Using interconnected CMM laboratory Modules for Geometric Dimension and Tolerancing, Metrology and Manufacturing processes area courses: Lessons Learned

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Introduction

Making good products requires collective knowledge of materials, metrology, and manufacturing processes. Metrology is the scientific study of measurement and contains all theoretical and practical aspects of measurement. A Coordinate Measuring Machine (CMM) is an excellent tool used for measuring the physical geometrical characteristics of a product. Preparing manufacturing engineering students with the metrology skills and knowledge required to be successful engineers in the 21st century is one of the primary objectives of undergraduate educators. From the results of CMM reports, manufacturing engineering students can detect and predict deteriorating cutting conditions through the continuous improvement of using a CMM. This paper introduces a new approach to developing CMM laboratory modules, teaching materials, hands-on lab activities, and projects developed as an integrated educational environment similar to ones implemented in today's industry. CMM laboratory modules are used as a post process confirmation of the machined test components and other discrete parts machined in drilling and milling machines. The purpose of CMM lab modules is to illustrate the interconnected laboratory modules of Geometric Dimensioning and Tolerancing (GD&T), Metrology and manufacturing processes area courses. To be productive, CMM measurement information must generate appropriate knowledge that is used as continuous improvement feedback for better product and process design use. The Manufacturing Engineering Department at Georgia Southern University (GSU) has been involved in a continuous effort to introduce new metrology related learning activities in Manufacturing Engineering laboratory and curriculum. The goal of CMM lab modules is to respond to the demand for Georgia regional industries and meet the 21st Century Workforce needs. The new CMM laboratory activities and projects include the following topics: (1) CMM part coordinate system, (2) CMM probe calibration, and (3) Gage Repeatability & Reproducibility (GR&R). This paper presents a method to improve the CMM learning modules and offer students the opportunity to enhance their hands-on activities.

Overview of Manufacturing Engineering Program at GSU

Georgia Southern University (GSU) is the state's largest and most comprehensive center for higher education south and east of Atlanta. GSU has been granted the first undergraduate manufacturing engineering program in the state of Georgia, and in fact, there is no similar program within a 500-mile radius of the Georgia Southern campus[1]. The introduction of Metrology into manufacturing engineering program at GSU not only enhanced students' hands-on practices and real-world experiences but also motivated them for pursuing advances research and education in Metrology and CMM programming[1,3]. CMM measurement hands-on experience plays a key role in manufacturing engineering education. It was an effective tool for student learning, as well as for encouraging participation in class learning and research outside the classroom. In general, The development of CMM laboratory modules can be integrated with the manufacturing program curriculum in four different courses (See Figure 1). They are: (1)

Geometric Dimensioning and Tolerancing (GD&T) in Engineering Graphics, (2) CMM measurements in Manufacturing presses 2 Studio, (3) Numerical Methods in Engineering, and (4) Quality Process Control. CMM laboratory modules can be used to facilitate the real-world experience for the students and motivate their interests in the various topics.

