Design and Development of a Manufacturing Process and Machining Technology Course Sequence

Junkun Ma (Professor)

Faculty working for Sam Houston State University with education background and interest in Mechanical Engineering , Manufacturing, and Mechanics of Materials

Suleiman Obeidat (Assistant Professor)

Design and Development of a Manufacturing Process and Machining Technology Course Sequence

Junkun Ma and Suleiman Obeidat

ABSTRACT

This work-in-progress paper presents the continuous efforts to design and develop project-based course materials that integrate CAD, AM, CAM, and CNC machine tools into a Manufacturing Processes and Machining Technology course sequence. Hands-on projects implementing CAD software for parts design and analysis, AM technologies for rapid prototyping, CAM software for developing manufacturing strategies, CNC machine tools for manufacturing functional prototypes with various practical applications, and related instructional materials and lab processes are being developed. The primary goal is to expose students to various manufacturing processes, emphasizing modern CNC processes, equipment, and tools. By teaming students into workgroups, these courses also emphasize developing the students' skills to apply theoretical knowledge to solve practical problems requiring critical thinking.

The Manufacturing Processes is a sophomore-level introductory course exposing students to modern industrial manufacturing methods and equipment focusing on the CAD/AM/CAM/CNC processes. The primary goal is to provide an overview of the product design and development process, including fundamentals of engineering materials, fast prototyping, and machining methods and processes. Instructional materials with hands-on activities are developed using equipment including 3D printers (based on FDM, SLA, and MJ technologies from Makerbot, Formlab, and Stratasys), a tabletop single tool milling machine, and a CO_2 and fiber dual-source laser cutter/engraver. Students are required to apply previous knowledge and skills to develop 3D models for components and systems satisfying predefined restrictions and requirements. Students will also be required to create assembly models for engineering analysis, such as motion study and 2D engineering drawing with detailed specifications. They will then be introduced to AM technologies and required to build and test working prototypes of the designed components. Finally, students are presented with the fundamentals of the CNC milling process with applications to build prototypes using a tabletop milling machine and custom-designed CAM software. Students will also learn to use the laser cutter/engraver to cut and engrave materials and components.

Instructional materials with lab activities for Machining Technology, a follow-up course focusing on CNC milling operations, are also being developed to cover coordinate systems, tool path designs, G/M codes, etc. The labs will be implemented using a three-axis CNC milling center equipped with a magazine for multiple tools operation.

INTRODUCTION

Economic prosperity in the US depends on a diverse and robust science, technology, engineering, and mathematics (STEM) talent pipeline. As technologies in the manufacturing industry are

evolving rapidly, there is a dire need to create and support an innovative and sustainable industry-driven workforce capable of adapting in response to these rapidly changing conditions. The recent survey about future work in the US manufacturing industry indicates a widening gap between the manufacturing jobs that need to be filled and the talent pool with the required skill sets.[1] It is estimated that the US manufacturing skills gap could leave up to 2.1 million jobs unfilled by 2030.[2] The three leading causes of this widening gap are: 1) the skills needed for jobs are changing due to the adoption of advanced technologies, and there is a lack of adequate preparation and diversity of domestic students in the educational pipeline;[3] 2) the decline in student engagement in pursuing science and engineering careers;[4] and 3) student and parent misperceptions about the nature of current manufacturing jobs as compared to traditional manufacturing jobs of the past.[5] In addition, although historical studies suggest that student interest in STEM-related fields as career options peaks during middle school, especially for minorities and young women,[6] recent research indicates that this trend is declining.[4] Moreover, women and minorities interested in STEM fields may experience additional challenges and may find fewer opportunities to develop necessary essential skills associated with more complex tasks related to engineering and technology.[7] The US manufacturing industry needs to become more flexible and adaptive to remain competitive, which requires a robust infrastructure and collaborative efforts among professionals capable of engaging the next generation of manufacturing industrial workers and professionals.

