolerance demonstrator – Concept 4 including artifact usage pictogram

I'm going to take a little detour here, Aubrey, but it will make sense when I tie it back in. It's probably not surprising, but I have scanned through design textbooks and engineering drawings from various periods dating back to the late 1940s, and I am disappointed that I never find any consideration given to aesthetics in engineering design. That post-war period seems to be the transition from artful design to coarse functionality in fabricated machines and structures. Pre-World War II, structures like bridges, towers and even buildings had elegantly shaped castings. Cast locomotive wheels had embellishments like stars, arrows, diamonds, and filigrees. Machine frames and enclosures, and flywheels were rough-cast, then machined to final dimensions, leaving the cast-in decorative elements in place. I was fortunate to spend an evening on La Tour Eiffel. While the panoramic view of Paris was incredible, especially at night, I marveled at the intricate detail in the metalwork. At first blush, aesthetics seemed an inherent part of engineering design in those days, but I couldn't find information on why aesthetics would be a consideration in machine design where the final product didn't justify aesthetic elements, and where any aesthetic elements may not even be recognized under layers of industrial grime. Well, it seems that aesthetic elements may have been used to distract from imperfections in materials and workmanship. As a young adult, I was intrigued by steam power and the evolution of the devices that it powered. In the earliest days of steam power, much of the workings were made from machined castings. When I first started down the rabbit hole of looking into steam power, I ended up on a side-tunnel that led to metal casting. Somewhere along the way, I happened to end up talking to someone who volunteered in the refurbishment of old steam locomotives. By then I was already curious about the aesthetic flourishes on the castings on old steam locomotives, so I asked him. He didn't know anything specific about their inclusion but knew that they weren't mechanically functional. We had a brief conversation that was more of a thought exercise. From our collective understanding of historical metal casting and machining processes, and a bit of basic metallurgy, we came to a conjecture about why they were present. Historically, castings were notoriously rough by nature of the process and materials used. That is, until process and materials were improved in the mid-1900s. The presence of a void in a casting would result in the casting being scrapped. To prevent voids, reservoirs of excess metal were included in the molds so that, even after cooling, there would be sufficient metal. To prevent sinkage and distortions where a casting's cross-section was too thick to cool and shrink uniformly, formed cores would be put into the mold to reduce the local cross-section. Metal removal machining could be expensive and imprecise, and was only done to a casting when it would add value. As a result, the reservoirs (protrusions on the casting) and pocketed forms (relieved areas in the casting) were left in the molded article. To minimize unwanted attention on these areas, pleasing geometric forms were used. That practice of coring to reduce cross-sections is still used today, but controlled geometries are used to minimize mold costs. The practice of using metal reservoirs also continues, but molds are now designed with multiple small risers that are economically machined from the casting. So, it seems reasonable that design aesthetics were historically included for reasons of subterfuge.

On the other hand, designed aesthetics have the ability to elevate perceived, if not practical, value. It is human nature that, given two otherwise equivalent options, we will select the more aesthetic. And that is where this detour returns back to my concepting. Concept 4 lacks aesthetics, and that bothers me.

Concept 5

This final concept is an attempt to reintroduce some aesthetic elements. As shown in Figure 4-24, the base component is a cylinder with reliefs machined radially into the top face; millimetre depths on one half, and inch depths on the other. The cross bar has been replaced with a light-guide ring that mounts on top of the base. Users would need to hold the artifact in their hand while trying to figure out the best orientation with respect to a light source to now see light under the ring. Though no pictograms were created for this concept, they could be added to the top surface of the ring.

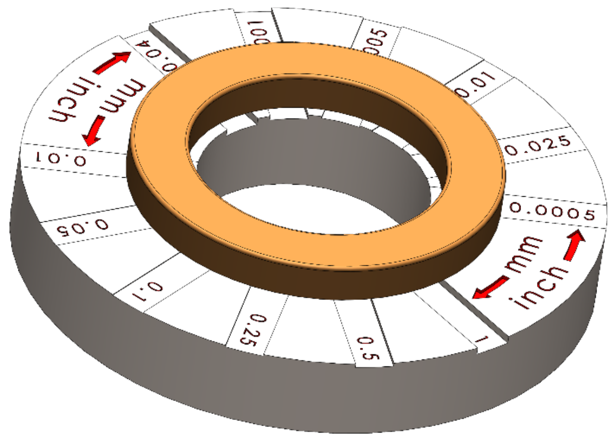


Figure 4-24 Tolerance demonstrator – Concept 5

Though this concept wasn't fully developed, it showed that the aesthetic could be improved by simply changing the base geometry. Unfortunately, that single change would also significantly increase the complexity of machining and therefore cost.

I see the potential for design elegance in this concept, Aubrey. Unfortunately it will likely cost more than the preceding concept, so my pragmatic side wins again.

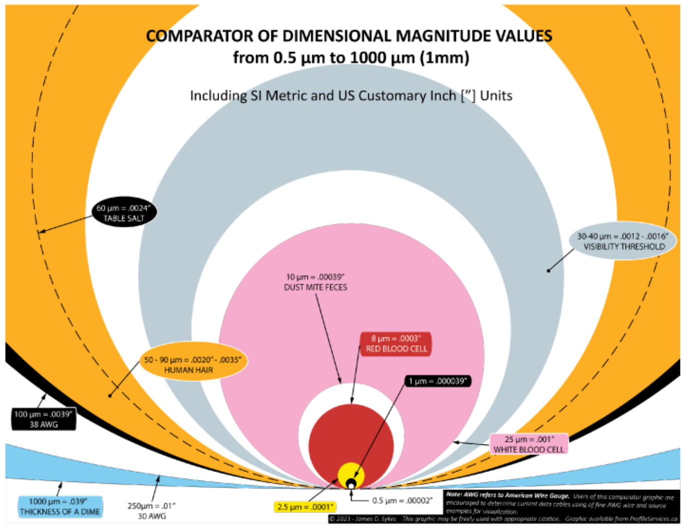
Final Design – Artifact 3 – Visio-Haptic Tolerance Demonstrator

The final design for Artifact #3 is Concept 4, shown in Figure 4-23. Both the base and the cross bars will be machined from AISI 416 stainless steel. The assembly's overall dimensions are 80mm (L) x 50mm (W) x 25mm (H), with an overall weight of 460 grams [1 lb].

Identification of each relief depth is engraved on the inclined faces. The pictogram, which communicates visual instructions, identification and engineering sourcing information is engraved on the top face of the base component. Assembly and component engineering drawings are provided in Appendix B.

Final Designs of Three Artifacts for Use in Learning of Tolerancing Practices

At one time, you asked me why there aren't more technical electives like AGC. I'm going to take my answer beyond the bounds of the University of Manitoba, Aubrey. Again and again, I have heard and experienced that today's mechanical engineering university curricula are so overloaded with emerging technologies and other new content that these institutions expect industry to teach graduates the practical skillsets and knowledge as needed for their daily tasks. Industry will smooth the rough edges of the mechanical engineering graduate's iron ring. I suspect that was a practical approach, long ago. However, those same industries employ subsequent generations of graduates of these same programs, and I have observed repeatedly that the practical knowledge base and skillsets have eroded or degraded over time. It's the engineering version of the game, telephone. The message is changed by each person that passes it along to the next person. The artifact designs developed in this study may reset the message so that it can be conveyed accurately, again and again. In that context, I believe that the three artifacts shown in Figure 4-25 will be useful.