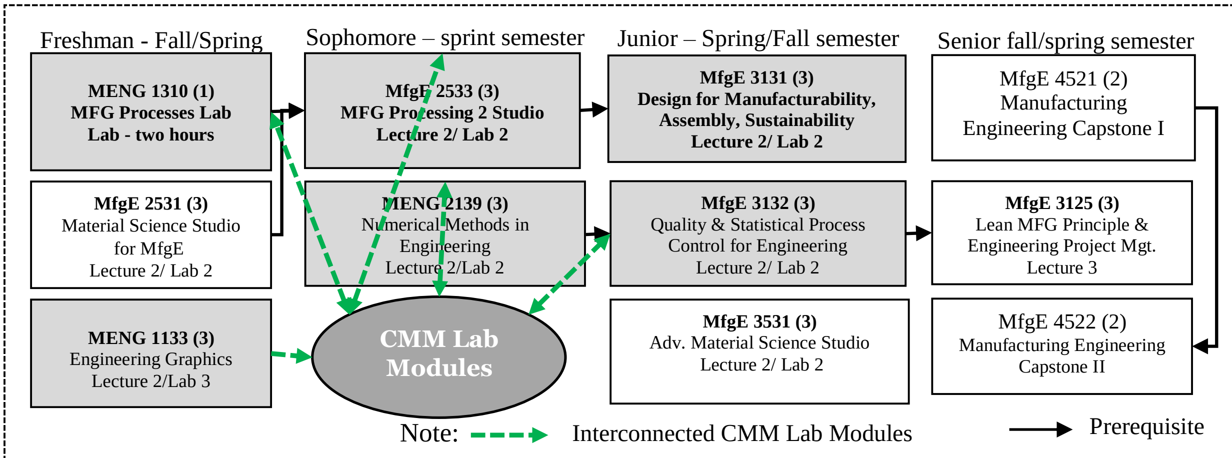


Figure 1 – GSU Manufacturing Engineering – program of study (Partial view)

CMM Laboratory Modules Overview

Interconnected CMM laboratory modules are not found in most Manufacturing Engineering programs in the USA[2]. These modules include the following topics: (1) fundamentals of Coordinate Measuring Machine (CMM), (2) Basic CMM operations, (3) CMM probe calibration, (4) Basic measurements, (5) Manual programming, (6) Gage Repeatability & Reproducibility. Here is a table which shows teaching and learning topics for CMM laboratory modules in manufacturing engineering program at GSU (see Table 2).

Table 2 – learning topics and lessons vs. CMM Learning Outcomes

Topics	Lessons	CMM Learning Outcomes
Fundamentals of Coordinate Measuring Machines (CMM)	1. What is a Coordinate Measuring Machine? 2. Characteristics of the CMM 3. Coordinate Configurations (number of Axes) 4. Part coordinate systems (Ex. Cartesian, polar) 5. Repeatability, Precision, and Accuracy 6. Probe calibration 7. Advantages and Disadvantages of CMMs	1. Identify the advantages of the coordinate measuring machine 2. Identify the main components of a CMM 3. Describe the operating XYZ axes 4. Recognize how points are located in a Cartesian coordinate system 5. Explain the purpose of alignment (Ex. Origin alignment) 6. Explain the purpose of probe qualification
Basic CMM Operations	1. General operations of a CMM 2. Types of coordinate systems 3. Alignment operation 4. Measurements 5. Manual programming 6. CNC programming	1. List the main components of a CMM 2. Describe the general operations of a manual CMM 3. Identify the different types of probes and explain when they are used 4. Explain the purpose of alignment 5. Define the terms base plan, the part coordinate system 6. Describe the step involved in planning a part program 7. Describe the machine maintenance procedures
CMM Probe Calibration	1. Stylus selection 2. Probe Data Management 3. Probe Calibration	1. Choose the right stylus for a specific application 2. Define and get the actual probe offset, diameter values 3. Add, delete, and edit a new probe for a specific application 4. Calibrate the probe and save to Probe Data Management
Basic Measurements	1. How to measure accurately 2. Coordinate location & size Measurement 3. Angle between elements Measurement 4. Distance between elements Measurement 5. Parallelism Measurement 6. Circularity Measurement 7. Position and runout Measurements	1. Know how to measure accurately 2. Know how to Measure coordinate location and size 3. Know how to Measure angle between elements 4. Know how to Measure distance between elements 5. Know how to Measure parallelism 6. Know how to Measure circularity 7. Know how to Measure position and runout

Manual Programming	1. Probe setup and calibration 2. Alignment programming procedures 3. Measurement programming procedures 4. Protocol code output procedures	1. Understand how to select an appropriate probe 2. Know how to set up a part program zero 3. Generate necessary procedures to measure part features 4. Determine if a part conforms to the specified tolerance
Gage Repeatability & Reproducibility	1. Gage R&R setup 2. Variable Gage R&R – long form 3. ANOVA method of source of errors	1. Know how to set up a gage R&R experiment 2. Estimate measurement uncertainty 3. Analyze the results 4. Know how to apply the results to improve measurement variation