The US manufacturing industry continues to shift jobs back due to growing concerns about rising labor costs overseas, costs associated with transportation, and supply chain instability.[8,9] Job openings have been growing at double-digit rates since 2017 and are nearing a historical high recorded in 2001.[10] The latest report released in October 2021 by the Bureau of Labor Statistics shows that the manufacturing sector continues to grow in eight major cities with as high as a 5.9% annual increase.[11] While US manufacturers show record optimism of continuous growth,[12] the labor market, particularly the skilled talent pool capable of filling these jobs, is becoming more and more challenging, and the gap is getting wider.

Sam Houston State University currently offers a minor and is developing a Bachelor of Science in Manufacturing Engineering Technology. One of the focal areas in the curricula is programing skills for CNC machining, which is one of the five critical skills expected to be needed to succeed in the future US manufacturing industry. A two-course sequence including an introductory Manufacturing Processes, which introduces students to modern product design and common manufacturing techniques, and Machining Technology, which focuses on CNC programming, were developed. The learning-by-doing (LBD) active learning method, which is a pedagogical approach that fosters skill development and application without predefined conditions, is adopted in the instruction of both courses.[13] The LBD involves students in hands-on activities focusing on knowledge and skill development to solve practical problems. The primary benefit of this approach is that students will develop practical skills that are relevant to real-world problems by applying instead of just knowing the factual knowledge. This paper presents the integration of the LBD teaching method into the design and development of instructional materials for the two courses.

The ultimate goal of this sequence of two courses is to expose students to various design tools and manufacturing processes focusing on CNC programming.

COURSE MODULE DESIGN

The Manufacturing Processes Course

The Manufacturing Processes is a sophomore-level course introducing students with prior fundamental engineering graphics and CAD knowledge to product design and prototype development processes. Since the course is designed for engineering technology students, emphasis is placed on developing students' skills to identify, research, and apply knowledge to solve practical engineering problems. By integrating LBD active learning strategy into the instruction, it is expected that students will be able to apply the following principles to solve real-world problems:

1. Fundamental concepts of common engineering materials and manufacturing processes
2. Outline and broad perspective of modern manufacturing methods involving various engineering materials
3. Basic calculations to determine parameters used in manufacturing processes
4. Practices of the CNC milling processes

Using the educational Mobile Inverted Pendulum (MIP)[14] robot as the platform, students are asked to redesign and build prototypes for selected components with restrictions using various lab-scale manufacturing equipment. The instructional materials are organized into the following three modules.

a) Fundamental of engineering materials

Understanding engineering materials' responses when subjected to various loading conditions, especially the mechanics and mechanical behaviors, is essential to any manufacturing process since it typically involves material alterations based on different mechanisms. This module discusses materials' mechanics and mechanical properties, including fundamental concepts such as stress, strain, elastic and plastic deformation, ductility, and hardness. ASTM standard test methods for tensile and flexural properties of materials are also introduced. Experimental tests are conducted to demonstrate how materials' properties, such as Young's Modulus, Poisson's ratio, and fracture toughness, are measured using two universal testing machines. Concepts based on these experimental tests, including yield strength, ultimate tensile strength, stiffness, toughness, and resilience, as well as loading and unloading processes, are also discussed. In addition, the laser processing technique is introduced and applied to make plastic tensile test samples out of various plastic sheets. *Figure 1a* shows the tensile test of a Type I standard sheet sample made out of high-density polyethylene (HDPE) plastic with an extensometer attached. *Figure 1b* shows the three-point bending test of a 2' x 4' x 10' pine wood board. Figure 2 shows the dual power source (CO_2/Fiber) Epilog Fusion M2 40 laser cutter/engraver and a few Type I standard plastic sheet samples.
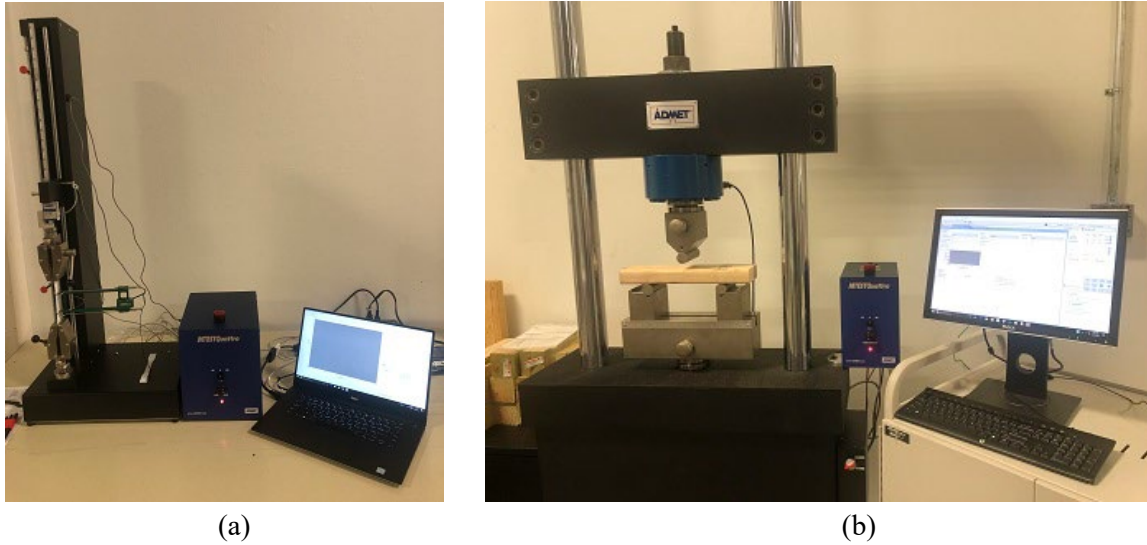
| (a) | (b) |

