Journal of
INDUSTRIAL TECHNOLOGY

Volume 20, Number 3 - June 2004 through August 2004

Dimensional Metrology: A Perspective on Structure and Lab Integration

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Peer-Refereed Article

KEYWORD SEARCH

Manufacturing
Metrology
Quality
Quality Control
Statistical Methods

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Dimensional Metrology: A Perspective on Structure and Lab Integration

By Dr. Bruce Marsh and Dr. Mark Miller

Introduction

Metrological error has a far greater cost impact now than in the past; product quality, the quality reputation of an organization, and customers' quality expectations are at stake. As indicated by Marsh (1995), such errors can be reduced if those involved in production and measurement activities possess an understanding of (a) metrological terms such as accuracy, precision, resolution, and gage repeatability and reproducibility (Gage R&R); (b) metrological system trade-offs and their impact on manufacturing goals, profits, and overall productivity; and (c) the considerations needed when using, comparing, upgrading, or purchasing metrological equipment. Peggs (1999) supported the need for greater understanding of dimensional metrology when he stated " . . . more and more members of the manufacturing community recognize the vital link that dimensional metrology provides between the design and the manufacture of engineering components. Trends now evident in manufacturing technology will continue to drive developments in dimensional metrology well into the next century to support industry's full range of diverse needs" (p. 22). Within the Industrial Technology department at Texas A&M University-Kingsville, investigations have been conducted over the last five years that have focused on identifying the types of instruments and the number of lab activities that can be successfully integrated into a undergraduate course in dimensional metrology without adversely affecting course content goals and objectives. The results of these investigations have led to the development of a comprehensive perspective on the structure of a dimensional metrology course including lab integration.

Course Description and Basic Layout

ITEN 3352 Dimensional Metrology was integrated as a departmental course offering at Texas A&M University in Kingsville during the Fall of 1999. The course was developed and integrated as an advanced IT elective and was listed in the university catalog as a 3(2-2) course; a 3-credit hour course with 2 hours of lecture and 2 hours of lab per week. It was also adopted as one of the required courses needed if a student wants to graduate with a departmental certificate in the Quality Assurance area. The textbook used in the course is *Fundamentals of Dimensional Metrology* (3rd edition) by Ted Busch, Roger Harlow, and Richard Thompson, Delmar Publishers, 1998. The principal objectives of the course are to help students develop: (1) an understanding of the terms and concepts related to dimensional metrology; (2) an understanding of two measurement systems used and the reasons why measurement is considered a language and essential for communication; (3) a working knowledge of the instruments used in inspection and gaging activities and the basis for their integration; and (4) a holistic perspective with respect to the purchasing or upgrading of metrological equipment. Other aspects associated with the structure and layout of a dimensional metrology course include: content sequencing, time allocations, and lab scheduling; lab equipment and purpose for integration; and lab activities combined with spreadsheet integration.

Content Sequencing, Time

Allocations, and Lab Schedules

Content sequencing of the course deviated somewhat from the chapter-based structure of the textbook. This is not an unusual occurrence given the fact that textbooks are dynamic in nature and constantly being revised and restructured based on faculty input or need. The following numerically-sequenced content areas form the basis upon which the course has been structured and sequenced:

