

Learning-by-Doing: Development of Project-Based Manufacturing Courses

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ABSTRACT

This paper presents the development of project-based course materials for a sequence of two new undergraduate manufacturing courses: Design and Prototyping and Machining Technology that are designed for freshman and sophomore level students. The course materials presented in this paper start with introducing students to a working product and then challenge them with problems requiring the redesign of components. Subsequently, various manufacturing methods, techniques, processes, and equipment are discussed in detail so that students can prototype these newly designed components in the laboratories. As part of the curriculum of an Engineering Technology program, these courses aim at developing students' ability to work in collaborative groups to apply engineering and technology knowledge to solve real-world technical problems requiring the application of practical procedures and methods.

The Design and Prototyping is an introductory manufacturing processes course which introduces students to commonly used manufacturing processes in the industry for manufacturing of a variety of products using different materials. The primary goal of this course is to provide a broad overview of fundamental concepts, tools, methods, and equipment that are used in the manufacturing industry. This course is based on an educational Mobile Inverted Pendulum (MIP) robot. As a follow-up, the Machining Technology course focuses on CNC machining. Fundamentals of both turning and milling operations and associated accessories and tools are introduced. A single cylinder horizontal Stirling engine kit is used as the platform in this course. Feedbacks from the first cohort of students completed the Design and Prototype course are also reported.

INTRODUCTION

Learning-by-doing (LBD) is a pedagogical approach in which the learning process is relevant and practical beyond passive and theoretical. Schank considers the primary goal of this approach is to foster skill development and the learning of factual information in the context of how knowledge can be applied without predefined conditions.¹ Some of the primary benefits of this approach include:

1. learning and gaining of knowledge occurs in the context of a clearly defined goal that is interesting and relevant to students
2. students develop practical skills by applying instead of simply knowing the factual knowledge

3. knowledge gained and skills developed are closely related to how they will be used outside of the learning environment in real-world applications.

As a form of active learning, the LBD involves students in hands-on activities and requires each student to actively engage in tasks such as identifying problems, researching for knowledge and tools, conducting analysis, performing tests, and evaluating results to solve practical problems.^{2, 3}

Despite the challenges and unanswered questions related to the LBD approach, numerous studies in the literature have reported experimental studies showing that this active learning approach is more effective, especially in the fields of science, technology, engineering, and math (STEM) education. Adair and Jaeger⁴ introduced a design project into a freshman mechanical engineering course, which provides functional interaction between students and instructors via hands-on experience and allowed students to gain a better understanding of their future profession. Jordi and Alfredo⁵ showed how the LBD methodology is incorporated into a series of two Electrical Machines courses and concluded that it provided students with a framework to acquire knowledge and develop competencies that are otherwise not possible using a traditional method. The students also play a more active role in the learning process. Fantozzi⁶ also demonstrated how a design project developed for an international engineering design competition that involved multi-disciplinary students from three different universities provided LBD experience for students.

Statistical data in the literature also shows that active learning increases the retention rate of engineering students. Freeman⁷ conducted a comparative study and found that the failure rate under traditional lecturing increases by 55% over the rate under active learning, and active learning results in a better average grade raise of a half letter grade. Keeping students interested by engaging them actively in activities that the students are interested in teaching introductory engineering courses is a critical factor to the students' success. Placing students into groups to work collaboratively on projects that are relevant to their field of studies early in their college education in introductory courses help them to gain a better understanding of different aspects of their field of studies, and it makes them more confident to pursue advanced topics and progress along their curricula.

This paper describes the integration of the LBD teaching methodology into course materials development for an introductory manufacturing processes course 'Design and Prototyping' and a follow-up 'Machining Technology' course. The Design and Prototyping course was designed to expose students to various product design and development techniques with emphasis on mechanical component design using Autodesk Inventor CAD software package and development of prototypes using various manufacturing methods including additive manufacturing (3D printing), injection

molding, metal casting, and fundamentals of CNC machining. A preliminary survey reporting students' feedback based on an experimental offering of this course during summer 2018 are presented. The Machining Technology course is designed as a follow up of the introductory Design and Prototyping course, and it focuses on the CNC machining technology. The Mobile Inverted Pendulum (MIP) robot developed by the Renaissance Robotics⁸ and the BeagleBone Organization⁹ is used in the Design and Prototyping course, and the DjuinoStar vertical single piston hot air Stirling engine¹⁰ developed and distributed by the Djuino Trading Co., LTD. is used in the Machining Technology course. The primary goal of this sequence of two courses is to engage students by exposing them to various design tools and manufacturing processes, and then challenging them with building and redesigning working products to attract and advance students to pursue a manufacturing career.