Figure 1 ADMET universal testing systems for tensile (a) and flexural (b) properties measurement

Figure 2 Epilog Fusion M2 laser cutting/engraving machine for tensile sample preparation

b) *Component redesign and prototyping using AM methods*

The MIP robot is an educational system developed based on the inverted pendulum theory, and it is available in the form of a kit. The robot has two wheels with the center of gravity of the whole system above the rotation axis of the two wheels. The single-board computer (SBC) BeagleBone Black and its robotic cape were initially designed to sense the robot's falling and subsequently control the motors driving the wheels to compensate for the fall. Consequently, the SBC and robotic cape balance the robot by sensing and controlling the robot in real-time. With the development of the new generation SBC BealgeBone Blue, which integrates the BeagleBone Black and its robotic cape into one compact package, there is an interference between the new SBC and a plastic part named 'bulkhead' in the kit. *Figure 3*a shows all components in the kit with the new BeagleBone Blue SBC, and the red arrow points at the 'bulkhead' component. *Figure 3*b shows the interference between the SBC and the bulkhead.
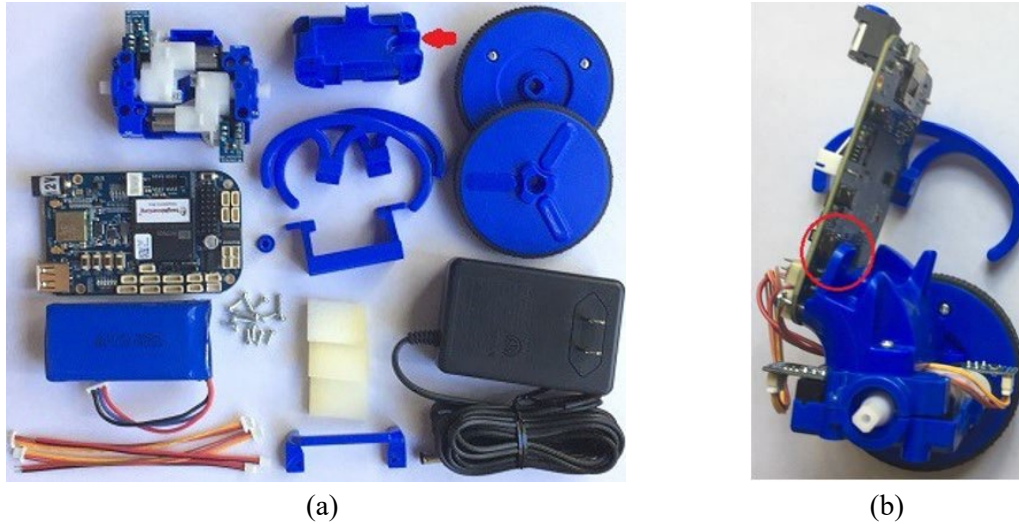
<div align="center">(a)   (b)</div>