Bloom's cognitive domain vs. CMM Learning Modules

In 1956, Benjamin Bloom created taxonomy of cognitive development levels[10]: (1) B1- Knowledge, (2) B2 - Comprehension, (3) B3 - Application, (4) B4 - Analysis, (5) B5 - Synthesis, and (6) B6 – Evaluation. These six levels of cognitive development help us describe and classify observable learning outcomes, knowledge, skills, behaviors and abilities. By creating CMM learning modules using measurable verbs (see Table 3), we indicate explicitly what the students must conduct, complete, and demonstrate student learning outcomes and thinking skills.

Table 3 - Mapping CMM Learning Modules into Bloom's Taxonomy of Cognitive Development

Level of Taxonomy	Bloom's Taxonomy Verbs	CMM Learning Modules	Thinking skills
B1: Knowledge - to recall or remember facts without necessarily understanding them	Define, list, name (label), count, order, assign, record, recognize	Module 1: **Define** a Coordinate Measuring Machine Module 2: **Recognize** different coordinate systems Module 3: **List** the main components of a CMM Module 4: **Name** two types of CMM Module 5: **Name** the two major categories of CMM programming Module 6: **Define** a Part Coordinate System (PCS)	Lower Order Thinking Skills
B2: Comprehension - to understand and interpret learned information	Identify, indicate, classify, discuss, locate, explain, review	Module 1: **Choose** a coordinate system to describe the positions Module 2: **Identify** the main components of a CMM Module 3: **discuss** the advantages of the CMM over surface plate equipment Module 4: **Explain** three different types of coordinate systems Module 5: **Locate** how points are located in a Cartesian Coordinate system Module 6: **Review** the basic operating principles of the CMM	
B3: Application - to put ideas and concepts to work in solving problems	Determine, apply, construct, operate, select, practice, sketch, use, solve	Module 1: **Operate** probe calibration Module 2: **Describe** the purpose of alignment Module 3: **Select** an appropriate probe head for specific part features Module 4: **Operate** different measurements (Ex. flatness, runout)	
B4: Analysis - to break information into its components to see interrelationships and ideas	Analyze, calculate, categorize, test, examine, inspect, question, differentiate contrast	Module 1: **Analyze** tolerances and fits Module 2: **Differentiate** between machine axes and part axes Module 3: **Inspect** part feature locations and sizes Module 4: **Calculate** GR&R Module 5: **Examine** distance between elements	Higher Order Thinking Skills
B5: Synthesis - to use creativity to compose and design something original	Create, design, develop, collect, formulate, propose, compose	Module 1: **Create** and **Generate** CMM programs Module 2: **Design** appropriate measurement for different geometric elements	
B6: Evaluation - to judge the value of information based on established criteria	Evaluate, appraise, assess, judge, justify, value, select	Module 1: **Evaluate** and Visualize geometric elements Module 2: **Select** the data used to create control charts and other graphs which can be used to analyze the manufacturing process	

Learning Outcomes for CMM Laboratory Modules

At the conclusion of learning CMM laboratory modules, the students in manufacturing engineering program at GSU will be able to:

1. Select an appropriate CMM measurement tool for a specific part feature.
2. Plan CMM measurement procedure
3. Create, modify, and execute different CMM programs
4. Create MACROs and subprograms to conduct recurring (repetitive) tasks
5. Use CAD images and interactive audio aids to repeat measurement tasks
6. Design and develop a manual CMM program for a part inspection
7. Troubleshoot and recover from common operation errors and faults