- Content 1. Measurement and Metrology (2 hours); uses of measurement, disciplines of measurement; applications of measurement.
- Content 2. Language and Systems of Measurement (2 hours); dimensional measurement, measurement terminologies; measurement systems (english and metric).
- Content 3. Statistics and Metrology (6 hours); meaning and aspects of statistics, data collection, frequency distributions and histograms; measures of central tendency, dispersion, skewness, and kurtosis; characteristics of the normal curve; Labs 1 & 2.
- Content 4. Measurement, Gaging, and Tolerance (2 hours); maximum and least material condition defined; methods and types of tolerancing.
- Content 5. Graduated and Scaled Instruments (4 hours); scaled instruments (steel rules); role and types of error; nonscaled instruments (dividers and calipers).
- Content 6. Vernier Instruments (4 hours); types of vernier instruments; advantages and disadvantages of vernier scales, vernier calipers, vernier depth gages, vernier height gages, and digital calipers; Lab 3.
- Content 7. Micrometers (4 hours); micrometer instruments (types, construction, and reading); care and inspection; Lab 4.
- Content 8. Gage Blocks (4 hours); why standards are needed; modern gage blocks and material; grades and sizes of gage blocks; care of gage blocks; wear blocks, holders, and end standards; uses of gage blocks; precalibrated indicator technique; Lab 5.
- Content 9. Measurement by Comparison (8 hours); review of direct measurement; principles of comparative measurement; role of amplication; functions and features of dial indicators; comparator amplification, sensitivity, resolution, and accuracy; balanced versus continuous; and indicator and accessory selection; Labs 6 & 7.
- Content 10. Calibration (2 hours); role of error, basic calibration procedures; calibration of calipers, micrometers, dial indicators, and gage blocks; calibration readings and wear considerations.
- Content 11. Reference Planes (2 hours); flatness defined; reference planes; types of granite surface plates; surface plate selection and functional considerations.
- Content 12. Surface Measurement (4 hours); surface description; surface evaluation; stylus method; wavelength, frequency, and cutoff; numerical values for assessment; types of assessment methods; fundamentals of roundness.
- Content 13. Optical Metrology (4 hours); microscopes and applications; optical comparators; advantages and disadvantages; optical comparator; image projection methods; comparator applications; Lab 8.
- Content 14. Coordinate Measurement (4 hours); role of CMMs, CMM design; modes of operation; hard probes versus soft probes; contact-based versus noncontact-based; factors of measurement variability; performance testing methods; Lab 9.

Lab Equipment and Purpose for Integration

Lab equipment is a critical and vital component of lecture/lab courses. Without varying types of equipment and a minimum number of instruments, lab activities would be difficult to incorporate and conduct. Without departmental and college support, the funds needed to purchase equipment may be difficult to come by unless it is initiated through equipment grant programs from instrument manufacturers. Fortunately for our department, the State of Texas has maintained an interest in the quality of their educational programs and has made equipment funds available on a regular basis to higher education institutions; funds that filters down to the departmental level through an internal grant process. Through the grant process, our department has been successful in proposing and obtaining the equipment we feel is necessary to properly support and sustain a dimensional metrology course for a class size of 20. These items include:

- Item 1. Dial, vernier, and digital calipers (10 each); vernier and digital micrometers (10 each); and digital indicators with test stand (10 each). These items were integrated with the intent of developing fundamental understanding of metrological concept relating to measurement precision, gage accuracy, gage repeatability and reproducibility, and instrument discrimination. Principal advantages associated with the inclusion of digital instruments are that they can also be integrated with SPC processors/printers or used as traditional instruments if the batteries are removed.
- Item 2. An assortment of gage block sets. These items were integrated with the intent of conducting measurement precision and accuracy tests and improving students' measurement techniques.
- Item 3. Optical comparator. This item was integrated with the intent of conducting group-based measurement activities on unique parts that can not be

inspected effectively using traditional, contact-based instruments (calipers, micrometers, etc.). One of the principal reasons for its integration was the speed to which measurements activities can be conducted and the ease to which small groups can use the machine at one time.
- Item 4. Coordinate measurement machine. This item was integrated with the intent of demonstrating automated, three-dimensional inspection systems using touch probe technology and computer-based inspection programming. The machine also offers the capability of being incorporated in two different ways (programmed inspection routines, teach mode).
- Item 5. Computer lab and departmental server. This item was integrated with the intent that students will conduct spreadsheet-based precision and accuracy analyses and need a central location to submit their lab results.