Figure 3 MIP robot kit (a) and the interference of components (b) (indicated in the red circle)

Students are introduced to the SolidWorks 3D modeling software to redesign and solve the issue between the new SBC and the bulkhead. As a prerequisite, students enrolling in this course already have fundamental knowledge about 2D engineering drawing, including coordinate systems, geometry construction, geometry relationship, orthographic projection, and dimensioning. Parametric design concepts are incorporated into this module, emphasizing design intention and parametric relationships. Fundamental operations, such as file template, working environment, geometric relationships between geometric entities in 2D sketches, and 3D modeling tools, such as extrusion, revolve, sweep, and loft, are discussed. The goal is to have students experience the process of product design/redesign with given restrictions. *Figure 4* shows the 3D models of the original and redesigned bulkhead.

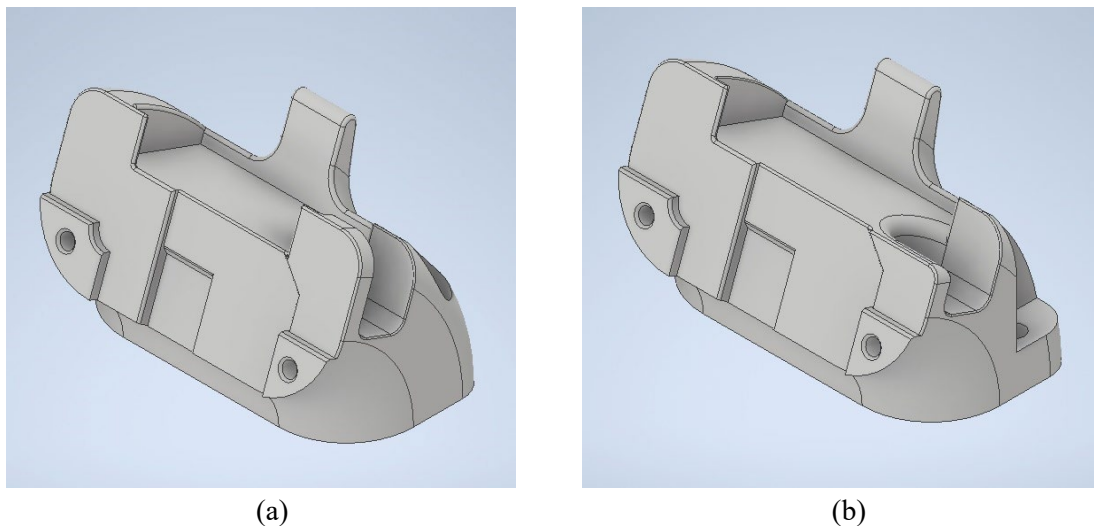<div align="center">(a)   (b)</div>

Figure 4 3D models of the original (a) and redesigned (b) bulkhead design

Subsequently, students are introduced to three different types of additive manufacturing (AM) mechanisms, including Fused Deposition Modeling (FDM), Stereolithography (SLA), Material Jetting (MJ) techniques, and equipment so that they can build prototypes of the redesigned

bulkhead. *Figure 5* shows the original and the redesigned bulkhead manufactured using the three AM methods. In addition, the fundamentals of plastic extrusion and injection molding processes are also included in this module.
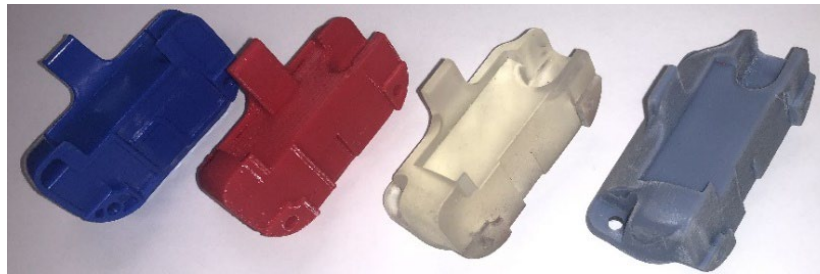