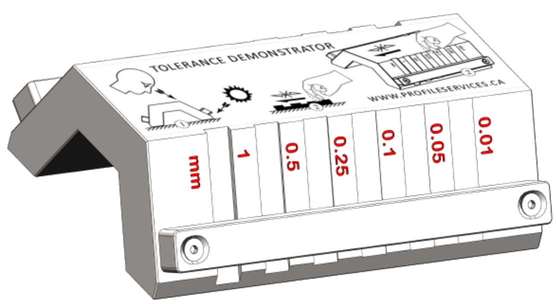


Figure 4-25 Final designs[xvii] for Artifact #1 - visual comparator (top), Artifact #2 - haptic fits demonstrator (centre), Artifact #3 -visio-haptic tolerance demonstrator (lower)

[xvii] Refer to Appendix C for information on artifact design dissemination.

Design of these artifacts has been a long journey, Aubrey. Intermittently over three decades, I've thought about the *instruction and learning* of dimensional tolerancing practices. Given that my experience seems to match the stories of many other engineers, perhaps I should resequence them as the *learning and instruction* of tolerance practices, because tolerancing is an element of mechanical design esoterica that must be learned in practice before it can be instructed in academe. As a mechanical engineering design *practitioner* with experience in both industry and academe, I am an outspoken advocate for a mechanical engineering design education that fosters an understanding of the visual and haptic aspects of Fits-based tolerancing and a physical understanding of the magnitude of the tolerances involved. I was surprised that I didn't find anything in the research literature that mentioned the contemplation or development of these kinds of artifacts. At the same time, it is understandable that instructors of tolerancing theory wouldn't perceive the need for artifacts to teach the practice of tolerancing. I'm sorry that I didn't get to this earlier in my career, so that I could have these artifacts in place when you took AGC.

This brings us to the end of our artifact design exploration, Aubrey. Thank you for letting me share this with you. Jim

Chapter 5 Discussion and Recommendations

Discussion of the Artifact Design Study

The design of the three artifacts is complete. They are not perfect, but they are adequate to consider them “done”. Inevitably, they will be revised, as design is an iterative process, but first they must be physically produced and evaluated in use. Intentionally, the build and test phases of a conventional engineering design study were not included in the artifact design study methodology. They are the next step in the evolution of these artifacts.

This study has described the design intent for three artifacts to develop cognizance of micron-scale tolerance magnitudes, and of ASME B4.2 clearance fits. Literature supports the use of visual, haptic, and visio-haptic techniques in perception of micron-scale dimensional magnitudes. Based on a developed collection of artifact design considerations, three artifacts were iteratively concepted, and final design completed for each (Figure 5-1 and Appendix B).

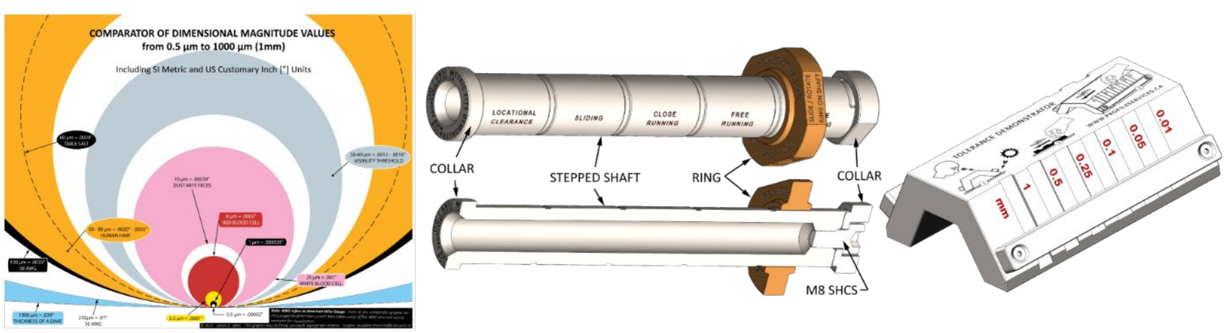


Figure 5-1 Final designs for Artifact #1 (L), #2 (C), and #3 (R)

Recommendations from Artifact Design Study

Next considerations for the three artifacts are to produce or manufacture them as appropriate, and update the designs for any issues that arise. In parallel, instructions for the use of the artifacts should be created, based on the designer's anticipated use.

The usability and effectiveness of the artifacts should be studied.

I would recommend that studies be conducted on how the artifacts are used, when provided to students without specific instructions beyond what is engraved on the artifacts, contrasted with how students engage with the artifacts when provided instructions. This may help to identify whether the artifacts are intuitive in their use, and whether additional changes are required.

Separately, the artifacts may be studied to see whether, and how effectively, they contribute to student cognizance of micron-scale tolerance magnitudes and clearance Fit-classifications.

Finally, if the artifacts are found to be usable and effective in developing such cognizance, consideration should be given to developing an independent micro course that instructors may assign, or students may elect to undertake, on the topic of Fits-basis tolerancing.

Discussion of the Self-Reflective Study

By the time that I started my graduate studies, I felt a growing unease at the way statistics could be misused in research, unintentionally, or intentionally, to skew findings, or interpretation of findings. I can accept that statistics have their place in research, but I remain concerned that sample sizes and sample pools do not adequately represent sociological aspects in research, including in education. That was the genesis of my interest in qualitative research, and the reason that I wanted to include it in my thesis research. The focus of my research shifted a number of times and, in the final decision, it initially seemed to focus on just the engineering *design* of artifacts for a specific instructional purpose. The scope of the design itself was considered adequate for a thesis topic. However, my design thinking for these artifacts does not follow a conventional linear path, and there seemed merit in conveying my design thinking as well. Qualitative research, specifically self-study research, provides me a means to tell my design story, and my tendency toward anecdotalism seemed an appropriate way to convey it. From there, the idea for invoking the Voice of my inner Design Companion emerged.

In keeping with the traditions of self-study, I recognized an area of opportunity to improve my own instruction practices, and placed myself at the center of an otherwise technical design study. In my self-reflections, I talk to Aubrey, a composite of my former AGC students and their experiences with me. Through these self-reflections, I tell Aubrey about my self-perceptions, and their evolution. In so doing, I also recognize that I have had significant achievements that reflect a contrary position to my self-perceptions.

Recommendations From the Self-Reflective Study

It is not easy to look in on yourself with the intention of publicly sharing what you see. Long ago, I recognized my fear of failure, and an insecurity in my capabilities, but I saw no value in addressing them. Self reflection, however, helped me to accept that those feelings developed from abusive experiences, and that in focusing significant efforts on avoiding those perceived shortcomings being made public, those same experiences contributed to my achievements. I can't say that self-reflection has negated those feelings, but I acknowledge that self-reflection has made me more aware of my achievements, and that recalling those achievements in moments of self-doubt does help me to move past them.

I recognize that my negative self-perceptions contributed to difficult interactions with colleagues. Throughout my career, I have developed personae to more effectively engage with others so that I can support them in their work. First as a subject matter expert, then a fixer, then Devil's Advocate, instructor, and most recently as a design coach. The realization of this last persona, the design coach, was solidified through this self-reflection, and made manifest through the development and invocation of the Voice of The Design Companion in this thesis. These personae are not unique to me other than, perhaps, in the conscious recognition and naming of them. These may be seen to reflect the attainment and valuation of certain skillsets, knowledge, achievements, and recognition in a design engineer's career path. I wonder if an exploration of them may provide value to engineering students contemplating a career in mechanical engineering design?

