

# Practice-Intensive Learning: An Effective Approach to Enhance the Fundamental Skills of PLC Beginners\*

ZHEN GAO, TOM WANYAMA and ISHWAR SINGH

W Booth School of Engineering Practice and Technology, Faculty of Engineering, McMaster University, Hamilton, Ontario, Canada.  
E-mail: gaozhen@mcmaster.ca, wanyama@mcmaster.ca, ishwar.singh@mohawkcollege.ca

Programmable logic controller (PLC) is an essential course for the students whose major are automaton related, since this course is highly connected to industry, and many other technical courses have a direct/indirect relationship with PLC. This paper is focused on thoroughly investigating the detailed contents and approaches to achieve the proposed paradigm called Practice-Intensive Learning. It provides a vision about how to re-design the PLC course to strengthen the theoretical knowledge and practical skills of beginners via hands-on and minds-on learning in all modules including interactive lectures, individual laboratories and innovative projects. The way about how to make the three modules fully integrated is also introduced. The evaluation results from the students and the peers have proven the effectiveness of the proposed method. Through the systematic integration of knowledge absorption, simulations, experiments and real-world implementation, beginners confidently and curiously stepped into the world of automaton by using PLC as an effective tool. The proposed methodology is also applicable for other technical courses in undergraduate and graduate levels.

**Keywords:** practice-intensive learning; hands-on and minds-on learning; integration of lecture and lab; PLC; process automation

## 1. Introduction

Modern industry especially the manufacturing sector is faced with revolutionary upgrading due to the global market competition, evolution of new technology such as Industry 4.0, and many other factors including environments, society, economics and political policy [1–5]. Automation technology as a solution to increase the reliability and continuous productivity has been widely applied in various manufacturing fields such as semiconductor, automotive, metal fabrication, and bio-manufacturing. PLC, as a flexible, reliable and stable technology, has been extensively adopted for process automation, and now it is a powerful tool for automation engineers, chemical engineers and manufacturing engineers [6–10].

PLC is an important course of automaton engineering and technology education. Taking the Process Automation stream in W Booth School of Engineering Practice and Technology at McMaster University as an example, PLC training is the backbone. There are at least five courses in this stream are PLC related who is taking the major role based on IEC 61131-3 standards [11, 12]. These five courses are PLCs and Automation I, PLCs and Automation II, SCADA II, Industrial Networks and Controllers, Advanced Systems Components and Integration, where PLC technology is covered from basic ladder logic, instructions, digital/analog control, communication, system integration, and industrial application. Many students who graduated from Process Automation stream were settled

with a PLC related job placement. Hence, designing and delivering an efficient PLC course is essential.

The major challenging of conventional PLC learning includes, (1) it is fast changing, (2) the system itself is comprehensive since it contains many modules that the beginners are not familiar with, and (3) it needs sufficient hands-on training, (4) class engagement.

*Definition Practice-Intensive Learning (PIL):* PIL as a proposed paradigm in this paper is a vision and approach about how to design/redesign a technical course to strengthen the fundamental skills of PLC beginners via hands-on and minds-on for all class delivering module, namely lectures, laboratories, case studies and mini-projects with the systematic integration of knowledge absorption, simulations, experiments and real-world implementation. As a PLC teaching scheme, PIL is to place the students in the center of active learning by reorganizing all the teaching modules in a way that can be efficiently delivered. Following figure illustrates the vision of PIL and the relationship of the knowledge, simulations and experiments of PLC training.

*Definition of Hands-On Minds-On:* as a PLC teaching philosophy, it is believed that knowledge is better understood by applying it in real-world practice. Besides, the practical skills are enhanced by the comprehension of the theory.

Specific examples will be given to elaborate the proposed paradigm. Since PLC is manufactured by various vendors, the students should be capable of transferring what they learnt to other PLC equipment. Thus, the instructor is expected to list out the

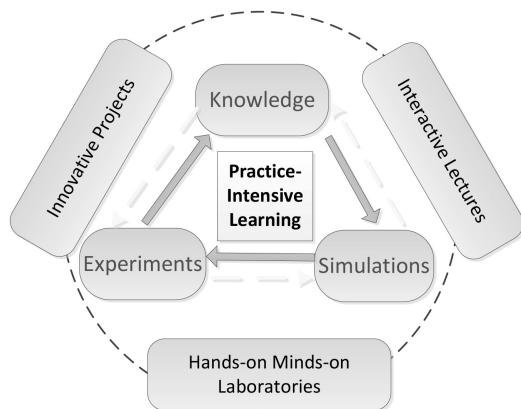


Fig. 1. The vision of practice intensive learning.

difference and similarity among PLC provided by companies. Eventually, the students will not only figure out the differences between two PLC types, but also know how to conduct the programming based on other similar systems.