Figure 5 Original and redesigned bulkhead (from left, original, FDM, SLA, and MJ)

Furthermore, students are required to redesign the wheel to use a simple and cheaper Pololu[15] tire with the restriction that it can still be mounted on the existing driveshafts. This newly designed wheel will also be used in the next module for CNC machining based on CAM software. The new wheel design is only prototyped using the FDM-based 3D printer. *Figure 6* shows the exploded and fully assembled original wheels and the Pololu tire (the Pololu wheels shown are not used). *Figure 7* shows a balancing MIP robot with a pair of redesigned wheels, each equipped with a Pololu tire and a redesigned bulkhead that are prototyped using the FDM method.

Figure 6 Original MIP wheel (left) and the Pololu 60mm wheel assemblies (right, the rim is not used)

Figure 7 A balancing MIP with redesigned bulkhead and wheel using the Pololu tire

c) CAM and CNC Milling Operations

The last module introduces students to basic two and a half dimensions (2.5D) CNC milling using a single tool desktop NomadPro 883 CNC milling machine.[16] Fundamental milling operations related to defining and setting up the NomadPro 883, including setting up bulk materials, defining origin and coordinate system, calibrating tool height, specifying tools, and tool change, are discussed in detail. The Carbide Create CAM software custom-designed for the NomadPro 883 based on toolpath design is used to develop G-code for milling the redesigned wheel. The toolpath design includes 1) contour with outside/right, inside/left, and no offset options; 2)pocket; 3)texture; 4)drill with full depth, peck, and peck with full retreat options; and 5)V-notch carving. The milling tools' fundamentals include cut length, flute length, helix angle, cutting edge, shank and cutting diameter, etc. are introduced. Types of milling tools, including ball nose end mill, flat end mill, V carve engraver, and surface coating for different materials, are also discussed. Concepts of feed and speed are introduced and used to calculate material removing rate and operation time.

With essential knowledge of the CNC milling process, students are required to modify the redesigned wheel to make its 2D projected contour suitable for 2.5D CNC milling operations while still satisfying the restriction of the hub for the driving shaft and rim for the Pololu tire.
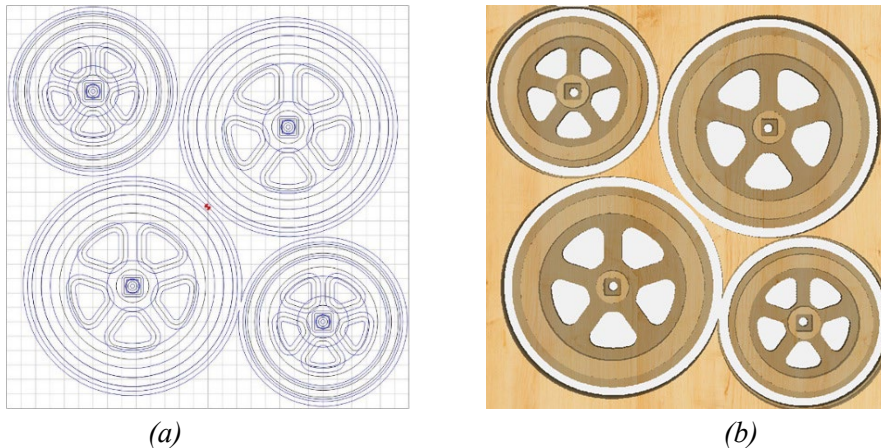

