An Innovative Approach of Team-Teaching Measurement Uncertainty and Metrology

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1. Introduction

Measurement plays an important role in all steps of the production process. Metrology is the science of measurement and it is a well-established discipline that is used to gain valuable product and process information. To be productive, this information must generate knowledge that is used as a basis for better product and process design.

Much of today's industry and technology relies on accurate measurement. Manufactured products are measured by instruments to check their conformance to specifications. All parts and products, from nuts and bolts to tiny microchips, require an accurate and precise international scale of measurement. This need is all the more important in the present global economy as measurement error causes false fails and false passes both of which are expensive.

Measurement systems are routinely analyzed using traditional gage repeatability and reproducibility (R&R) studies including ANOVA methods. Measurement science is becoming more complex, with mathematics and statistics having an increasingly important role to play.

Understanding the practical principles of measurement science, calibration, uncertainty evaluation, including geometric dimensioning and tolerancing (GD&T) should be an important part of engineering technology education which helps to impart the hands-on aspect of the subject area. To achieve this objective of providing practical knowledge skills, precision instrumentation with controlled environment is needed which may not be easily available in university laboratories.

This paper describes an innovative approach of team-teaching this new course in metrology. A working relationship has been established with a local A2LA-certified (American Association for Laboratory Accreditation) calibration laboratory where students get to learn the practical aspects of precision measurements. The paper describes the course structure and gives some sample theory and experiments that students learn. The paper also discusses the lessons learned from the students' performance and their feedback on the course learning outcomes.

2. Background

There is a basic metrology course at the freshman/sophomore level that teaches principles of hands-on measurements using common instruments such as vernier calipers, different types of vernier micrometers, gage blocks, dial indicators, and CMMs (Coordinate Measuring Machines). It was decided to develop the new higher-level metrology course at the junior/senior level that would supplement the material covered in the basic course. Also, students learn the GD&T theory in their freshman/sophomore level and in this new metrology course they apply the theory in understanding and making correct GD&T measurements.

In a well-known local company, it was found that they were using gage R&R software for finding the gage variation and its performance criteria. In instances where the average part readings on a range chart were outside the limits, the software gave very good gage R&R results. This showed that the quality personnel in the company did not understand the basic concepts of measurement variation.

Our Industrial Advisory Committee recommended to add metrology concepts in our MET and IET curriculum. The industrial interest was driven primarily because companies have realized the tremendous benefits of understanding the basic principles of measurement variation without which it is impossible to implement six sigma.

Six sigma is a quality-improvement tool that is designed to make businesses as successful as possible. Its primary objective is to deliver world-class performance, reliability, and value to the customer. The tools of six sigma are applied within a framework known as Define-Measure-Analyze-Improve-Control (DMAIC). In DMAIC, the measure phase establishes techniques for collecting data about the current performance and how well it is meeting customer requirements [1]. Upon completion of this phase, the six sigma team expects to have reliable and accurate measurements for further analysis and action. In the successful execution of DMAIC, the impact of measurement variability becomes ever more significant.

The need to understand measurement variation known as measurement systems analysis (MSA) becomes crucial in the present global economy as measurement error causes false fails and false passes both of which are expensive as shown in Table 1.

Table 1. Risk of Measurement Errors.

Reference Value	**Measurement**	**Error**
Good	Good	None
Bad	Bad	None
Good	Bad	Type A
Bad	Good	Type B

The course covers areas of metrology such as, gage R&R, bias, linearity, impact of R&R on process capability, measurement uncertainty, inspection of size, form and orientation tolerances using 1994 GD&T standard. The course includes a written report and oral presentation of student projects showing application of the measurement principles and practices.

The course has nine laboratory experiments that students perform hands-on in groups. These experiments are: (1) determining gage R &R of vernier calipers, (2) determining gage R&R of outside vernier micrometers. In both these labs students use short and long form methods, draw average and range charts for the measurements taken by them, (3) calculating bias and linearity of micrometers, (4) measurement of size, (5) flatness, (6) parallelism, (7) circularity, (8) runout, and (9) position tolerances of sample parts.

The assignments, experiments, and project work together allow students to integrate and apply the course material, and obtain sufficient breadth and depth of knowledge. The next section describes the course structure, including some examples of assignments done by the students.

3. Course Structure

This course was designed to teach metrology theory and principles in the first part of the semester and then let students work in teams to do the experiments. The course content and learning outcomes are given in Table 2. Each student writes a separate laboratory report using and comparing the data obtained by all the members in the team.

The text book on measurement variation is a well-known and commonly used in industry, that is the Measurement Systems Analysis book popularly referred to as the MSA book [2]. The text book used for GD&T measurements is given in [3].

Some of the guidelines and established practices of business were discussed by senior personnel of a local A2LA-certified calibration laboratory. There were some sessions conducted by them

Table 2: Metrology Course Content and Learning Outcomes.