To achieve the objective of Practice-Intensive Learning, PLC simulator is recommended to deploy since students can be exposed the maximized opportunity of a similar programming environment. It also functions well as a bridge between theory and practice. Through this, the lecture and the labs are fully integrated to reach optimal effectiveness. These simulations stimulate their passion and motivation by applying gained skills to address real-world issues. Besides, the students as future automation engineers are problem solvers as well. She/he should not only follow instructions but also can define an engineering problem, envision the design process and propose the alternative approaches, and also be capable to decompose and integrate the automatic systems. Therefore, how to provide the students with meaningful and insightful projects is as essential as the projects themselves.

The basic information about the course is added as follows:

- Hours of classroom instruction: 36.
- Hours of laboratory: 39.
- Text used: lecture notes.
- Student level: the 2nd year student.
- Years taught: 3 years.
- Student background/specialization: Process automation technology.
- Full grading scheme:
  - Lab Reports: 10%.
  - Lab Mid-term Test: 10%.
  - Lab Final Exam: 20%.
  - Quizzes/Assignments: 5%.
  - Midterm Test: 15%.
  - Final examination (tests cumulative knowledge): 40%.

The overall goal of this course is to offer the fundamental theory and practice of Programmable Logic Controllers. The students will understand and gain the skills of PLC programming at an introductory level including PLC addressing, components, I/O modules, basic instructions, timers, counters, math and compare instructions, program control instructions and sequential process control.

These materials will serve to establish a foundation for the balance of the course that will consist of an in-depth study of PLC programming. It put more emphasis on the hands-on labs and project in which way the students is able to create and run programs based on RSLogix 5000 to solve industrial control issues including process control and motion control.

The overall objective of this course is given as follows:

1. Understand the relationship between digital logic and industrial process control.
2. Solve industrial process problems using standard relay ladder logic.
3. Understand the structure of the Allen-Bradley line of PLC-5000 systems.
4. Design basic and advanced PLC programs using timers, counters, math, compare and messaging instructions.
5. Solve sequential problems.
6. Understand the relationship between digital logic and industrial process control.
7. Solve real-world problem based on PLC independently.

## 2. Transferability of PLC programming skill

Different with generally purpose languages such as C++, Python, Java and many others, PLC programming follows the IEC 61131-3 standard. Underneath this standard, PLC vendors can use at least 5 ways for various programmable controllers. These methods include ladder diagram, function block diagram, structured text, instruction list, and sequential function chart [13–15], in which ladder diagram is the main technique that were widely accepted by many PLC manufacturers such as Siemens, Omron, Rockwell Automation, Eaton, and Automation Direct.

The ideal way is to let the students be exposed in different PLC programming environments; thus, they can compare and transfer the programming skills based on firsthand experience. However, due to the limitations of resources in most educational institutes, it is probably impossible to provide the students extra and expensive PLC equipment only for enhancing their experience transferring skills, e.g., transfer from Allen Bradley PLC programming

to Siemens PLC programming. In this scenario, PLC emulators and simulators are great options to make the students exposed to various programming environments.

As a matter of fact, the working principles of different PLC equipment are quite close to each other since most of them follow the standard of ladder diagram which will not be changed for a while. Besides, the instructor is responsible to make the beginners be aware of the similarities and differences of the current PLC devices. Through the learning of the first PLC course, the students should gain the capability to self-learn other PLCs which cannot be covered in a single course in a quick manner.

Hypothetically, if the students cannot imagine the differences between PLC, setting up a live demonstration in the classroom is a choice when solving the same problem with different PLCs. For example, following problem was defined and addressed based on Eaton PLC rather than the Allen Bradley PLC.

1. For the first time to turn on the RED pilot light, you need to press and hold the Red Button for more than 5 seconds. For the following times, you just need to press and release immediately when the PLC is powered.
2. For the first time to turn on the Green pilot light, you need to put the switch in the left

position, and press and release the Green Button for 3 times. For the following times you just need to put the switch in the left position to turn the green light on.

3. When the green light is on, the relay is on simultaneously.
4. Press the E-Stop to turn off the red light.
5. Put the switch to the right position to turn off the green light and relay.
6. If you press the E-Stop for more than 10 times, the white light will be turned on and it stays on.