(a)   *(b)*

Figure 8 Carbide Create toolpath (a) and simulated finished wheel(b)
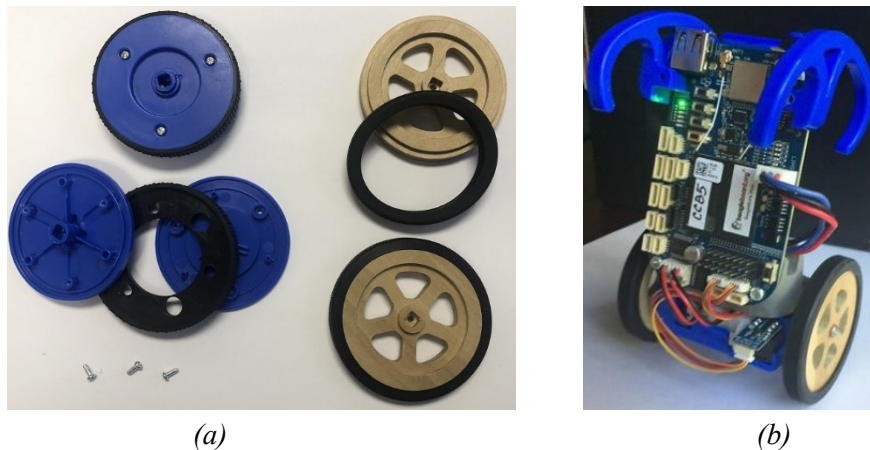

(a)   *(b)*

Figure 9 CNC milled wheel (a) and a balancing MIP running the wheel and Pololu tire (b)

The Machining Technology Course

As a follow-up course to the Manufacturing Processes, Machining Technology discusses CNC milling operations based-on G-M codes. As shown in Figure 10a, a FANUC CNC simulator will be used to examine the validity and functionality of designed CNC codes before being loaded to an EMCO Concept Mill 55 milling center for actual machining.

The course is being designed and developed and will be offered and assessed in Fall 2022. Similar to the Manufacturing Processes course, by implementing the LBD pedagogical strategy, the expected students' learning outcomes are the following.

1. Gain fundamental knowledge of the CNC milling center and key concepts, such as basic milling operations and their sequence, tool selections, and cutting conditions,
2. Develop machining strategies, such as defining key nodes and designing tool paths
3. Design CNC programs for the fabrication of functional components
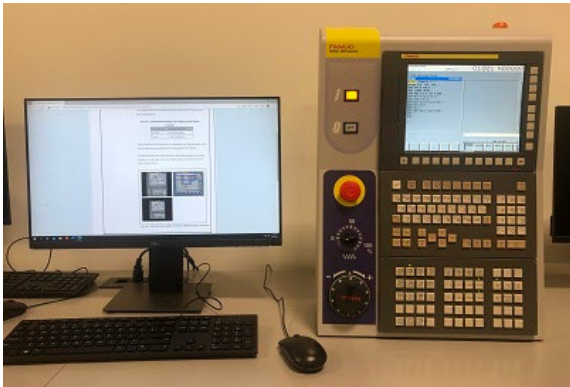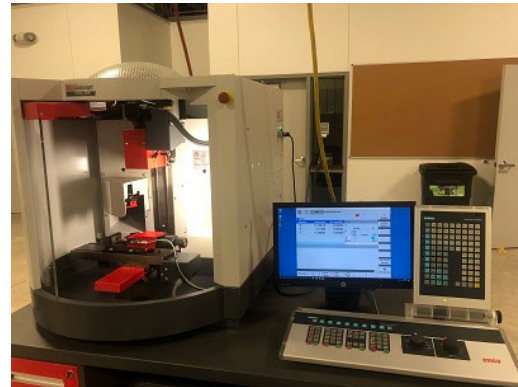
(a)   (b)

Figure 10 FANUC CNC simulator (a) and EMCO Concept Mill 55 milling center (b)

Instructional materials and lab manuals for the following learning modules are being developed to achieve these outcomes.

a) Fundamentals of a milling center, milling operations, and CNC programming

This module aims at developing a fundamental understanding of a milling center, the milling operations it can perform, and the basics of CNC programming. Students should be able to perform the following tasks after completing this module.

1. Develop essential knowledge of a milling center, such as types, essential components, and axes of moving
2. Determine milling operation parameters such as speeds and feeds based on workpiece materials, tools, and cooling conditions
3. Describe steps and associated tasks of job flow in a CNC milling center
4. Understand workpiece coordinate system, workpiece coordinate system offsets, and methods to measure these values
5. Determine and set up tools and fixtures to hold the workpiece in the milling center
6. Gain knowledge of the structure of the CNC program, programing words and syntax, execution of a program, and limitations of G-M codes

7. Identify required machining operations and their sequence, cutting conditions and tools to use, and calculate coordinates based on engineering drawing

b) Types of motion

This module introduces students to the three fundamental types of motion: rapid, linear, and circular motions. The goal is for students to understand how CNC machining centers interpolate motions. The following characteristics of motion types will be discussed.