Lab Activities Combined with Spreadsheet Integration

Hands-on experiences with measuring instruments is an important facet for student learning. These experiences can be enhanced when collected data from measurement activities is evaluated using the data analysis capabilities of the MS Excel program. These analyses are used to assess individual user techniques and instrument effectiveness (an assessment of the variation within and between individual operators commonly referred to as repeatability and reproducibility or Gage R&R). The data analysis process can also be enhanced through the use of course/lab-specific spreadsheet templates; sample templates are detailed within this section. Labs that have been incorporated into the course, as well as the purpose for their inclusion, include:

- Labs 1 and 2. Fundamentals of statistical analysis. The purpose of these two labs are to acquaint students with statistical aspects within metrology and the descriptive statistic capabilities within MS Excel. Specifically, the various techniques that are employed to assess the shape, spread, and normality of a given data set using measures of central tendency, measures of dispersion, skewness, kurtosis, and histograms. Each lab activity is based on an instructor-supplied Excel templates in which students integrate the following: (1) Excel functions and formulas, (2) Menu pulldowns: Tools > Data Analysis > Descriptive Statistics, and (3) Menu pulldowns: Tools > Data Analysis > Histogram (see Figure 1 on page 5).
- Labs 3 and 4. Caliper and micrometer measurement activities, respectively. The purpose of these two labs is to acquaint students with the proper use of calipers and micrometers and further reinforce statistical aspects within metrology and the data analysis capabilities within MS Excel . Specifically, the lab introduces students to the various techniques that can be employed to deterrmine and assess measurement error (deviation) at different confidence levels. The analysis of collected data is performed using techniques learned in Labs 1 and 2. Lab worksheets are based on instructor-supplied Excel templates in which students integrate the following: (1) Selective Excel functions and formulas and (2) Menu pulldowns: Tools > Data Analysis > Descriptive Statistics (see Figure 2 on page 6.).
- Labs 5 and 7. Gage R&R activities using micrometer and digital indicator, respectively. The purpose of these two labs are to provide background knowledge of Gage Repeatability and Reproducibility testing on traditional instruments. In both labs, students are provided the tools they need to assess and compare their technique in using precision measuring instruments as well as the inherent stability of the measuring instruments themselves. In our labs, worksheets are based on an instructor-supplied Excel template that are limited to data entry only. Students are also given the option to earn extra credit points by developing their own Gage R&R worksheets using a supplied handout indicating the calculations required for a two-trial, two-operator Gage R&R assessment.
- Lab 6. Digital indicator accuracy test. The purpose of this lab is to acquaint students with the techniques and procedures required to conduct instrument accuracy tests. Lab worksheet is based on an instructor-supplied Excel template in which students integrate selective Excel functions and formulas (see Figure 3 on page 7).
- Lab 8. Optical comparator measurement activity. The purpose of this lab is to acquaint students with optical comparator operation and the importance of this instrument for measurement activities involving unique parts that can not be inspected using traditional, contact-based instruments (calipers, micrometers, etc).
- Lab 9. Coordinate measuring machine (CMM) measurement activity. The purpose of this lab is to acquaint students with the operation of a CMM and the importance of this instrument for measurement activities involving the assessment of multiple features on a given part. Depending on time constraints, this lab may be based on the operation of a pre-written inspection routine or a teach program routine.

Research Implications

Given the importance of dimensional metrology and its overall impact on quality, how do future metrologists develop the knowledge and expertise they need to grow and prosper within the field? How do people planning careers in quality assurance and production management develop the insight needed to fully understand the link between metrology and other areas of production? From the standpoint of future metrologists, Stein (2001) indicated that this topic has been of

Figure 1. Sample Excel Template for Labs 1 and 2

Figure 1. Sample Excel Template for Labs 1 and 2

Is the distribution symmetrical or asymmetrical? Explain in detail using the analysis values determined below.

The distribution is asymmetrical; more specifically, the distribution is moderately peaked (kurtosis = 0.607) and negatively skewed (skewness = -0.645). The asymmetrical nature of the distribution of the given data is also supported in the histogram.