COURSE MODULES

The Design and Prototyping Course

The Design and Prototyping course is developed as an introductory manufacturing processes course for students with basic engineering graphics and CAD knowledge. Since the course is designed for engineering technology students, the course materials were designed with an emphasis on developing students ability to select the knowledge, techniques, skills, and modern tools used in the manufacturing industry and apply to broadly-defined engineering technology activities. The course provides students with an LBD experience in which students will design and prototype components for the MIP robot using various design tools and equipment. The expected student outcomes are the following:

1. be able to design 3D models of mechanical components and their assembly using the Autodesk Inventor software package;
2. become familiar with the procedures, tools, accessories, and operations of various manufacturing methods, including additive manufacturing (AM), plastic injection molding, sand casting, and machining;
3. be able to apply fundamental concepts of both design tools and manufacturing processes to design and develop a prototype.

This course engages students immediately by providing a detailed assembly instruction manual and requiring students to assemble the MIP robot kit and balance it. Students will encounter an issue in this process as a plastic component called 'bulkhead' in the kit is not designed for the latest BeagleBone[®] Blue (BBB)¹¹ microcontroller used in this course. As a result, students are introduced to the Autodesk Inventor 3D CAD design software so that they can redesign the bulkhead and then build a prototype using AM equipment based on different techniques before reassembling using the redesigned and prototyped

bulkhead. After successfully reassembling the MIP robot using the modified bulkhead and balancing it, students are required to redesign and prototype a pair of wheels so that it will be able to use the Pololu 60x8mm tires¹² that mount differently from the ones in the kit but still work with the driveshaft hub of the existing driving mechanism. Plastic injection molding, sand casting, and Computer-aided Manufacturing (CAM)/CNC are introduced, and students build a prototype of the new wheel design using the Nomad 883 Pro¹³ desktop CNC milling center. The course materials were designed and organized into the following modules:

- a) Assemble the MIP robotic kit
- b) Bulkhead redesign
- c) Bulkhead prototyping using AM methods
- d) Wheel redesign and prototype
- e) Sand casting
- f) Wheel prototyping using CAM/CNC technique

a) Assemble the MIP robotic kit

This module introduces the features and functions of the individual component in the MIP robotic kit, detail procedures and associated components for assembly, and a fully assembled working MIP robot to students who work collaboratively in small groups of two or three students. Fig. 1 shows the components in the kit and a fully assembled MIP robot with the redesigned bulkhead in a balanced and stably suspended position. As the students proceed with assembling the kit, they will notice that the bulkhead (the component where the red arrow is pointing at in Fig. 1(a)) interferes with the BBB microcontroller preventing it from being securely installed. This problem exists since the kit was designed for the previous generation BBB microcontroller. The red circle in Fig. 2 shows the interference.