Course Learning Outcomes	
Process and Measurement variation	Inspecting size tolerances
Variable Gage R & R – long form	Flatness
Variable Gage R & R – short form	Straightness
Attribute Gage R & R – long form	Circularity
Attribute Gage R & R – short form	Parallelism
Bias, Linearity and Stability	Perpendicularity and Angularity
ANOVA method for sources of errors	Circular and Total Runout
Observed and Actual Cp and Cpk	Concentricity
Errors in measurement	Position Tolerancing
Measurement Uncertainty	Functional Gage Design

in a classroom setting and there was a visit made to their laboratory site by the students where they saw demonstration of how precision measurements are done. In particular, there were demonstrations given on a digital gage block tester which has precision of nano-inches, roundness testing machine, and a programmable CMM. Examples of different grades of gage blocks were shown and their use in calibration and the chain of traceability shown. These sessions were useful and enjoyed by the students as evident from their feedback on the course.

There are few universities that teach metrology concepts, for example, Cornell University, Arizona State, North Carolina State, Farmingdale State University of New York, to name a few. In the existing courses, the metrology concepts are taught along with quality control or quality assurance, or with manufacturing. These courses are accordingly developed to meet the local needs of the industry. Our approach and need is met by combining metrology concepts of GD&T measurements with emphasis on MSA methods for variable and attribute gaging.

3.1 *Sample Assignments in Metrology*

Some sample examples of work done by students as assignments are shown below. It gives a broad picture of learning that students go through in meeting some of TAC/ABET criteria requirements of use of ability to solve technical problems, use of math and statistics, application of technical skills learned in class and others. Their background in theory can be found in [2], [4], and [5]:

<u>On gage R&R concepts</u>: If σ_{EV} is .0001", σ_{AV} is .0002", what is R&R? If total tolerance is .010", what is %R&R of tolerance? If σ_{PV} is .002", what is %R&R of TV? EV is equipment or gage variation, AV is appraiser or operator variation, PV is process variation, and TV is total variation.

<u>On gage performance curve</u>: Determine the probability of accepting a part using the following data and then draw a gage performance curve for this example. Figure 1 shows an example of a gage performance curve using the following data: Upper Limit = 10 Nm, Lower Limit = 7.5 Nm, Bias = 1 Nm, and $\sigma_{R\&R}$ = 0.05 Nm.

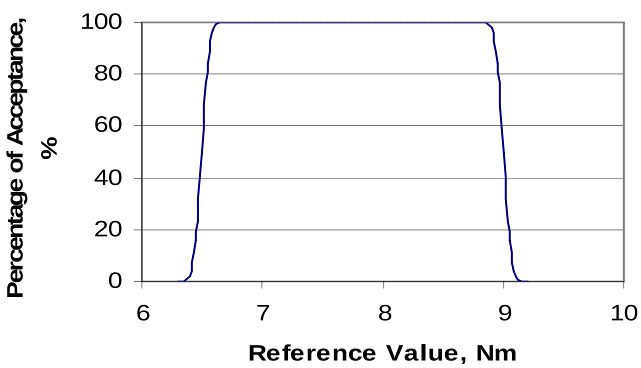

Figure 1 Gage Performance Curve.

<u>On sine and cosine errors:</u> These two errors are of importance in understanding measurement variation. An example of sine error [3] is given below and in Figure 2.

If a part is not aligned perpendicular to the micrometer axis but has a 5 degree misalignment, what is the sine error in the total reading of the part size if the diameter of the micrometer anvil is .250”? This example uses the sine function of trigonometry to come to the size of error.

<u>On the effect of R&R on process capability:</u> The basic Cp and Cpk concepts are done in the introductory class. Here they learn the effect of measurement variation on C_p and C_{pk}. A measurement system used for a manufacturing process has 30% R&R of total variation and 10%

bias. Determine actual C_p (C_{pa}) of the process if its observed C_{pk} (C_{pko}) = 1.20. Using the concepts given in [2] on pages 191-194, C_{pa} comes out to be 1.57.

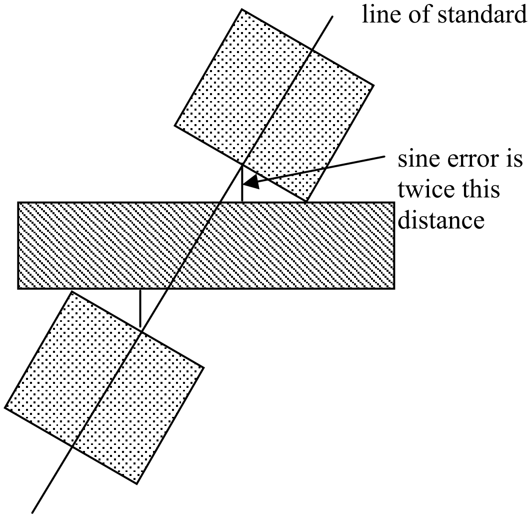

Figure 2 The Concept of Sine Error.

On attribute gage study (short method): Table 3 shows use of attribute gage study known as the short method. The result is that the attribute gage is not acceptable as long as both appraisers do not agree with the standard in both of their trials for all parts.