Given Data	Bin Group Midpoints	Bin Inteval
0.995	0.991	
1.005	0.993	0.002
1.004	0.995	0.002
0.996	0.997	0.002
1.003	0.999	0.002
0.997	1.001	0.002
1.002	1.003	0.002
0.998	1.005	0.002
1.001		
0.999		
1.000		
0.996		
1.004		
0.997		
1.003		
0.998		
1.002		
0.999		
1.001		
0.991		
0.997		
1.003		
0.998		
1.002		
0.999		
1.001		
1.000		
0.998		
1.002		
0.999		
1.001		
1.000		
0.999		
1.001		
1.000		
0.993		

END OF DATA

Measures of Central Tendency

Mean =	1.000
Median =	1.000
Mode =	1.001

Range Determinates

Max =	1.005
Min =	0.991
Interval =	0.002

Measures of Dispersion

Range (R) =	0.014
Standard Deviation ( ) =	0.003

Other Measures

Skewness =	-0.645
Kurtosis =	0.607

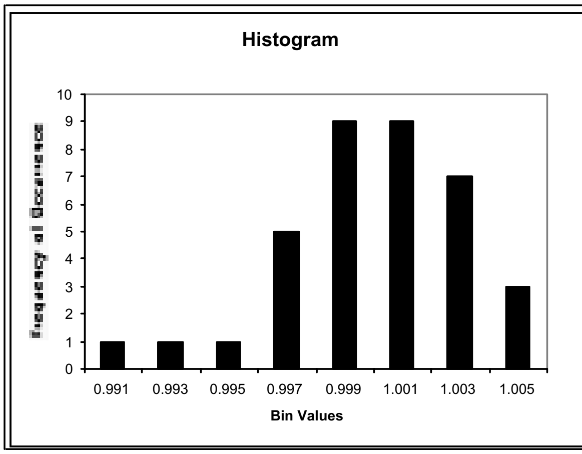
Total Dispersion/Spread

∝±1 =	0.006
∝±2 =	0.012
∝±3 =	0.019
90% =	0.010
95% =	0.012
99% =	0.016

Descriptive Statistics

Given Data	
Mean	1.000
Standard Error	0.001
Median	1.000
Mode	1.001
Standard Deviation	0.003
Sample Variance	0.000
Kurtosis	0.607
Skewness	-0.645
Range	0.014
Minimum	0.991
Maximum	1.005
Sum	35.984
Count	36

Bin	*Frequency*
0.991	1
0.993	1
0.995	1
0.997	5
0.999	9
1.001	9
1.003	7
1.005	3



Bin Group Criteria (varies from 5 to 20)

0 to 100 data points	5 to 9 groups
100 to 500 data points	8 to 17 groups
500+ data points	15 to 20 groups

Excel Functions Used:

Mean --> Average()
Median --> Median()
Mode --> Mode()
Maximum --> Max()
Minimum --> Min()
Standard Deviation --> Stdev()
Skewness --> Skew()
Kurtosis --> Kurt()

Excel Formulas Used:

Mean (∝) = Average()
Range = Max() - Min()
Bin Interval = Range / Number of Bin Groups
∝±1 = (∝ + 1)-(∝ - 1)
∝±2 = (∝ + 2)-(∝ - 2)
∝±3 = (∝ + 3)-(∝ - 3)
90% = (∝ + 1.65)-(∝ - 1.65)
95% = (∝ + 1.96)-(∝ - 1.96)
99% = (∝ + 2.58)-(∝ - 2.58)

Excel Menu Commands Used:

Tools > Data Analysis > Descriptive Statistics

Tools > Data Analysis > Histogram

Figure 2. Sample Excel Template for Labs 3 and 4

Figure 2. Sample Excel Template for Labs 3 and 4

Is the distribution symmetrical or asymmetrical? Explain in detail using the analysis values determined below.