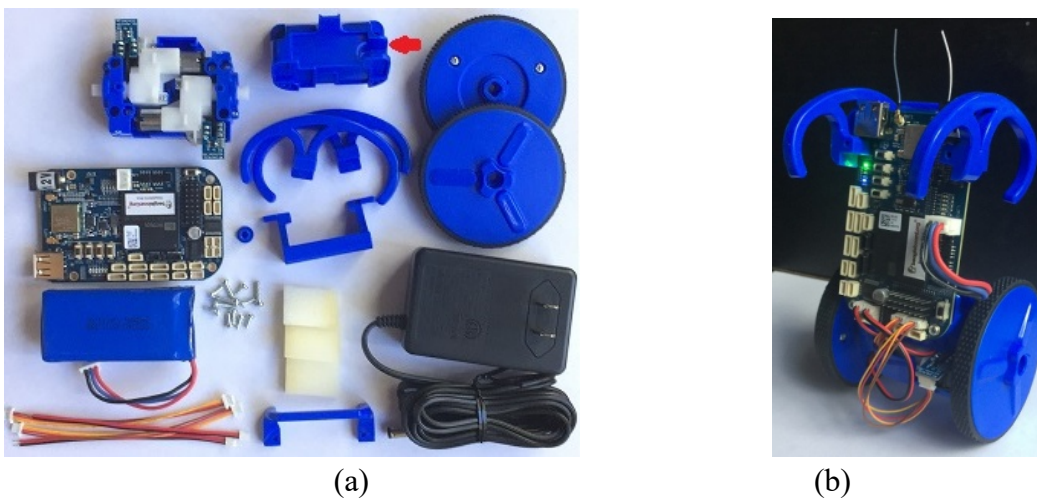


Fig. 1 a) MIP robot kit, b) fully assembled and balancing MIP robot

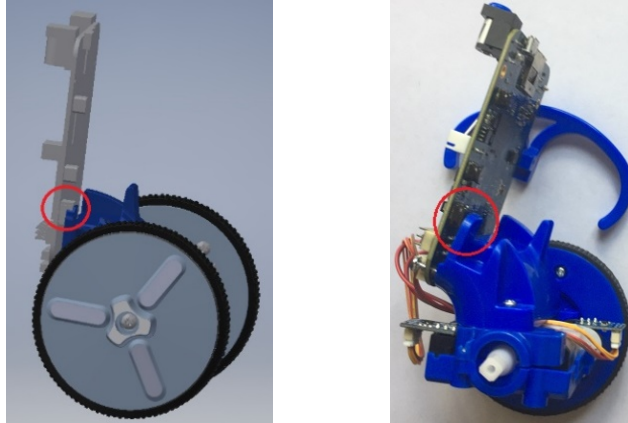


Fig. 2 Interference between the BBB microcontroller and the bulkhead

b) Bulkhead redesign

As a prerequisite, students entering this course are required to have basic knowledge of engineering graphics such as geometry construction, orthographic and isometric projections, and dimensioning. In this module, students are introduced to the Autodesk Inventor 3D modeling tool. Fundamental operations such as creating project space and starting new model files in correct types and units, software environment including work features (plan, axis, point, and UCS) and constraints, and 2D sketch as well as 3D modeling tools including extrude, revolve, sweep, loft, fillet/chamfer, emboss, rib, pattern, and mirror, etc. are discussed in detail in class. The goal is to modify the geometric features of the bulkhead so that the latest version BBB microcontroller can be installed on it without any interferences.

c) Bulkhead prototyping using AM methods

In this module, students are introduced to three different types of AM (also known as 3D printing) equipment: the Makerbot Replicator+¹⁴ based on Fused Deposition Modeling (FDM) technique, the Formlabs[®] Form2¹⁵ based on Stereolithography (SLA), and the Stratasys[®] Objet30 Pro¹⁶ based on Material Jetting (MJ) are introduced to students for building a prototype of the redesigned bulkhead. Fig. 3 shows the original bulkhead in the kit and the redesigned ones built using the three 3D printers and techniques. After the prototype of the redesigned bulkhead is made, students are required to complete the assembly and ensure that the MIP robot starts to balance.



Fig. 3 Original and 3D printed Bulkhead (from left: original, FDM, SLA, and MJ)

d) Wheel redesign and prototype

In this module, students are required to redesign a wheel with the restrictions that it will use the Pololu 60x8mm tire and still be able to be mounted on the existing driveshaft. Plastic injection-molding process and injection-molding mold design using the Autodesk Inventor are introduced, and students are required to design the injection-molding mold for their newly designed wheel. Fundamental concepts such as the equipment, process, and equipment, as well as the common practical design considerations such as location and type of gates, draft for de-molding, wall thickness, parting lines, and possible defects associated with the injection molding processes are discussed.

Since the process to build an injection-molding mold out of metals such as aluminum alloys requires precision machining that typically involves CNC machining, the High Temp Resin (HTR) for the Form 2 3D printer is used to build the mold prototype. The designed HTR working temperature up to 289⁰C makes it suitable for molding low melting temperature polymers such as the medium-and high-density Polyethylene (PE) (melting point typically in the range of 120⁰C to 180⁰C). Fig. 4 shows the original and Pololu 60x8mm wheel-tire assembly and Fig. 5 shows an example of the 3D model of a redesigned wheel, its mold for injection molding, and a 3D printed mold prototype.