The learning modules of table three contain six different levels of cognitive domains. In the learning process, critical thinking involves logical thinking and reasoning skills such as creating, analyzing, designing, and comparison. Creative thinking involves creating and generating something new. It also involves the skills of brainstorming, modification, attribute listing, and originality[10]. The purpose of creative thinking is to stimulate curiosity among students and promote manufacturing operation and process simplification. Bloom's Taxonomy provides a useful structure in which to categorize learning modules when assessing student learning outcomes[10]. Asking students to think at higher levels is an excellent way to stimulate student's thought processes. In the learning process, the purpose of writing Bloom's questions is to apply Bloom's theory of developing higher levels of thought processes to CMM learning modules. Asking high-level questions of your shared inquiry groups is one way of making personal connections to literature, creating a bridge to the imagination, and developing self-directed learning[10].

Learning Activities - Laboratories and Projects

Research has shown that project-based learning is an extremely effective learning activity[5]. Many university professors accept this method to help students make the transition from passive active learning learners in their classrooms[8]. This section details lab 1 activity and presents CMM student projects.

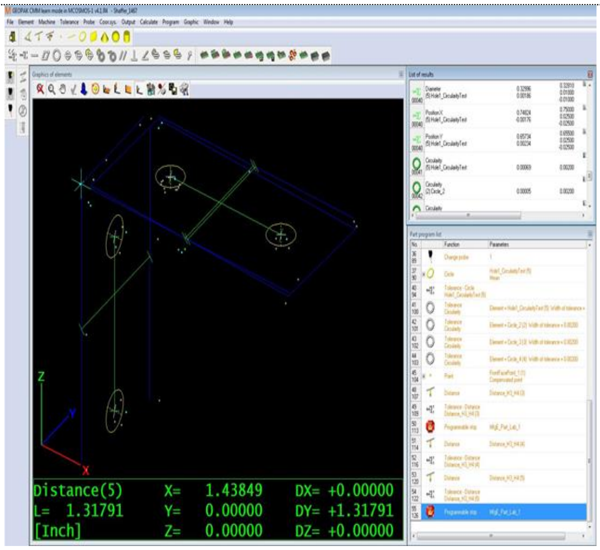
Lab 1 – Set up a Part Coordinate System

1. Objectives – upon successful completion of this lab, the students will be able to:

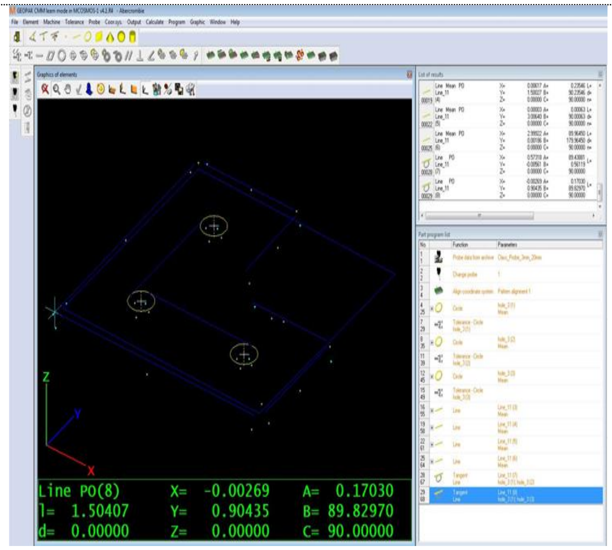
1. Know how to create a part origin (Part Coordinate System – PCS),
2. Create a part program to measure different geometric elements (Ex. hole diameters, locations, and sizes),
3. Conduct probe head calibration, and
4. Select an appropriate stylus for feature measurements.