Table 3 A Sample of Attribute Gage Study. (G=good, NG=Not Good)

Parts	Standard	Appraiser A		Appraiser B	
		Trial 1	Trial 2	Trial 1	Trial 2
1	G	G	G	G	G
2	G	G	G	G	G
3	NG	NG	G	G	G
4	NG	NG	NG	NG	NG
5	G	G	G	G	G

On measurement uncertainty: Although, the degree of rigor needed in estimation of measurement uncertainty may vary, but evaluating and expressing uncertainty has been adopted widely by the U.S. industry. Nevertheless, this concept is relatively new for the industrial, testing, and academic community. A simple example done by the students is shown below:

A milliohm meter is used to measure the resistance of a resistor. At the selected range of the meter for the measurement, the calibration certificate states an uncertainty of 0.4 mΩ at 95% of confidence level. Effects of room temperature and humidity on the measurement are found to be negligible. Table 4a and 4b give the data and results of measurement evaluation.

The above are just a few examples of how students learn the different program outcomes according to TAC/ABET criterion 2. The assessment of the course is given in the next section.

Table 4a Measurement Data of the Measurement Uncertainty Example.

Reading	1	2	3	4	5	6	7	8	9	10
R mΩ	9.4	9.1	9.4	9.8	9.7	9.4	9.8	9.7	9.4	9.4

Table 4b Evaluation of the Components of Measurement Uncertainty.

Source of Uncertainty	Type	Uncertainty Value, mΩ	Distribution	*k*	*c*	*u*, mΩ	*cu*	*v* *degrees of freedom*
Repeatability	A	0.165	-	-	1	0.165	0.165	9
Calibration	B	0.400	normal	1.96	1	0.204	0.204	∞

4. Assessment

As part of the course requirement, students complete a learning outcome survey immediately after their final exam when they are expected to have assimilated maximum of the course material. For the survey students are asked to rate how well they learned a given learning outcome on a 0 to 10 scale, with 10 being ‘very satisfactory’ and 0 being ‘not satisfactory at all’. Table 5 contains the summary of their feedback for Spring 2007 class.

The learning outcomes also include their feedback on (a) functioning as a team in laboratory and (b) on use of effective verbal and written communication through project work that they present to the entire class and in a written report. Students are also given an opportunity to give general written comments on the survey sheet as well. Students commented in general that they liked doing the laboratory experiments, although opinions differed on the difficult of the ANOVA method. Some found it interesting and useful while few thought it was too abstract and detailed. Students did comment that the class assignments (given in section 3.1) helped them to appreciate the complexity of metrology. Overall student responses were positive and enthusiastic. The only consistent suggestions for changing the course had to do with (1) sufficient practice of the instruments before gage R&R labs are formally conducted, (2) more examples on measurement uncertainty, (3) more experiments using GD&T, and (4) dissatisfaction with one of the textbooks. Some also suggested to cover CMM programming in the course.

5. Conclusions

Based on the course assessment, there are some significant changes planned for teaching the metrology course: greater concentration on ANOVA method as applied to determining sources of measurement variation, initial practice on instruments as a review of the introductory course, more examples on determining measurement uncertainty, and introducing the basics of CMM programming. Overall the course appears to be meeting its objectives and learning outcomes according to the student feedback and assessment evaluation. Instructor feedback is that students have been engaged in the course, with satisfactory exposure to the theoretical and practical aspects in the field of measurement science. The structure of first grounding in basic theory and then hands-on measurement setups with some demonstrations, and finally with an independent project work appears to have worked well and it will be maintained.

Table 5 Assessment Evaluation of the Metrology course.

No.	Learning Outcomes	Program Outcomes	6*	7	8	S/NS**
1	Variable Gage R & R – long form	a, b, c	1	1	4	NS
2	Variable Gage R & R – short form	"		1	2	S
3	Attribute Gage R & R – long form (analytic method)	a, b, f		2	3	S
4	Attribute Gage R & R – short form	"			1	S
5	Bias, Linearity and Stability	a, b, c, f		1	2	S
6	ANOVA method for sources of variation	a, b, f	2	2	3	NS
7	Observed and actual Cp and Cpk	"			3	S
8	Errors in measurement – sine and cosine	"		2	2	S
9	Measurement Uncertainty	"	1	3	4	NS
10	Inspecting size tolerances	b, c, g		1	3	NS
11	Flatness	"		1	2	S
12	Straightness	"		1	3	NS
13	Circularity	"		1	2	S
14	Parallelism	"		1	1	S
15	Perpendicularity and Angularity	"		1		S
16	Circular and Total Runout	"		1	2	NS
17	Concentricity	b		2	1	NS
18	Position Tolerancing	b, c, g		1	1	S
19	Functional Gage Design	a, b, f			2	S
20	Function effectively in teams	e		1	1	S
21	Communicate effectively through oral presentation	g		3	2	S
22	Communicate effectively through technical writing	b, d, g		2	3	S

* The number of students who gave scores of 6, 7, or 8, the least scores obtained on the 0-10 scale. Respondents=12.
** S is Satisfactory and NS is Not Satisfactory. Based on the spread of responses, learning outcomes that should be improved in the next offering of the course are given NS.

6. Bibliography

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