Fig. 4 Original (left) and Pololu 60x8mm (right) wheel-tire assembly

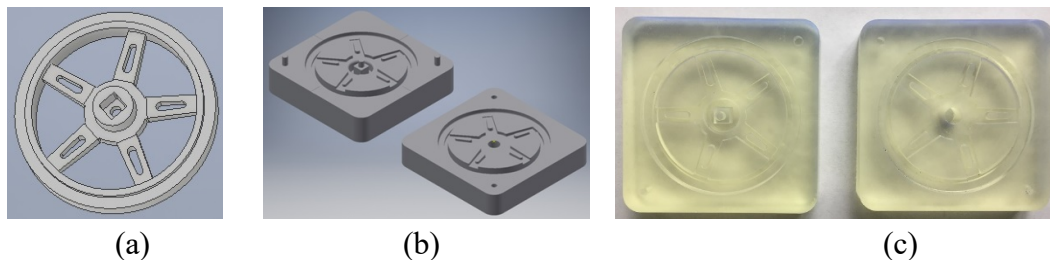


Fig. 5 Example of a redesigned (a)wheel, (b)mold design, (c)3D printed mold

e) Sand casting

Referring to common practice in industry and considering the HTR may not withstand the stress developed during the injection-molding process, a metal enclosure to hold and reinforce the HTR mold is required. In this module, students are introduced to the metal sand casting process including the design and fabrication of patterns, sand casting mold building, metal melting and pouring, and casting post-processing. Fundamental concepts

such as cope, drag, core, riser, runner, pouring cup, and downsprue, as well as practical design considerations such as the draft, thin wall features, and shrinkage during solidification and cooling processes, are also discussed. Students are required to design the pattern for the enclosure that will work with their injection-molding mold for the redesigned wheel. Due to time and resource limits, only one cast is performed, and Fig. 6 shows the 3D model for the enclosure pattern, sand casting mold, 3D printed enclosure pattern, and the casting out of aluminum alloy. Since the enclosure casting requires further precise milling, drilling, and tapping operations before it can be assembled with the 3D printed injection-molding mold, this course does not go beyond. Instead, a commercial aluminum mold and hand injection molding machine are used to demonstrate the plastic injection-molding process.

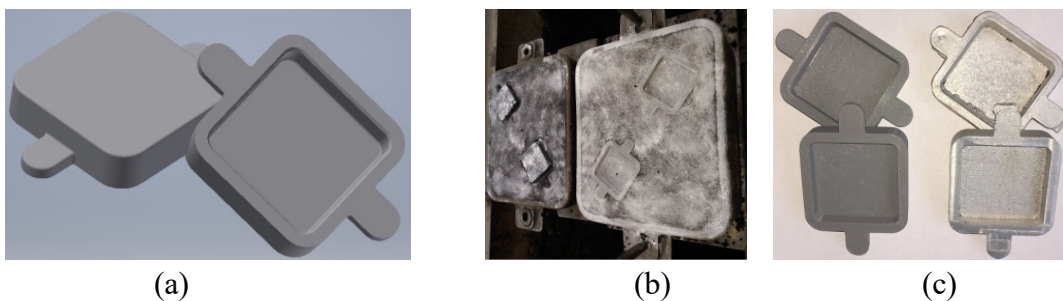


Fig. 6 Metal Enclosure (a) model, (b)FDM printed pattern and casting, (c) sand mold

f) Wheel prototyping using CAM/CNC technique

The last module of this course introduces students to basic CNC milling operations using the desktop NomadPro 883 CNC milling machine. Fundamental operations related to defining and setting up the NomadPro 883 such as motions along x, y, and z directions, tool height calibration, bulk material specification, defining a relative coordinate system and its origin, as well as tool specification, tool change, tool path design are discussed in detail. Equipped with this fundamental knowledge, students are required to design the toolpath and generate related G-code required to make their own redesigned wheels using the Carbide Create software. Subsequently, the G-code is loaded to the Carbide Motion software which controls the NomadPro 883 to build wheel prototype out of wood. Fig. 7 shows an example of a pair of redesigned wheels mounted with the Pololu tire and a MIP robot balancing with the new wheel and tire assembly.