2. Procedure

1. Write a CMM program to measure 4-hole inside corner bracket (see figure 4)
2. Use CMM learn mode to measure part feature locations and sizes (see figure 5)
3. Use different probe heads and/or types to measure YZ-plane part features
4. Must be performed by a group of 2 students. All students have to work in groups
5. Must complete and demonstrate your lab to the instructor

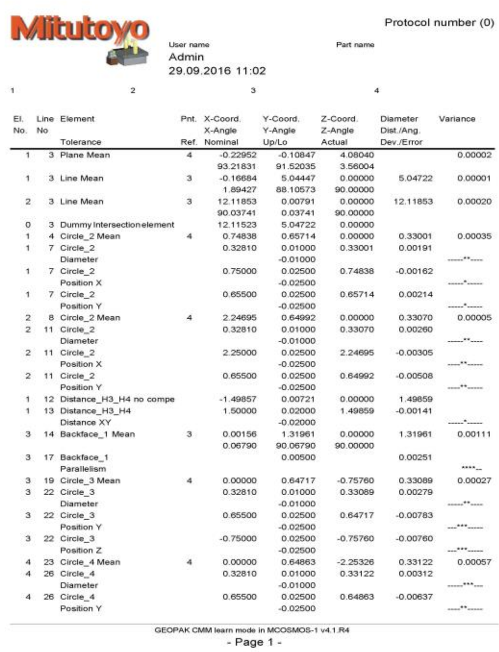


Lab 2 – CMM measurement program (CMM learn mode)



Lab 3 – 4-hole Square Plate (CMM measurement program)

Figure 4 – Lab 3 CMM program for 4-hole Square Plate



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Protocol number (0)

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Part name

1 2 3 4

El. No.	Line No	Element / Tolerance	Pnt. Ref.	X-Coord. / X-Angle / Nominal	Y-Coord. / Y-Angle / Up/Lo	Z-Coord. / Z-Angle / Actual	Diameter / Dist./Ang. / Dev./Error	Variance
1	3	Plane Mean	4	-0.22952	-0.10847	4.08040		0.00002
				93.21831	91.52035	3.56004		
1	3	Line Mean	3	-0.16684	5.04447	0.00000	5.04722	0.00001
				1.89427	88.10573	90.00000		
2	3	Line Mean	3	12.11853	0.00791	0.00000	12.11853	0.00020
				90.03741	0.03741	90.00000		
0	3	Dummy Intersection element		12.11523	5.04722	0.00000		
1	4	Circle_2 Mean	4	0.74838	0.65714	0.00000	0.33001	0.00035
1	7	Circle_2		0.32810	0.01000	0.33001	0.00191	
		Diameter			-0.01000			-----**----
1	7	Circle_2		0.75000	0.02500	0.74838	-0.00162	
		Position X			-0.02500			-----*-----
1	7	Circle_2		0.65500	0.02500	0.65714	0.00214	
		Position Y			-0.02500			-----*-----
2	8	Circle_2 Mean	4	2.24695	0.64992	0.00000	0.33070	0.00005
2	11	Circle_2		0.32810	0.01000	0.33070	0.00260	
		Diameter			-0.01000			-----**----
2	11	Circle_2		2.25000	0.02500	2.24695	-0.00305	
		Position X			-0.02500			----**-----
2	11	Circle_2		0.65500	0.02500	0.64992	-0.00508	
		Position Y			-0.02500			----**-----
1	12	Distance_H3_H4 no compe		-1.49857	0.00721	0.00000	1.49859	
1	13	Distance_H3_H4		1.50000	0.02000	1.49859	-0.00141	
		Distance XY			-0.02000			-----*-----
3	14	Backface_1 Mean	3	0.00156	1.31961	0.00000	1.31961	0.00111
				0.06790	90.06790	90.00000		
3	17	Backface_1			0.00500		0.00251	
		Parallelism						****_
3	19	Circle_3 Mean	4	0.00000	0.64717	-0.75760	0.33089	0.00027
3	22	Circle_3		0.32810	0.01000	0.33089	0.00279	
		Diameter			-0.01000			-----**----
3	22	Circle_3		0.65500	0.02500	0.64717	-0.00783	
		Position Y			-0.02500			---***-----
3	22	Circle_3		-0.75000	0.02500	-0.75760	-0.00760	
		Position Z			-0.02500			---***-----
4	23	Circle_4 Mean	4	0.00000	0.64863	-2.25326	0.33122	0.00057
4	26	Circle_4		0.32810	0.01000	0.33122	0.00312	
		Diameter			-0.01000			-----***---
4	26	Circle_4		0.65500	0.02500	0.64863	-0.00637	
		Position Y			-0.02500			----**-----