Eaton PLC is quite unique compared with other PLCs. Traditionally, modules such as digital input, digital output, analog input, analog output and comminution modules stand beside the CPU module separately.

However, Eaton PLC integrates I/O modules with a ribbon cable based on the SmartWire-DT Technology. The addresses of these I/O modules including position switches, pushbuttons, contactors, protectors, emergency button and pilots are connected in an order on the cable. The configuration and the network layout are conducted by using easySoft-Pro software.

Finally, the ladder diagram to solve the aforementioned problem was shown in the classroom thus the students observed the similarity and difference between Allen Bradley PLC and Eaton PLC, as displayed in Fig. 2. In order to show the students

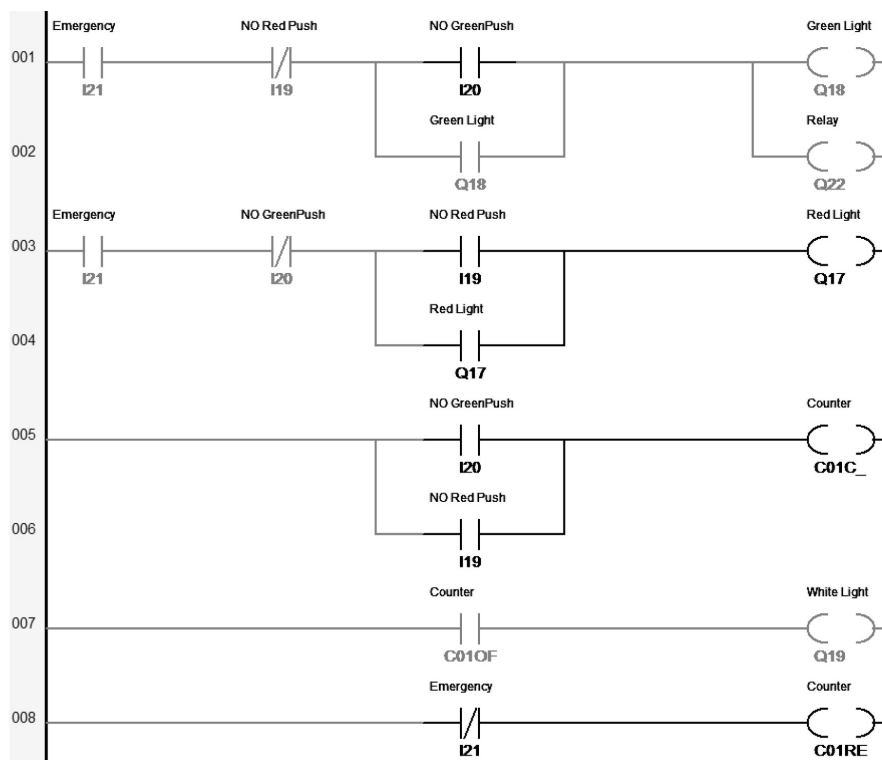


Fig. 2. Energization of input and output of sample diagram.

how the Eaton PLC program works, the red button and green button on the Eaton PLC board were pressed for more than 5 times, then it could be observed that white light on the board was turned on. Besides, it was explained in highlighted part in the diagram. The relationship of logic flow and energization of input/output were also explained.

In the laboratory section, the Allen Bradley PLC 5000 was employed. While in the lecture section, in order to make the students be engaged in different programming environments, LogixPro, an emulator of Allen Bradley PLC5 was used in the classroom. Thus, the characteristics of them were explained and compared.

For example:

LogixPro: I:5/0 is equivalent to RSLogix5000:  
Local:5:I.Data.0.

LogixPro: O:6/4 is equivalent to RSLogix5000:  
Local:6:O.Data.4.

Besides, in LogixPro the relative data types should be utilized to generate a Timer or Counter. However, in Allen Bradley PLC 5000 it is conveniently created by defining the data type and by applying the tag names. By practicing both in the real laboratory and on the simulator, the students not only sense the differences between them, but also know how to transfer programming skills to other systems.

### 3. Practice-intensive for lecture module

For lecture module, PowerPoint (PPT) as traditional but effective approach combined with programming practice on PLC emulator was conducted inside and outside the classroom [16–19]. PPT together with the white board, black board and handout sheets were used to introduce the key knowledge points. The PLC emulator was purchased and installed on the desktop of the classroom podium. The emulator was utilized frequently when introducing new instructions and conducting case studies. Many students purchased the license of this emulator and installed it on their laptops. When they attended the lectures, some of them used the emulator to reinforce what they were learning in the classroom.