Fig. 7 CNC milled redesigned wheel (left) & a MIP with the new wheels (right)

The Machining Technology Course

The Machining Technology course is developed as a follow-up of the introductory manufacturing process course for students with experiences in engineering design using CAD software and basic CAM design to develop CNC machining skills. Like the introductory course, this course is designed with an emphasis on skill development and the ability to apply knowledge to solve practical engineering and technology problems. It builds on the CAM knowledge students learned in the introductory course, and further develops students' CNC machining knowledge by providing a project-based LBD experience in which students use various tools such as caliper, micrometer, and height gauge etc. to measure the selected existing components of the DjuinoStar Stirling engine, to develop engineering drawings for these components, and then build these components using CNC machining and any other required processes such as drilling. The expected student outcomes are the following:

1. develop a competency to use various tools to complete tasks such as measuring dimensions using appropriate tools;
2. be able to create 3D models and develop engineering drawings for components ready for manufacturing;
3. acquire the skills to operate CNC machining equipment to build components including both milling and turning operations.

This course introduces students to basic CNC operations using the DjuinoStar Stirling engine as the platform. It engages students by requiring them to disassemble the engine to gain access to the support of the engine and the flywheel so that they can measure the dimensions of the two parts to develop both 3D models and engineering drawings for them. Fig. 8 shows a fully assembled DjuinoStar Stirling engine where the red arrow indicates the support and the blue arrow points at the flywheel.

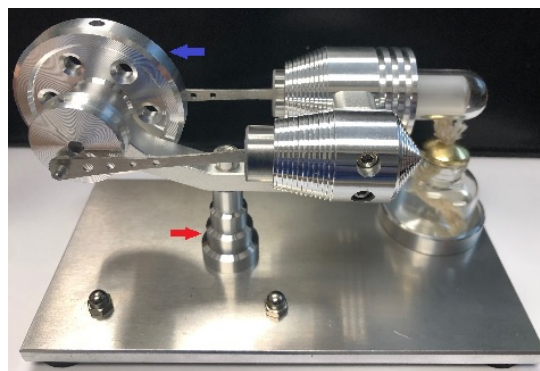


Fig. 8 A fully assembled DjuinoStar single cylinder hot air Stirling engine Basic turning operations such as facing and parallel turning are discussed based on the support, while milling operations such as face milling and plain milling are introduced based on the flywheel. The course materials are designed and organized into the following modules:

- a) measurement of the support and the flywheel
- b) 3D model and engineering drawing development
- c) CNC milling of the flywheel
- d) CNC turning of the support

a) Measurement of the support and the flywheel

This module discusses precision measuring tools commonly used by a machinist in a machine shop to make dimensional measurements. Students learn to operate these tools and develop hand sketches with all required dimensions for the support and the flywheel in the engine kit. The following common machine shop tools are discussed:

- Vernier caliper for measuring the external/internal diameter and depth
- Inside/outside caliper for measuring internal/external size
- Compass/divider for marking out location or measuring distance between locations
- Micrometer for high precision external size measurement
- Height gauge for measuring the height of an object
- Bore gauge including telescopic, small-hole, and beam gauges for various size diameter measurement
- Radius/fillet gauge for measuring the radius
- Tap and die set for making an internal and external thread

b) 3D model and engineering drawing development

Based on the measured dimensions and sketches developed, students are required to develop both the 3D models and engineering drawings for the support and the flywheel. Students are given the option to use their preferred software package to develop their models and drawings (the university provides access to both Inventor and SolidWorks CAD software packages). Fig. 9 shows the flywheel and its 3D model and Fig. 10 shows the engineering drawing for it that is developed using Inventor.