1. Motion type in CNC remains at the last specified mode until it is changed
2. All tool movements start at the current position of the tool and require the coordinates of the end-point to perform a specific motion
3. Motions could be specified as either absolute mode, in which coordinates are relative to the origin of the workpiece coordinate system and incremental mode, in which coordinates of the end-point is relative to the current position

Commonly used tools, including flat/ball end mills, drills, reamers, and taps, and their programming will be introduced.

c) Compensations

The third module discusses the concepts and programming practice of three types of compensations: tool length compensation, tool radius compensation, and workpiece coordinate system offset. Students should be able to apply the following knowledge to program compensations.

1. Understand the tool length compensation concept and determine tool length compensation based on measurements using the CNC machine with application to program tool length compensation
2. Understand the tool radius compensation concept and determine tool radius compensation based on tool specifications with application to program tool radius compensation
3. Understand the workpiece coordinate system offsets and how to set up and program multiple workpiece coordinate system zero points

d) Structure of CNC program and special programming features

The last module discusses the structure of CNC programs and a few selected features that simplify the programs. Students will be able to apply the following programming practices to develop well-structured and most efficient CNC programs.

1. Essential CNC program elements and how to structure them in CNC programming with consideration of efficiency, ease of use and modification, safety, and potential impacts between different CNC machines
2. Program start, tool start, tool end, and program end structures and their applications to structured CNC programming
3. Special features including subprogram, canned cycles for drilling, and other selected special programming features
4. The concept of parametric programming and how to design general-purpose subprograms

STUDENTS' FEEDBACK

The Manufacturing Processes was offered during the Fall 2021 semester, with 15 students enrolled. A progress self-assessment survey with the following questions was also given to this cohort of students to obtain student ratings of learning on relevant objectives.

1. Gaining a basic understanding of the subject (e.g., factual knowledge, methods, principles, generalizations, theories)
2. Developing knowledge and understanding of diverse perspectives, global awareness, or other cultures
3. Learning to apply course material (to improve thinking, problem-solving, and decisions)
4. Developing specific skills, competencies, and points of view needed by professionals in the field most closely related to this course
5. Acquiring skills in working with others as a member of a team
6. Developing creative capacities (inventing; designing; writing; performing in art, music, drama, etc.)
7. Gaining a broader understanding and appreciation of intellectual/cultural activity (music, science, literature, etc.)
8. Developing skills in expressing myself orally or in writing
9. Learning how to find, evaluate, and use resources to explore a topic in-depth
10. Developing ethical reasoning and ethical decision making
11. Learning to analyze and critically evaluate ideas, arguments, and points of view
12. Learning to apply knowledge and skills to benefit others or serve the public good
13. Learning appropriate methods for collecting, analyzing, and interpreting numerical information

Table 1 shows the distribution of students' self-assessments. The scores range from 1.0 to 5.0 with 1.0 intervals for the listed 'No Apparent Progress,' 'Slight Progress,' 'Moderate Progress,' 'Substantial Progress,' and 'Exceptional Progress' correspondently, and the mean scores of the survey results. Average summative scores of 4.6, 4.5, and 4.6 out of 5.0 for the following three categories, respectively: Summary, Progress on Relevant Objectives, and Ratings of Summative Questions, were calculated based on the survey. In addition, students' qualitative comments are also highly positive.

Questions	No Apparent Progress	Slight Progress	Moderate Progress	Substantial Progress	Exceptional Progress	Mean Score
1	0%	0%	0%	30%	70%	4.7
2	10%	0%	10%	30%	50%	4.1
3	0%	0%	10%	30%	60%	4.5
4	0%	10%	0%	40%	50%	4.3
5	0%	0%	0%	40%	60%	4.6
6	0%	0%	10%	10%	80%	4.7
7	10%	0%	10%	20%	60%	4.2