The week-by-week in-class activities are provided as follows:

*Week 1.* Introduction to logic and industrial automation concepts.

*Week 2.* Relay ladder logic and motor control.

*Week 3.* Introduction to the RsLogix and PLC-5000.

*Week 4.* PLC Addressing, I/O modules.

*Week 5.* Wiring and basic programming.

*Week 6.* Timers and applications.

*Week 7.* Counters and applications.

*Week 8.* Math instructions and applications.

*Week 9.* Compare instructions and applications.

*Week 10.* Program control instructions.

*Week 11.* Sequential process control.

*Week 12.* Industrial applications of PLC.

As a course for PLC beginners, typically the instructor would like to focus on explaining the working principle of different types of relays at the beginning. This newly designed course did not begin with too much of this. Instead, more emphasis was put on the logic, programming and problem design. The students understood the functionality of relay and advantages of PLC compared with traditional relay circuit via doing the related experiment in the beginning, i.e. in lab 2 after they finished the lab of circuits based on logic gates. Fig. 3 shows the sample diagrams of ladder logic which were developed to achieve the basic function to start, stop and maintain a relay coil by using the internal contact, namely ‘hardware seal’, or without internal contact of a relay, namely ‘software seal’. By doing so, the students could well understand the functionality and working principle of internal contacts from the relay chassis. Through the comparison lab of ‘software seal’ and ‘hardware seal’, most of them could deeply comprehend why manufacturing and automaton industry adopted PLC instead of relays. Besides, it also helped them understand how PLC program worked.

For advanced math instructions like TOD and FRD, the instructor tried to use diagram to explain. Taking the TOD instruction as an example, they knew it meant the data was converted from decimal value to a binary coded decimal value. These two diagrams, as shown in Figs. 4 and 5, explained the working principle and sample application of TOD, and physical wiring to send data from output card to 7-segment display via TOD instruction.

A simulator named LogixPro was frequently adopted in the process of lecture delivery to help connect theory to practice by serving as a bridge between them. By using a simulator, first of all, simulation became possible and available for any student if wanted to have extra training on PLC programming and case study. The students can download the simulator for 15 days’ free use. Due the slight difference of the simulator and the real PLC, the emulator is also employed in the classroom when discussing the applications of specific instructions. There are many self-carried projects in the simulator that the students can work on it to enhance the hands-on and minds-on capability. After a few attempts by the students, they have no problems to deal with the difference among various

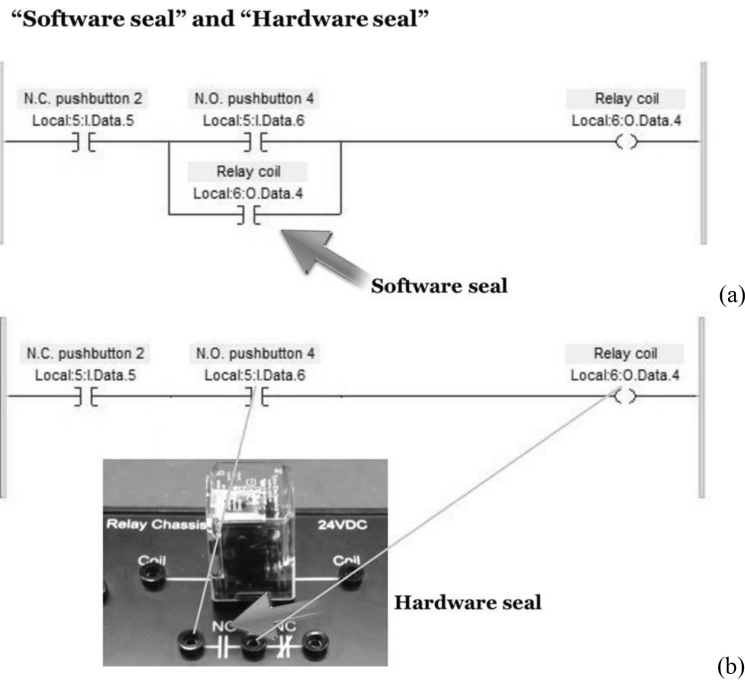


Fig. 3. Concepts of ‘software seal’ and ‘hardware seal’; (a) without internal contact, (b) with internal contact.

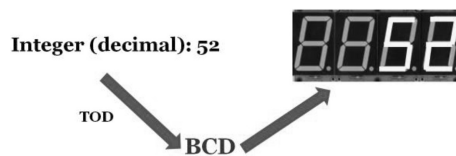


Fig. 4. Working principle and sample application of TOD.