Recommendations Regarding Design Esoterica

Previously in this writing, dimensional tolerancing was introduced as one element of mechanical engineering design esoterica. I have watched mechanical engineer design education curricula evolve since the 1990s, and I have witnessed traditional skills of two-dimensional (2-D) drafting of representations of solid objects, and print reading replaced with three-dimensional (3-D) CAD modeling and 3-D printing (additive manufacturing). Understandably, as traditional drafting courses were removed from curricula, so too was their extended design content that I refer to as esoterica. Terms like fillets, rounds, chamfers, slots, flanges, etc., are no longer uniformly understood by senior mechanical undergrads. Knowledge of specialized geometries such as undercuts and custom thread profiles is no longer available to undergrads. As a mechanical engineering design practitioner, the loss of this esoteric knowledge from engineering education is disheartening; it seems a step back from knowledge we once gained before graduating. However, the same tools that supplanted traditional drafting may be used to create new learning opportunities and new ways of delivering some of the content. Exploration and communication of the broad field of mechanical design esoterica is a journey of a thousand miles, and this exploration of the design of three artifacts for instructing dimensional tolerancing is a first step.

Conclusion

As outlined earlier, there were two facets to be explored in this thesis. The design of three visio and visio-haptic artifacts has been completed, with their evolution illustrated. In the disclosure of the design evolutions, self-reflections on my design thinking for the various concepts and the final designs are conveyed. Further, the evolution of my design thinking that culminated in the three designs has been explored in a way that exposes the root of my motivations and shows how my lived experience is an intrinsic element in my design. In this way, readers may come to recognize and respect the presence of their own humanity and lived experience reflected in their mechanical engineering designs.

Appendix A Artifact Design Considerations

As discussed in Chapter 4, the following tables demonstrate their use on Artifact #1, the comparator graphic.

Design Considerations – Artifact 1: Visual Comparator Graphic

Table A.1 General considerations – Artifact 1

C#	Consideration Query
C1	Q: What are the *instructional* goals for the artifact? A: Provide basis for visual perception of micron-scale magnitudes. Q: What are the *learning* goals for the artifact? A: Develop an understanding of the relative magnitude of micron-scale magnitudes.
C2	Q: Are all features incorporated into the artifact meaningful in their use? A: Arguably, yes. The inclusion of inch values may / may not be useful to learners. Q: If not, can they be excluded from the artifact? A: Yes, but potential learning value would be diminished.
C3	Q: Are there other existing artifacts, individually or collectively, representing the same concepts? A: None found Q: If so, explain why this new artifact design is needed.
C4	Q: Is the artifact design rooted in a predecessor? A: Only tangentially Q: If so, identify predecessor and describe insights (strengths and deficiencies) carried over to the new artifact. A: Fasteners & other components are sometimes shown in size comparators, but generally located beside each other, which does not show a "fit" or "fit within" relationship.
C5	Q: How is the artifact broadly useful? A: Micron-scale magnitudes / tolerances are generally theoretical knowledge. Graphic provides a relative relationship to Q: If not, identify specific limitations (sizes, conditions, etc.).
C6	Q: How has the artifact been designed to be extended in use from the particular context to additional practical uses? A: Consideration was given to including the tolerance bands specific to the 5 clearance fits of Artifact #2. However, Artifact 2's tolerances are for a specific hole/shaft size, and this would have actually reduced broad applicability to other hole/shaft sizes.
C7	Q: How is the underlying technical concept clear and distinguishable from the physical details of the artifact? A: Consideration is not relevant.
C8	Q: What are the specific design elements and functionalities represented by the artifact? A: Consideration is not relevant.

C9	Q: What elements of the artifact design are intertwined in ways that are not immediately apparent? Explain any changes to the artifact that are necessary. *A: Consideration is not relevant.*
C10	Q: How are critical and non-critical physical characteristics of the artifact differentiated? *A: Consideration is not relevant.*
C11	Q: What is the anticipated usage environment (lighting, temperature, hygiene, other)? *A: Typical office or classroom environment.*
C12	Q: What sensory inputs are anticipated in the artifact's use? A: **Visual** / Olfactory / Haptic / Auditory / Taste / Other
C13	Q: How are intended functionalities of artifact made explicit? *A: Graphic title, descriptors of physical comparators are provided.*
C14	Q: What other artifacts should / must be chained with this artifact to convey the core concept? *A: Consideration not relevant.*
C15	Q: What other chain of artifacts may this artifact be added into or substituted to convey a core concept? *A: May be used independently, or with Artifacts #2 & 3 to compare scale of magnitudes involved.*
C16	Q: Will the artifact be produced physically? *A: User may print or view on digital display* Q: How will the artifact be incorporated into teaching? *A: May be incorporated into an Independent Micro Course (I µC), Individual Micro Credential, or regular undergraduate engineering design core or elective courses, with or without Artifacts #2 & 3 to compare scale of magnitudes involved.*
C17	Q: What are the limitations of useability based on location, disability, capability, or capacity? *A: Moderate to high visual acuity suggested. Ability to perceive spatial relationships and relative magnitude required.*
C18	Q: How does the artifact design encourage a critical evaluation of merits and concerns about the elements demonstrated? *A: Provision of known physical elements provides a comprehensible basis for comparison of physical magnitudes* Q: How may the artifact be used in group discussion? *A: Students could be assigned to annotate the graphic with specific fit-gap magnitude-circles to represent their design fitments. Provides perspective on absolute magnitude of tolerances involved.*
C19	Q: How do you anticipate the user's perspective and understanding of the various elements to evolve as they engage with the artifact? *A: When discussing or considering which Fit-Class to select, Students may bring physical samples of table salt, human hair, a dime, and potentially various AWG samples for further visualization benefit.*
C20	Q: Is the technical nature of the artifact effectively documented and communicated such that instructors can readily understand and use the artifact? *A: As an independent visualization tool, it is adequate as is. However, instructions may be added for use in conjunction with Artifacts #2 and/or #3. These may be added to the front of the graphic, or on a second sheet, tbd.*

Table A.2 Tolerance artifact design considerations – Artifact 1

C#	Consideration
C21	**Safety**
	Injuries - Significant Potential
	Injuries - Moderate Potential
	Injuries - Low Potential
C22	**Ergonomics**
	Moderate to High Vision Acuity
	Finger size
	Weight Limit
	Size Limits
C23	**Operating / Usage** *Not Applicable*
	Lubrication
	Hygiene
	Static / Dynamic
C24	**Assembly** *Not Applicable*
	Complexity
	Features
	Techniques
C25	**Design Complexity** *Not Applicable*
C26	**Aesthetics and Handling**
	*Noticeable **Colours** without overpowering graphic*
	Chamfer / Radius / Sharp Edges
	Surface Reflectivity
	Text Format

C#	Consideration
C27	**Communications – instructions**
	Pack/ Unpack
	Handling
	*Consider adding **Use** as a second sheet* / Operation
	*Consider adding **Learning Goals** on a second sheet*
	Maintenance
C28	**Material** *Not Applicable*
	Durability
	Corrosion
	Lubrication
C29	**Manufacturing** *Not Applicable*
	Design Complexity
	Processes
	Tolerance Requirement
	Surface Finish
	Markings
C30	**Shipping** *Not Applicable*
	Method
	Packaging Type
	Size
C31	**Design Rules of Thumb** *Not Applicable*
C32	**Reference Artifacts** *Not Applicable*

Appendix B Artifact Technical Specifications

The following are the design specifications for each of the three artifacts whose design developments have been illustrated in this thesis.