GEOPAK CMM learn mode in MCOSMOS-1 v4.1.R4
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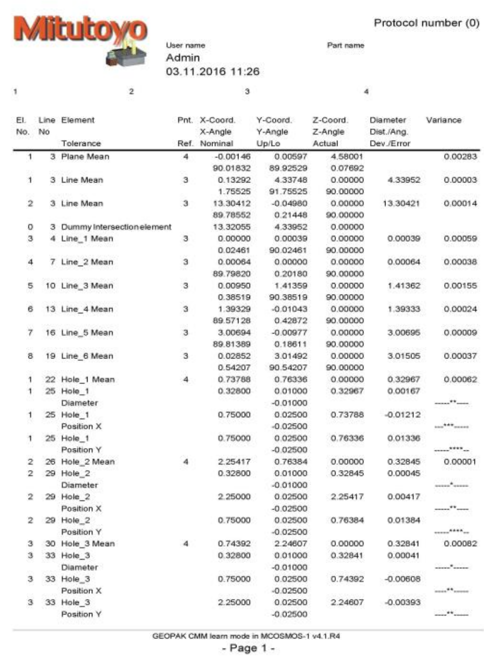

Mitutoyo

Protocol number (0)

User name
Admin
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Part name

1 2 3 4

El. No.	Line No	Element / Tolerance	Pnt. Ref.	X-Coord. / X-Angle / Nominal	Y-Coord. / Y-Angle / Up/Lo	Z-Coord. / Z-Angle / Actual	Diameter / Dist./Ang. / Dev./Error	Variance
1	3	Plane Mean	4	-0.00146	0.00597	4.58001		0.00283
				90.01832	89.92529	0.07692		
1	3	Line Mean	3	0.13292	4.33748	0.00000	4.33952	0.00003
				1.75525	91.75525	90.00000		
2	3	Line Mean	3	13.30412	-0.04980	0.00000	13.30421	0.00014
				89.78552	0.21448	90.00000		
0	3	Dummy Intersection element		13.32055	4.33952	0.00000		
3	4	Line_1 Mean	3	0.00000	0.00039	0.00000	0.00039	0.00059
				0.02461	90.02461	90.00000		
4	7	Line_2 Mean	3	0.00064	0.00000	0.00000	0.00064	0.00038
				89.79820	0.20180	90.00000		
5	10	Line_3 Mean	3	0.00950	1.41359	0.00000	1.41362	0.00155
				0.38519	90.38519	90.00000		
6	13	Line_4 Mean	3	1.39329	-0.01043	0.00000	1.39333	0.00024
				89.57128	0.42872	90.00000		
7	16	Line_5 Mean	3	3.00694	-0.00977	0.00000	3.00695	0.00009
				89.81389	0.18611	90.00000		
8	19	Line_6 Mean	3	0.02852	3.01492	0.00000	3.01505	0.00037
				0.54207	90.54207	90.00000		
1	22	Hole_1 Mean	4	0.73788	0.76336	0.00000	0.32967	0.00062
1	25	Hole_1		0.32800	0.01000	0.32967	0.00167	
		Diameter			-0.01000			-----**----
1	25	Hole_1		0.75000	0.02500	0.73788	-0.01212	
		Position X			-0.02500			---***-----
1	25	Hole_1		0.75000	0.02500	0.76336	0.01336	
		Position Y			-0.02500			-----****--
2	26	Hole_2 Mean	4	2.25417	0.76384	0.00000	0.32845	0.00001
2	29	Hole_2		0.32800	0.01000	0.32845	0.00045	
		Diameter			-0.01000			-----*-----
2	29	Hole_2		2.25000	0.02500	2.25417	0.00417	
		Position X			-0.02500			-----**----
2	29	Hole_2		0.75000	0.02500	0.76384	0.01384	
		Position Y			-0.02500			-----****--
3	30	Hole_3 Mean	4	0.74392	2.24607	0.00000	0.32841	0.00082
3	33	Hole_3		0.32800	0.01000	0.32841	0.00041	
		Diameter			-0.01000			-----*-----
3	33	Hole_3		0.75000	0.02500	0.74392	-0.00608	
		Position X			-0.02500			----**-----
3	33	Hole_3		2.25000	0.02500	2.24607	-0.00393	
		Position Y			-0.02500			----**-----