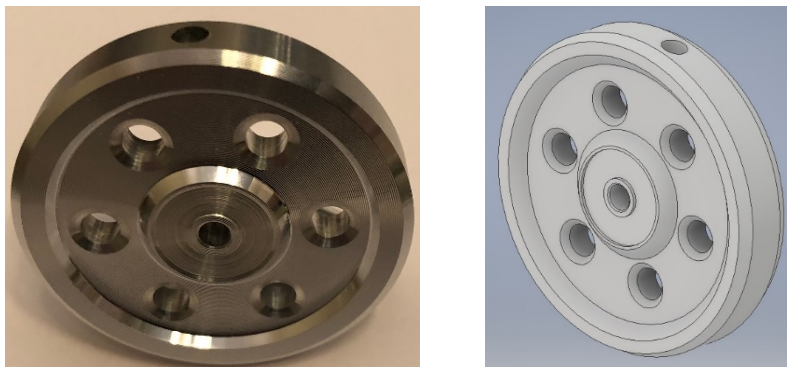


Fig. 9 Flywheel and its 3D model

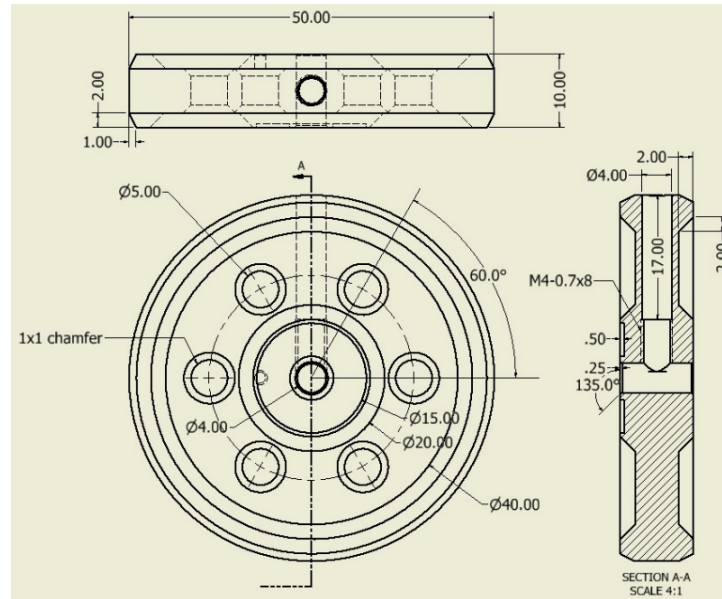


Fig. 10 Engineering drawing for the flywheel

c) CNC milling of the flywheel

This module focuses on the process of manufacturing the flywheel using a CNC milling machine. A drill press is also introduced to make the setscrew hole as shown in Fig. 10, and tapping is applied to make the setscrew thread. Students are also introduced to turning operations by using a manual lathe to make the chamfers on the flywheel. The following topics are discussed:

- Milling cutters such as flat/ball end cutter, shape-formed cutter, and V cutter
- Accessories such as a vise, feeler gauge, and 1-2-3 block
- Tool setup process
- Basic milling operations such as face milling, end milling, and side milling and offset directions including pocket, outside/right, inside/left, and no offset
- Carbide Create CAM system and basic of G-Code

Fig. 11 shows a toolpath design and simulated cut results (without the chamfers and setscrew hole) for the flywheel using the Carbide Create software.

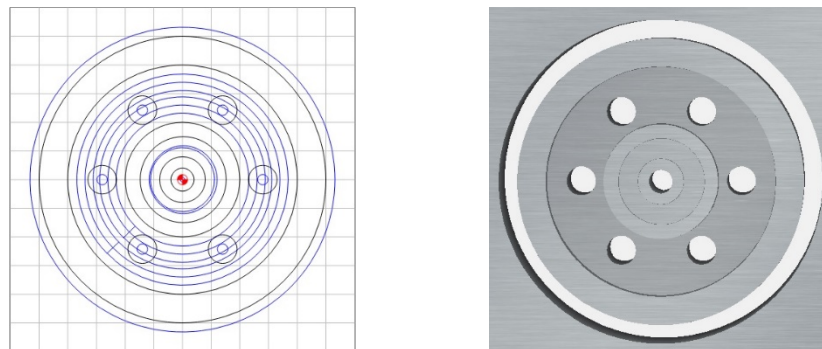


Fig. 11 Flywheel toolpath and simulated cut results

d) CNC turning of the support

This module is similar to that of module c) above with the goal to build the support using a CNC lathe. Turning tools such as facing tool, grooving tool, and parting tool as well as basic lathe operations are discussed in this module. Fig. 12 shows the support and the following five major turning operations required to make it.

- Facing off the top surface
- Drilling for the center hole
- The external turning of the four sections
- Tapering to create the chamfers
- Parting to cut the part off the stock



Fig. 12 Support, 3D model, and engineering drawing

Student Feedbacks

The Design and Prototyping course was offered to the first cohort of 11 students as a special topic in summer 2018. The student feedbacks are extremely positive with comments such as:

- *Great class! Best class that I have taken in my career. It is hands-on which helps with learning and being interested in the material presented.*
- *All the techniques we covered were very interesting. I would like to learn how to use all the machines available.*
- *This is a very engaging course, and I only wish it lasted longer. I enjoyed the team-based aspect of this course.*
- *I enjoyed getting to experience so many different techniques and machines that I have never been exposed to in the past. The course was a lot of fun and didn't always feel like work. My problem-solving skills have also greatly improved.*
- *I believe I took in a lot more information because we designed and prototyped which is a process that happens in the real world. I learn more by doing and working on projects.*

- *I truly enjoyed all the hands-on work we did. This would be an excellent freshman, introductory class. It gave me the opportunity to learn more about what goes into the design process.*

A progress self-assessment survey with the following questions was also given to this group of students.