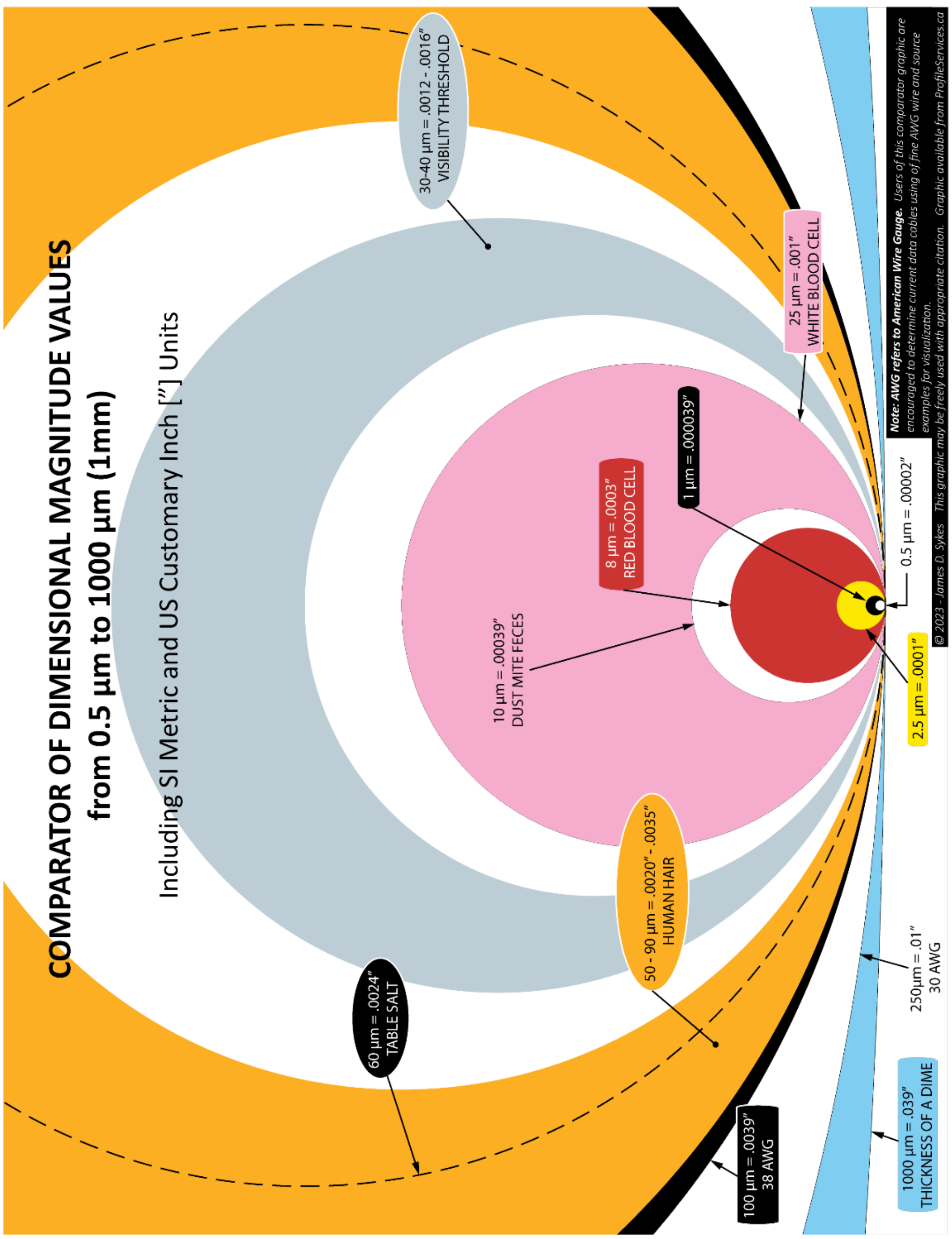


Figure A.1 Artifact #1

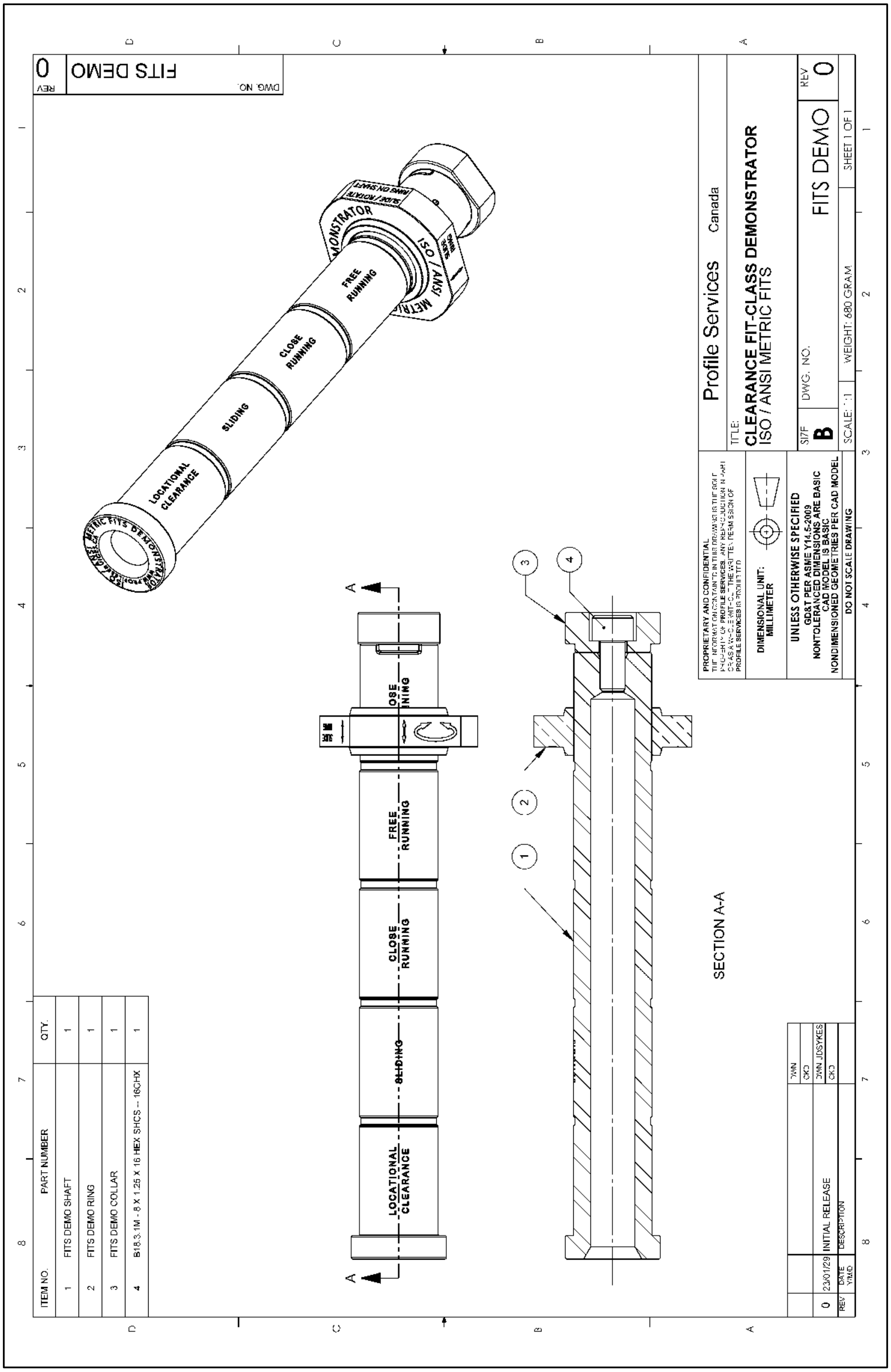


Figure A.2 Artifact #2 – Assembly

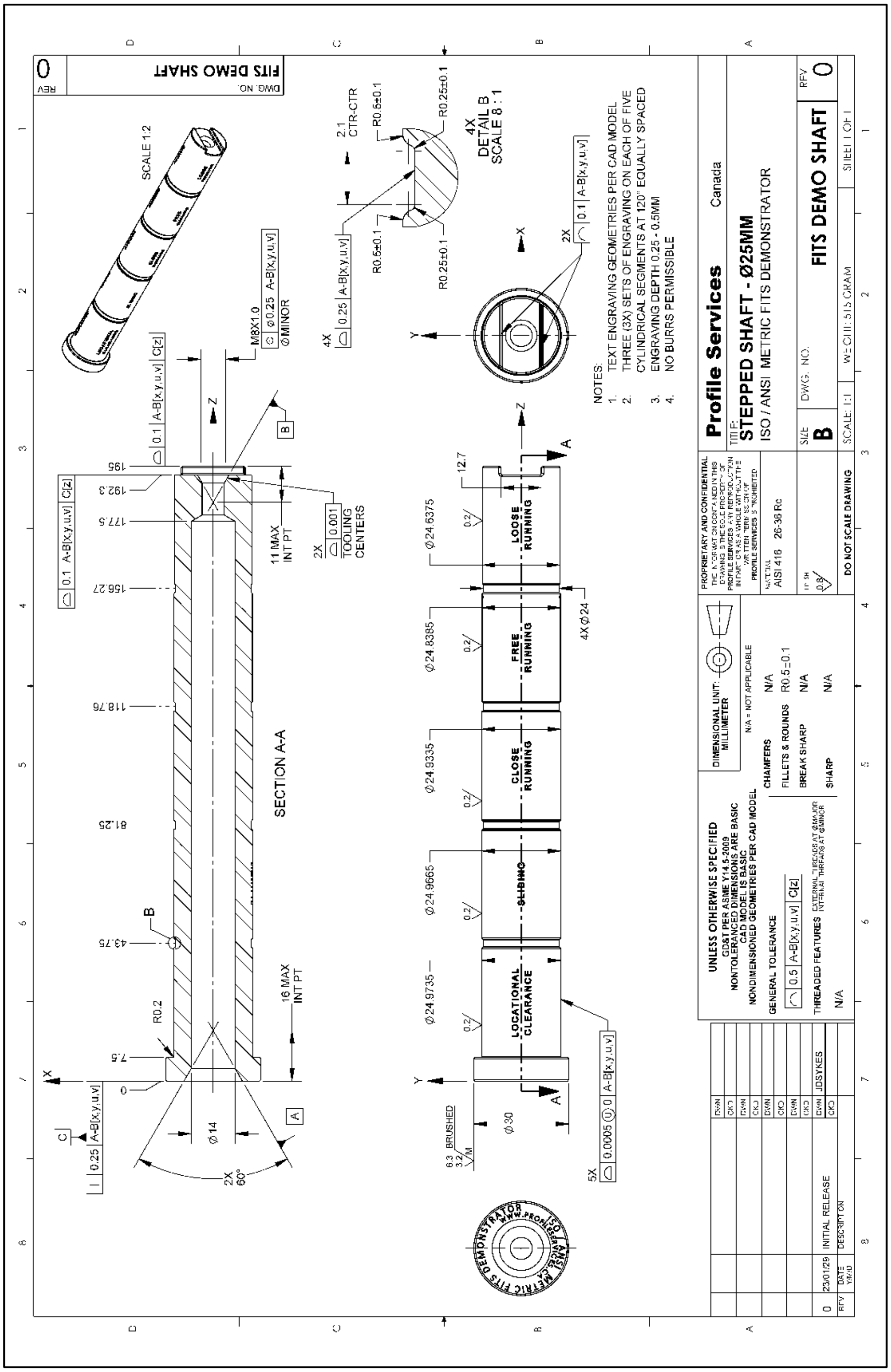


Figure A.3 Artifact #2 – Stepped shaft specification

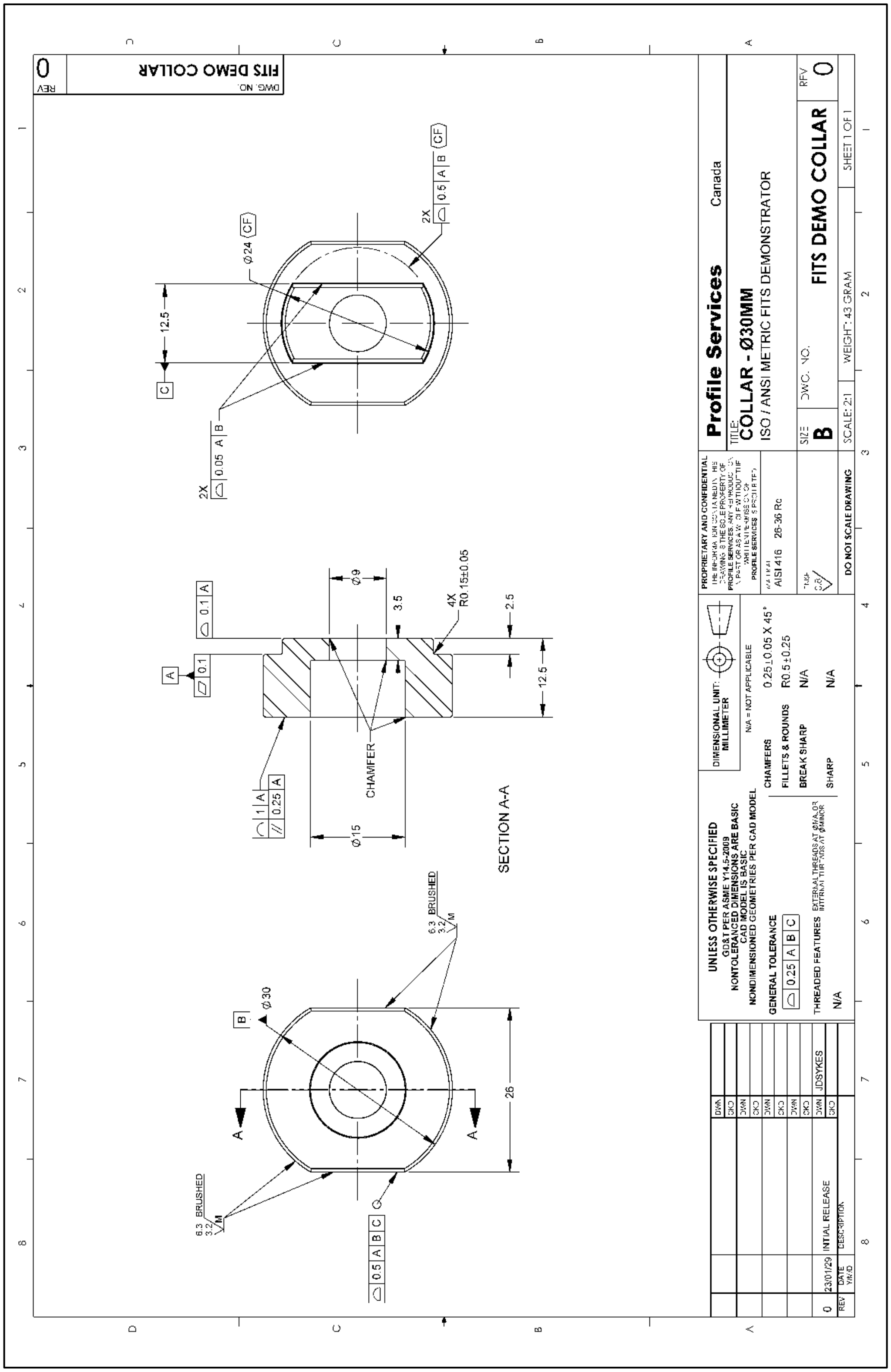


Figure A.4 Artifact #2 – Collar specification

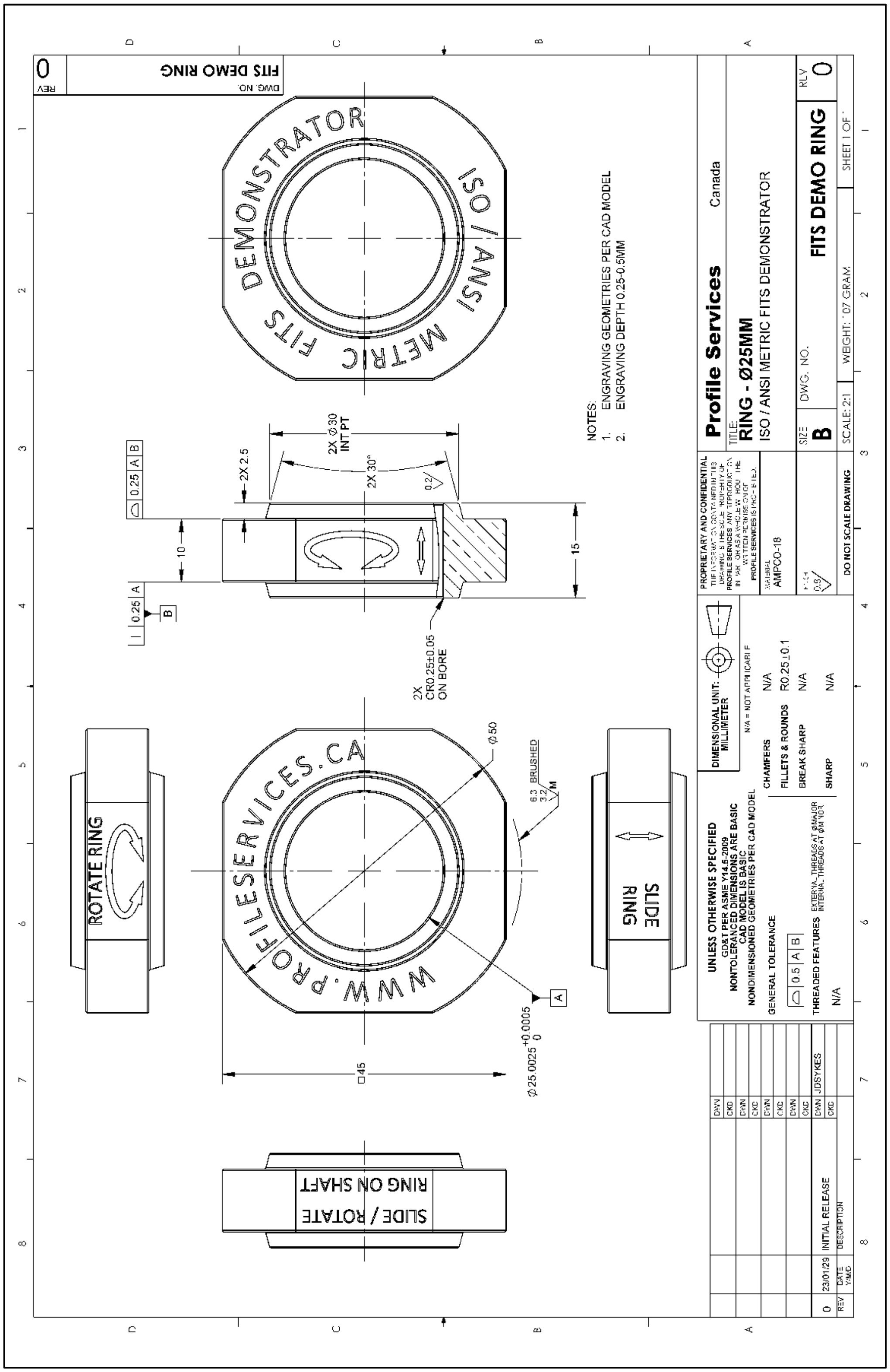


Figure A.5 Artifact #2 – Slide ring specificatio

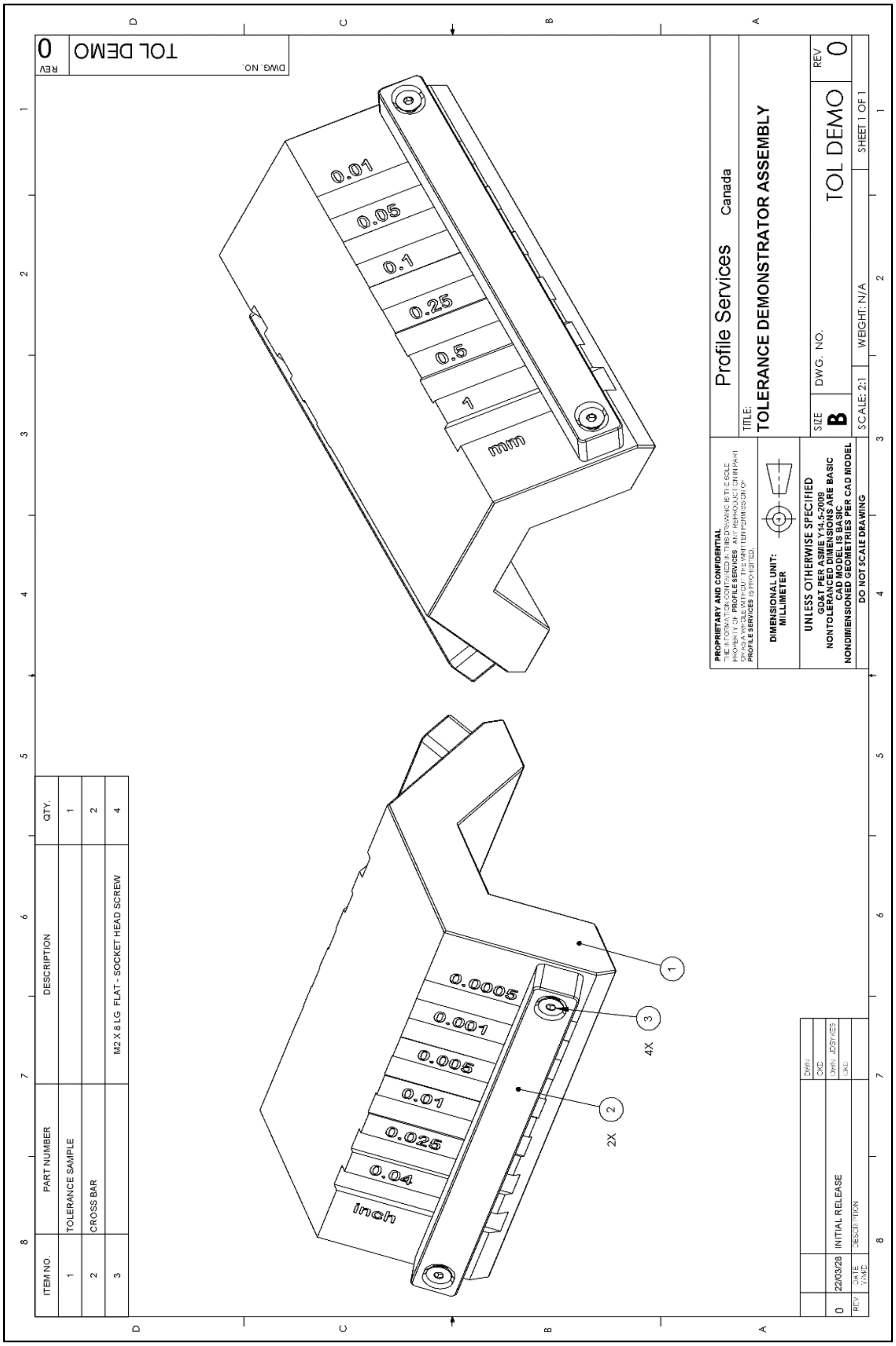


Figure A.6 Artifact #3 - Assembly

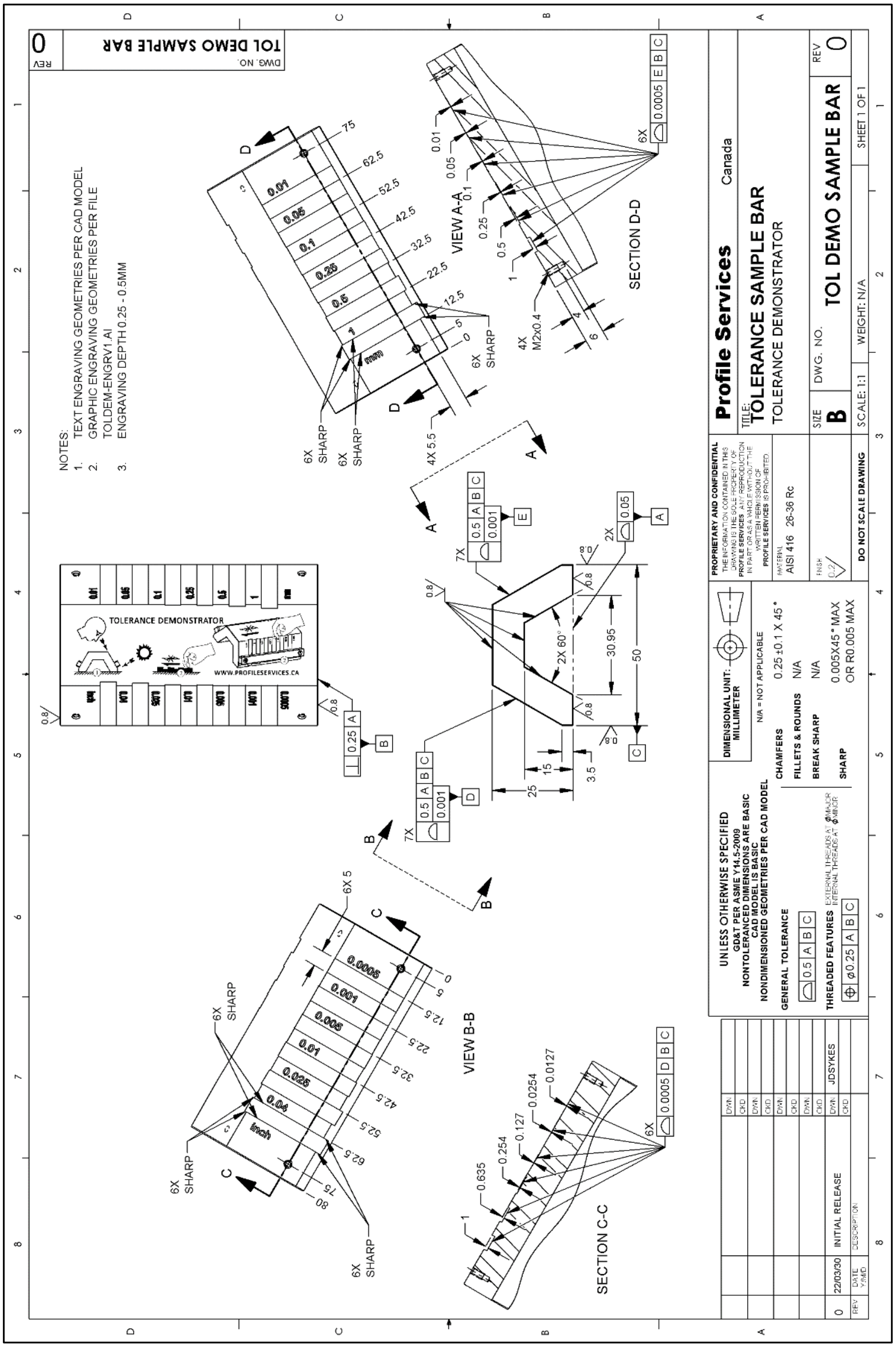


Figure A.7 Artifact #3 – Tolerance sample bar specification

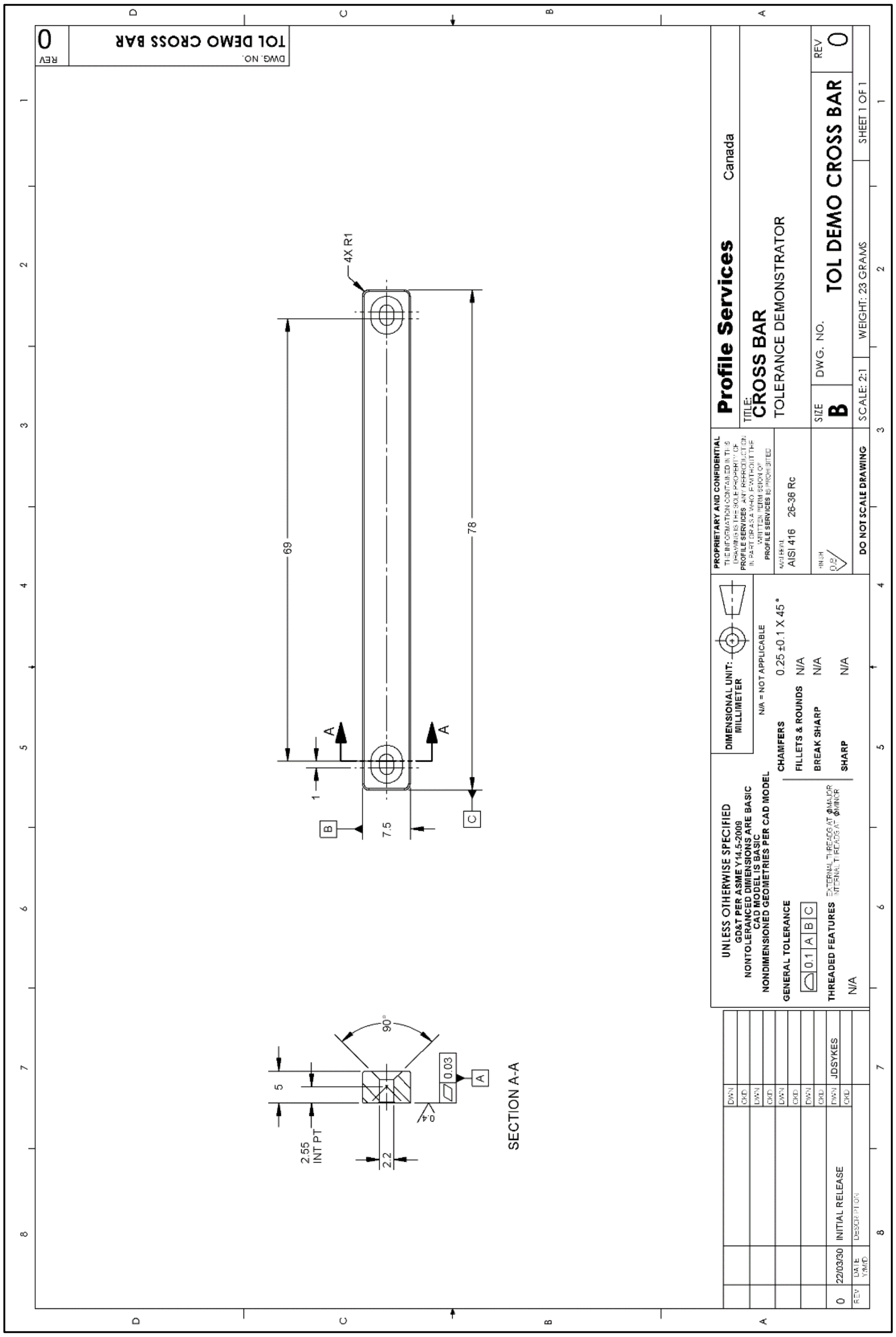


Table A.3 Artifact #3 – Cross bar specification

Table A.4 Artifact #3 – Engraving detail

Appendix C Artifact Design Dissemination

Beyond the use in my thesis, I hope that early-career design engineers, and anyone involved in undergraduate mechanical design education, might find these artifacts useful. While the first artifact can be printed and used by anyone so inclined, the second and third artifacts are only useful if manufactured. Recognizing that few people will read this thesis, dissemination of the graphic and the design specifications can only be achieved by posting the files (graphic, technical drawings, CAD models) on or through a public website and promoting their existence and use.

While my intent is that the files associated with the three artifacts will be in the public domain, I have found that public domain content still need to be owned to be maintained. Therefore, I will retain custodial ownership of all the files related to the artifacts while simultaneously making them available and free to access and use, indefinitely, from my website, www.profileservices.ca, or from a public content website as directed on my website.