The distribution is asymmetrical; more specifically, the distribution is highly peaked (kurtosis = 0.919) and slightly negatively skewed (skewness = 0.140). The asymmetrical nature of the distribution of the given data is not fully supported in the histogram but would be if a different number of bin groups would have been used to develop the histogram (7 or 9 bin groups)

Operator Measurements	Measured Size	Actual Size	Measurement Deviation	Bin Group Midpoints	Bin Interval
A1	0.145	0.150	-0.005	-0.006	
A2	0.106	0.106	0.000	-0.004	0.002
A3	0.104	0.110	-0.006	-0.002	0.002
A4	0.147	0.140	0.007	0.000	0.002
A5	0.205	0.200	0.005	0.002	0.002
A6	0.111	0.109	0.002	0.004	0.002
A7	0.107	0.108	-0.001	0.006	0.002
A8	0.103	0.103	0.000	0.008	0.002
A9	0.104	0.105	-0.001		
A10	0.102	0.100	0.002		
B1	0.125	0.130	-0.005		
B2	0.500	0.500	0.000		
B3	0.400	0.400	0.000		
B4	0.250	0.250	0.000		
B5	0.103	0.102	0.001		
B6	0.108	0.107	0.001		
B7	0.200	0.200	0.000		
B8	0.105	0.106	-0.001		
B9	0.102	0.104	-0.002		
B10	0.100	0.100	0.000		
C1	0.108	0.109	-0.001		
C2	0.104	0.108	-0.004		
C3	0.103	0.103	0.000		
C4	0.105	0.105	0.000		
C5	0.108	0.107	0.001		
C6	0.200	0.200	0.000		
C7	0.107	0.106	0.001		
C8	0.100	0.100	0.000		
C9	0.115	0.110	0.005		
C10	0.135	0.140	-0.005		

Measures of Central Tendency

Mean = 0.000

Median = 0.000

Mode = 0.000

Range Determinates

Max = 0.007

Min = -0.006

Interval = 0.002

Measures of Dispersion

Range (R) = 0.013

Std Dev ( ) = 0.003

Other Measures

Skewness = 0.140

Kurtosis = 0.919

Total Dispersion/Spread

∝±1 = 0.006

∝±2 = 0.012

∝±3 = 0.017

90% = 0.010

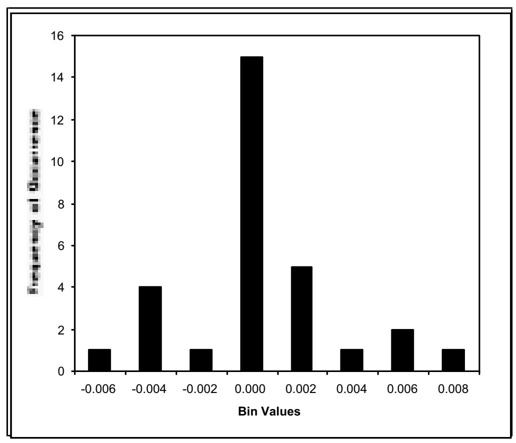
95% = 0.011

99% = 0.015

Descriptive Statistics

Measurement Deviation	
Mean	0.000
Standard Error	0.001
Median	0.000
Mode	0.000
Standard Deviation	0.003
Sample Variance	0.000
Kurtosis	0.919
Skewness	0.140
Range	0.013
Minimum	-0.006
Maximum	0.007
Sum	-0.006
Count	30

Bin	*Frequency*
-0.006	1
-0.004	4
-0.002	1
0.000	15
0.002	5
0.004	1
0.006	2
0.008	1



OPERATOR A:

OPERATOR B:

OPERATOR C:

Bin Group Criteria (varies from 5 to 20)

0 to 100 data points	5 to 9 groups
100 to 500 data points	8 to 17 groups
500+ data points	15 to 20 groups

Excel Functions Used:

Mean --> Average()
Median --> Median()
Mode --> Mode()
Maximum --> Max()
Minimum --> Min()
Standard Deviation --> Stdev()
Skewness --> Skew()
Kurtosis --> Kurt()

Excel Formulas Used:

Measurement Deviation = Measured size - Actual Size
Mean (∝) = Average()
Range = Max() - Min()
Bin Interval = Range / Number of Bin Groups
∝±1 = (∝ + 1)-(∝ - 1)
∝±2 = (∝ + 2)-(∝ - 2)
∝±3 = (∝ + 3)-(∝ - 3)
90% = (∝ + 1.65)-(∝ - 1.65)
95% = (∝ + 1.96)-(∝ - 1.96)
99% = (∝ + 2.58)-(∝ - 2.58)

Excel Menu Commands Used:

Tools > Data Analysis > Descriptive Statistics

Tools > Data Analysis > Histogram

Figure 3. Sample Excel Template for Lab 6

Figure 3. Sample Excel Template for Lab 6

Operator's Name:

Partner's Name:

Indicator Code Number:

Indicator Model Number:

Indicator Serial Number:

Instrument Specifications

Instrument Range: 0.5000 inches

Instrument Standard (ANSI): B89.1.10/AGO Gr.2

Instrument Resolution Spec: 0.00005 inches

Instrument Accuracy Spec: 0.00012 inches

	Measurement #	Measured Size of Unknown	Actual Size of Unknown	Measurement Deviation	Determined Accuracy (%)	Accuracy Spec (%)	Accuracy % Difference
Beginning of Travel Range	1	0.10008	0.10010	-0.00002	0.020	0.024	0.004
	2	0.10082	0.10080	0.00002	0.020	0.024	0.004
	3	0.10046	0.10050	-0.00004	0.040	0.024	0.016
	4	0.10203	0.10200	0.00003	0.029	0.024	0.005
	5	0.10096	0.10100	-0.00004	0.040	0.024	0.016
Middle of Travel Range	6	0.10024	0.10020	0.00004	0.040	0.024	0.016
	7	0.10042	0.10040	0.00002	0.020	0.024	0.004
	8	0.10604	0.10600	0.00004	0.038	0.024	0.014
	9	0.30000	0.30000	0.00000	0.000	0.024	0.024
	10	0.10075	0.10070	0.00005	0.050	0.024	0.026
End of Travel Range	11	0.10496	0.10500	-0.00004	0.038	0.024	0.014
	12	0.10035	0.10030	0.00005	0.050	0.024	0.026
	13	0.10095	0.10090	0.00005	0.050	0.024	0.026
	14	0.10000	0.10000	0.00000	0.000	0.024	0.024
	15	0.10904	0.10900	0.00004	0.037	0.024	0.013

	Part Number	Measured Size of Unknown	Determined Accuracy (%)	Smallest Expected Part Measurement	Largest Expected Part Measurement
Beginning of Travel Range	1	0.10008	0.020	0.10006	0.10010
	2	0.10082	0.020	0.10080	0.10084
	3	0.10046	0.040	0.10042	0.10050
	4	0.10203	0.029	0.10200	0.10206
	5	0.10096	0.040	0.10092	0.10100
Middle of Travel Range	6	0.10024	0.040	0.10020	0.10028
	7	0.10042	0.020	0.10040	0.10044
	8	0.10604	0.038	0.10600	0.10608
	9	0.30000	0.000	0.30000	0.30000
	10	0.10075	0.050	0.10070	0.10080
End of Travel Range	11	0.10496	0.038	0.10492	0.10500
	12	0.10035	0.050	0.10030	0.10040
	13	0.10095	0.050	0.10090	0.10100
	14	0.10000	0.000	0.10000	0.10000
	15	0.10904	0.037	0.10900	0.10908

<u>Excel Formulas Used:</u>

Measurement Deviation = Measured size - Actual Size

Determined Accuracy (%) = ABS[(Measurement Deviation) / Actual Size of Unknown] * 100