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 skill 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

Fig. 13 shows the summary of the progress self-assessment results. Students reported a 100% ‘substantial progress’ or ‘exceptional progress’ on questions 1 to 5, 9, 11, and 13; a 91% ‘substantial progress’ or ‘exceptional progress’ and 9% ‘moderate progress’ on questions 6, 10, and 12; 82% ‘substantial progress’ or ‘exceptional progress’ and 18% ‘moderate progress’ on question 8 which addresses the oral presentation and writing skills. The authors will revisit the course materials to address the needs of students to develop these skills, particularly to develop creative capacities and express themselves orally.

Although the authors have not gotten a chance to offer the Manufacturing Technology course, they are planning to offer the Design and Prototyping course in summer 2019 and then follow up with the Manufacturing Technology in fall 2019. The instructors are designing a comprehensive assessment plan including a pre and after class survey and student self-assessment with the goal to systematically evaluate the effectiveness of these two courses.

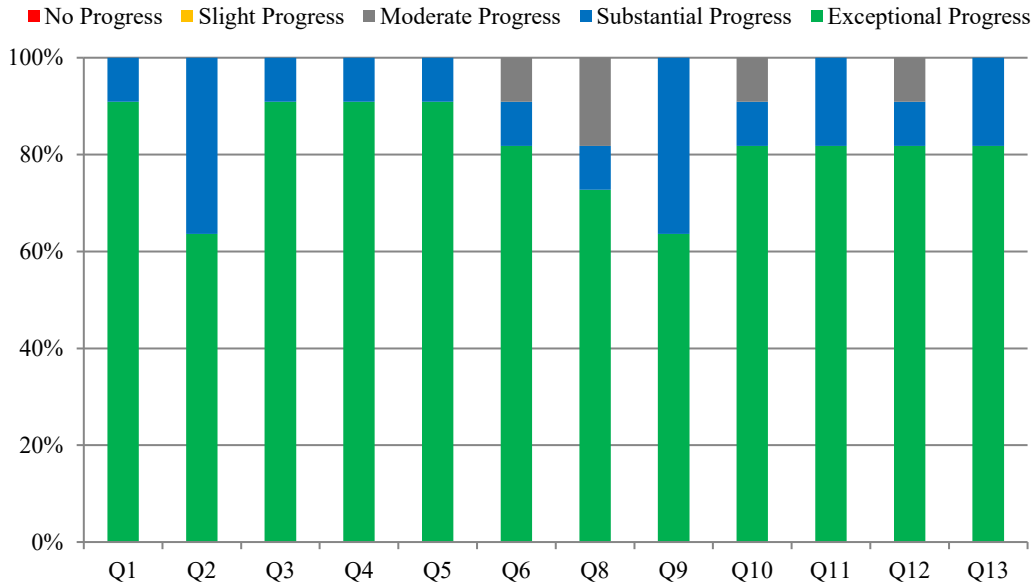


Fig. 13 Progress self-assessment survey results

Conclusions

Based on the MIP robot and the DjuinoStar Stirling engine educational platforms, the LBD pedagogical approach is successfully adapted to the design and development of two manufacturing courses - the introductory manufacturing processes course that exposes students to various processes and equipment used for design and prototype, and the advanced course which focuses on CNC machining including both milling and turning. Modules of course materials are successfully developed to involve engineering design and application of a knowledge of sciences, technology, engineering, and mathematics to solve authentic engineering and technology problems.

Feedbacks from students during the experimental offering of the introductory manufacturing processes course in summer 2018 show a high acceptance amongst students to this teaching approach and the way course materials are delivered. The feedbacks also indicate that the students have a better understanding of various manufacturing processes and show interest in advanced topics. Students also demand additional manufacturing processes such as laser processing should be incorporated into this course as well as offering this class as a regular semester course to allow more time for creative activities and development of both oral presentation and writing skills

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