8	10%	10%	10%	10%	60%	4.0
9	0%	10%	10%	20%	60%	4.3
10	0%	0%	10%	40%	50%	4.4
11	0%	0%	0%	30%	70%	4.7
12	0%	10%	10%	20%	60%	4.3
13	0%	0%	20%	20%	60%	4.4

Table 1 student ratings of learning on relevant objectives

CONCLUSIONS

This paper presents the work-in-progress design and development of a two-course sequence, including the introductory Manufacturing Processes and CNC machining focused Machining Technology. The Manufacturing Processes introduce students to a broad overview of various manufacturing processes and equipment, including the fundamentals of CNC milling operations. The Machining Technology discusses in-depth CNC milling operations based on G-M codes and Fanuc CNC Simulator. The Manufacturing Processes was offered in Fall 2021, and feedback from this cohort of students is very positive, with areas to be further improved. More activities and tasks should be designed and incorporated to develop students' skills in expressing themselves orally or in writing and knowledge and understanding of diverse perspectives, global awareness, or other cultures. Machining Technology is still being developed to be offered and assessed in Fall 2022.

References

[1] Giffi, C., Wellener, P., Dollar, B., Manolian, H., Monck, L., & Moutray, C. (2018). Deloitte and The Manufacturing Institute skills gap and future of work study. *Deloitte Insights*.

[2] Deloitte, US Manufacturing Skills Gap Could Leave As Many As 2.1 Million Jobs Unfilled By 2030, Deloitte and The Manufacturing Institute Study Finds, https://www2.deloitte.com/us/en/pages/about-deloitte/articles/press-releases/deloitte-manufacturing-skills-gap.html, accessed on February 5, 2022.

[3] Weaver, A., & Osterman, P. 2017. Skill demands and mismatch in US manufacturing. ILR Review, 70(2), 275-307.

[4] Blotnicky, K., Franz-Odendaal, T., French, F., & Joy, P. (2018). A study of the correlation between STEM career knowledge, mathematics self-efficacy, career interests, and career activities on the likelihood of pursuing a STEM career among middle school students. *International journal of STEM education, 5(1), 1–15*.

[5] Ramezany, Ali. 2017. Critical Review of Factors that lead to the Negative Image of the Construction Industry. Journal of Multidisciplinary Engineering Science and Technology. 4: 6796-6802.

[6] Cummings, S., & Taebel, D. (1980). Sexual inequality and the reproduction of consciousness: An analysis of sex-role stereotyping among children. *Sex Roles, 6(4), 631–644*.

[7] Sutton, A., Bosky, A., & Muller, C. (2016). Manufacturing gender inequality in the new economy: High school training for work in blue-collar communities. American sociological review, 81(4), 720-748.

[8] Boak, J. US factories closed out 2017 with a boom, USA Today. https://www.usatoday.com/story/money/economy/2018/01/03/us-factories-closed-out-2017-boom/999663001/. Accessed on February 05, 2022

[9] Ellram, L. M., Tate, W. L., & Petersen, K. J. (2013). Offshoring and reshoring: an update on the manufacturing location decision. Journal of Supply Chain Management, 49(2), 14-22.

[10] Bureau of Labor Statistics. Job openings and labor turnover survey. https://www.bls.gov/jlt/. Accessed on February 05, 2022.

[11] Bureau of Labor Statistics, Houston Area Employment – October 2021. https://www.bls.gov/regions/southwest/news-release/areaemployment_houston.htm. Accessed on February 05, 2022

[12] Shapiro, M., NAM Survey: Record Optimism Among Manufacturers Continues, March 2019. https://www.nam.org/nam-survey-record-optimism-among-manufacturers-continues-782/. Accessed on February 05, 2022

[13] Schank, R. C., Berman, T. R., & Macpherson, K. A. (1999). Learning by doing. Instructional-design theories and models: A new paradigm of instructionaltheory, 2, 161-181.

[14] UCSD Flow Control & Coordinated Robotics Lab, https://www.ucsdrobotics.org/edumip, accessed on February 05, 2022.

[15] Pololu Robotics & Electronics, https://www.pololu.com/product/3409, accessed on February 05, 2022.

[16] Carbide 3D Inc., https://shop.carbide3d.com/products/nomad883?variant=1257580459, accessed on February 05, 2022.