Accuracy Spec (%) = [Instrument Accuracy Spec / Instrument Range] * 100

Accuracy % Difference = ABS[Determined Accuracy (%) - Accuracy Specification (%)]

Smallest Expected Part Measurement = (Measured Size - (Measured Size * Determined Accuracy))/100

Largest Expected Part Measurement = (Measured Size + (Measured Size * Determined Accuracy))/100 particular interest to the American Society for Quality (ASQ) Certification Board since their approval of the development of a certified calibration technician program and their associated commitment to identify the education and training requirements for the program's body of knowledge. Stein went on to state that " a metrologist with a broad, well-rounded education should have a strong grounding in physics and applied statistics (very similar to statistics in the quality field) " (p. 95).

From the standpoint of people planning careers in quality assurance or production management (people who need to possess knowledge of the field but not necessarily expertise), this need is being met to a great degree through Industrial Technology programs that have integrated a dimensional metrology course into their manufacturing curriculum. Within these programs, efforts are being made to determine the appropriate mix of subject matter content and hands-on experiences that can be successfully integrated into an introductory course in dimensional metrology and other more advanced courses. During these investigative activities, one is always contending with the notion that student learning of concepts and principles through a variety of organized instructional activities needs to be developed and integrated in conjunction with course-based time constraints. This is nothing new to those who has taught lecture/lab courses in the field of Industrial Technology. Within the Industrial Technology department at Texas A&M University-Kingsville, investigations have been conducted over the last five years that have focused on identifying the types of instruments and the number and types of lab activities that can be successfully integrated into a undergraduate course in dimensional metrology without adversely affecting course content goals and objectives.

One aspect that emerged during the course of the investigations was the manner in which student comprehension and understanding was evaluated. Assessing student progress and understanding takes on a different flavor when integrating spreadsheet-based lab templates and assignments. One aspect that should be considered to ease the collection and distribution of student lab files is a departmental or college file server. The principal advantage afforded by a file server is the protection and security it provides for student and class-related files—user access to selected student or class folders can be granted or limited depending on their collective or individual needs (read-write, read only, or drop box). Other aspects that need to be given consideration with spreadsheet-based template inclusion include:

- the tagging of template copies with hidden codes to verify the uniqueness of submitted student files;
- the development of student handouts detailing needed instructions and secondary template aspects such as page setup, printing, and file submittal;
- the examination of submitted student files to determine correctness or causes of errors;
- the employment of a digital projector to display common or unique errors committed by students within their individual files; and
- the incorporation of lecture and lab testing to assess student comprehension of textbook concepts and their ability to work with spreadsheet-based data analysis.

Student learning of dimensional metrology concepts can be facilitated through the use of structured lab template files. The effectiveness of structured templates as a tool for instruction and learning hinges on several factors, such as

- the skill level of the individual creating the spreadsheet templates;
- the degree of planning prior to template development (actual purpose of the template);
- the degree of template testing and validation prior to its integration and use;
- the inclusion of cell protection utilizing both locking and hidden aspects;
- the inclusion of colors, borders, and other items to emphasize or differentiate specific areas or aspects of the templates.

Summary

This paper is intended to aid professionals in the field into the ways and means upon which a dimensional metrology course can be structured and lab activities integrated in conjunction with class-based time constraints and instructional objectives. It is not the intent of this paper to infer that this is the only workable format for course structure and lab integration, it is one that has worked with the program at Texas A&M University-Kingsville and one that could work for other programs. It is hoped that this paper will stimulate further interest in the area and generate future papers with respect to this topic area. As a final note, an online survey of dimensional metrology curriculum in industrial technology programs within the U.S. was conducted by DeRuntz and Lee in 2001. The results of the survey identified various U.S. universities and colleges that offered a course in dimensional metrology and provided information with respect to major sources of funding for programs interested in starting or expanding their inventory of equipment and capabilities within the area of dimensional metrology.

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