GEOPAK CMM learn mode in MCOSMOS-1 v4.1.R4
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Figure 5 – Students' CMM measurement reports

Course Outcome Evaluation

Course outcome evaluation is a key factor for recognizing the benefits, identifying the deficiencies, and improving course contents. Through the evaluation, the author should be able to assess students' feedback in class. The typical evaluation process includes assessing students' labs, projects, and exams. In addition, the author can get feedback from students through the use of questionnaires. These outcomes can be mapped into Bloom's Taxonomy expertise levels to see how much the students are learning from these interconnected laboratory modules. There are several approaches to assessing student learning outcomes. Each assessment method has different advantages and disadvantages and yields only partial insight into student learning and teaching effectiveness. However, a combination of direct and indirect outcome measures can provide valuable information that can be used to address students' problems and enhance instructional materials and delivery. To measure the learning performance, the author used the following methods to assess the outcomes and collect all the necessary data:

(1) Course-based quizzes and examinations - what basic knowledge and abilities have students acquired from lectures, labs, and project activities,
(2) In-class observation - students can demonstrate their skills by conducting CMM measurement and programming in the classroom,
(3) Student survey - according to our university policy, we have to collect and conduct student surveys at the end of each semester,
(4) Project Presentation - students can present their results and findings to the class (use project rubric for outcome assessment: peer evaluations 50% + instructor grading 50%),
(5) Project report - students report include written assignment, probe selection and calibration, measurement procedure, and CMM manual programming.

The author will continuously use the above student evaluation information to support and improve instructor teaching materials and contents, not contribute to instructors' fear, stress and alienation. The class size was 39 students, and the total number of responses was 38. Some of the results from these student assessments presented as follows:

1. 95% of the students had strong confidence in their ability to apply CMM knowledge and correctly solve a similar problem in the future,
2. 84% of the students were able to create and run CMM programs, recover from error and fault,
3. 30 students ranked CMM measurement project experience in the top two activities they liked in the overall course activities,
4. 32 students agreed that they are more likely to remember the content delivered in these courses because of this new curriculum
5. When compared to a traditionally-taught course, 36 students preferred this approach over the traditional one.

The result of the evaluation indicated that CMM measurement and programming skills can enhance student learning outcomes and techniques. These findings also showed that developing interconnected CMM lab modules can create an extremely effective learning environment to actively involve all the students in the class.

Conclusion

This study investigated new interconnected laboratories of teaching manufacturing engineering students' CMM knowledge and skills that they need for a successful future. The author also examined GSU manufacturing engineering curricula to ensure the students are familiar with the trends in Metrology technology. These CMM laboratory modules challenged manufacturing engineering students to practice CMM measurement and programming skills. Learning CMM modules also helped the students to understand precise measurement principles and guidelines better. In addition, it allowed the students to strengthen their CMM measurement concepts and manufacturing process skills, exercise their creativity and practice their hands-on skills. The student learning process was motivational, fun, and enlightening activities that provided students a hands-on opportunity while combining and practicing manufacturing, design, and precise measurement skills. Finally, they demonstrated their fundamental knowledge and insight by using gage R&R to reassure the measurement process and equipment. They understood how this might be helpful to them in their design and manufacturing process learning.

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