Appendix D Professional Biography

Jim (James) Sykes graduated with a bachelor's degree in mechanical engineering (management concentration) from Carleton University, Canada, in 1993.

During the next twelve years, Jim worked as a mechanical design engineer for two companies in the plastics (resin) molding industry. During those years, he developed expertise in engineering design for metal-removal manufacturing processes, for resin and powdered-metal molding, and experience in early additive manufacturing processes. It was during that time that he developed an interest in the acquisition and dissemination of knowledge of design esoterica. Jim led industry participants in the voluntary standardization of design technologies and the resolution of an industry-wide design safety issue. In the last five years of conventional industrial employment, Jim developed and evolved his knowledge of geometric dimensioning and tolerancing.

In May of 2005, Jim started an engineering support services company, Profile Services, and in July, he attained his GDTP-S (Geometric Dimensioning and Tolerancing Professional – Senior Level) certification from ASME. Jim started teaching GD&T in industry in March 2006. Since then, he has taught at numerous mechanical, electronics, medical and other manufacturing based companies internationally, and has trained design and machinist instructors at a college. From 2016 through May 2021, Jim was employed as an Engineer-in-Residence (EiR) at the University of Manitoba's Price Faculty of Engineering. In that role, he instructed Advanced Graphical Communications (AGC), a GD&T-based mechanical engineering elective, as well as advising and coaching capstone projects, design-build-test competition teams, and both engineering and combined engineering and commerce case competition teams. As the COVID-19 pandemic closed schools to in-person instruction, Jim created and instructed online a Mechanical Design Skills Workshop (MDSW) in early summer of 2020, and then instructed the final offering of AGC, online in winter of 2021.

During his career, Jim was named on several patents and patent applications, has authored articles in trade magazines, participated in the standardization of design and engineering technologies and processes, and authored a chapter in a textbook.

Jim began his graduate studies at the University of Manitoba's Price Faculty of Engineering in January 2019.

Glossary

additive manufacturing, AM is a field of manufacturing that progressively builds layers of material into a final article

advanced graphical communications, AGC refers to a fourth-year mechanical engineering technical elective offered from 2016 through 2021 at the University of Manitoba, Price Faculty of Engineering

afferents are nerve fibres or vessels bearing or conducting impulses toward the central nervous system

ANSI / ASME B4.2 is an industry and national standard specifying Fit-basis tolerances

ASME is the American Society of Mechanical Engineers, an organization focused on developing and disseminating standards for technologies and practices related to the field of mechanical engineering

CAD refers to Computer Aided Design and/or Computer Aided Drafting, without distinction

CAM refers to Computer Aided Manufacturing, typically referring to computer numeric controlled (CNC) machining practices

capstone project is a senior-year project which demonstrates the design learning of the student

CMM refers to Coordinate Measuring Machines, which can be contact or non-contact, without distinction

Comparator refers to a sample which has been created to demonstrate or represent something such as surface finishes, scales, collections of a type of item, etc.

dorsal edge of the fingernail refers to the upper, leading edge of the fingernail

Fit-Class, Fit-Classification, Fits-basis refer to standardized mating conditions between two components, one of which will mate, or reside, within the other

fuse deposition modeling, FDM refers to an extrusion-based additive manufacturing process, in which successive layers of extruded resin or other materials are thermally bonded to predecessor layers

geometric dimensioning and tolerancing (GD&T) is a language used to convey designer intent on mechanical engineering drawings

haptic refers to the perception of touch, particularly as relates to sensing and manipulating things

heutagogy refers to self-directed learning

ideation is a current, preferred term for brainstorming

independent micro-courses (IµC) are a proposed structure of independent learning modules that may be invoked within a conventional course, or as part of independent study on specialized topics

individual micro credentials are recognitions of achievement related to discrete bundles of knowledge metrology refers to attribute measurement-based inspection, as opposed to conventional inspection which establishes pass / fail criteria

micron, µm is a measurement equivalent to one millionth of a metre

microscale, micron-scale refers to sub-millimetre magnitudes, typically in the range of 1-100µm

master moldmaker refers to a tradesperson, capable of designing and fabricating mold components, with significant experience beyond journeyman designation

nanoscale refers to magnitudes smaller than 1µm

proprioceptors are sensor receptors within the body, which respond to movement and spatial position

selective laser sintering, SLS refers to an additive manufacturing process, in which successive layers of metal powder or other materials are melted by a laser, allowing them to bond with predecessor layers

self-reflexivity is an iterative examination of self to explore cause and effect, either as an individual or an element in society

somatosensory refers to the network of neural connections throughout the body and brain, which perceive touch, temperature, spatial location, and pain

subject matter expert, SME is a person with deep knowledge, beyond that of a typical practitioner, in a specific field

thou, thousandth of an inch are terms common used to represent magnitudes, below 1 inch and to the third decimal place

tolerance is an allowable deviation from ideal or stated nominal dimensional values

tooling refers to elements such as cutting inserts, grinding materials deposited on mandrels, workpiece holding fixtures, and other elements used in the manufacturing process in the production of a workpiece

visio relates to something that is vision-based

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