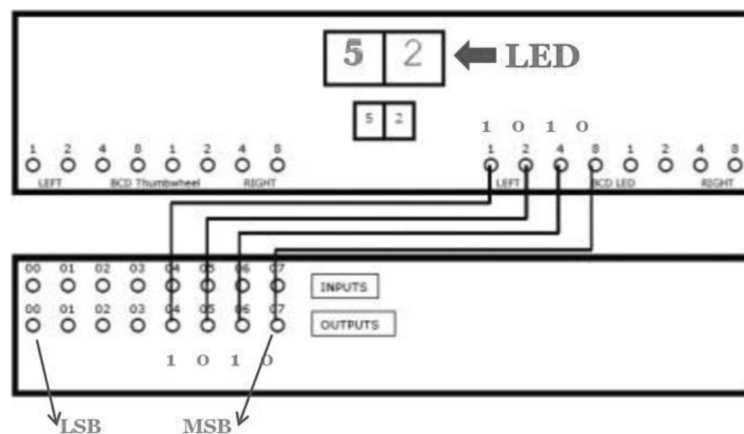


Fig. 5. Physical wiring to send data from output card to 7-segment display via TOD instruction.

PLC programming tools. The simulator functions similarly as a real PLC device except that it could not handle/produce the physical I/O signals. However, students could deal with the physical I/O signals in all the lab hours. Thus, this minor issue does not affect the function and role as a simulator. Besides, the license of the simulator is affordable for every student if it was treated as a textbook. Inside of the simulator, it carries sufficient real-world

application scenarios which could simulate the students’ learning interests. These real-world applications include but not limited to garage door opening, traffic light control, process control, elevator control, product line control and so on. Through exercising on these virtual scenarios, the students obtained some sense about how to apply the PLC skills in industry. Eventually, with the integration of simulation, labs and projects, their

PLC learning experience can be directly applied in industry.

Test is always an irreplaceable part for PLC training. Sample question of final exam:

“Imagine Robert is a research and develop engineer of Boston Dynamics. He had two autonomous mobile robots in his basement. He designed a PLC based remote controlling system with pushbuttons on the wall to engage and shut down the robots. Each robot has its own start pushbutton, but they have the same stop pushbutton. Due to limited space, Robert cannot run the two droids simultaneously. (Note the communication between remote PLC and local controller of robot is not the focus of this problem)”

This problem actually examined whether the students could apply the appropriate interlocking function to solve a real-world problem using PLC.

#### 4. Hands-on minds-on laboratories

Laboratory section is essential for PLC course because this is the most effective way to enhance the students' programming skills of PLC. For any undergraduate technical courses at W Booth School of Engineering Practice and Technology of McMaster University, normally attending laboratory is mandatory. For those students who did not regularly attend the lab and did not perform the lab in person, their final grades would be either very low or they could not pass the course. Thus, lab portion is a great indicator to observe the students' real performance of PLC learning. Following record shows the final grade range of PLC class in the semester of winter 2017.

Number of students = 52.

Overall mean grade percentage = 70.3%.

Overall median grade percentage = 72.8%.

Number of As (equal or greater than 80%) = 17.

Number of Bs (in between 70% and 79%) = 12.

Number of Cs (in between 60% and 69%) = 10.

Number of Ds (in between 50% and 59%) = 10.

Number of Fs (below 50%) = 3.

For the students who failed the course, all of them failed the lab portion. There were five students who received A+, namely 90% overall, and four of them received 95% or above in the lab portion. This proved the lab part was critical for PLC learning. Thus, how to design effective lab manual and how to make the students engage in the lab work is essential for the successful delivery of this course. There are totally 8 labs for this course. They are listed as follows.

*Lab 1.* Safety, Lab Intro and Digital Logic (This lab provides students with an introduction to problem solving using digital logic fundamentals. Lab safety protocols are also discussed).

*Lab 2.* Simple Relay Logic Circuits (This lab provides students with an introduction to relay logic fundamentals with hands-on experience in the design and wiring of simple relay logic circuits).

*Lab 3.* Introduction to the Allen-Bradley PLC-5000 (This lab is about how to correctly setup, connect and startup the PLC hardware, and how to edit PLC logic using basic programming instructions).

*Lab 4.* Motor Control Logic Basics and Reversing Motors (This lab is about how to translate word problem descriptions and schematics into PLC ladder logic programs, and how to examine the applications of the PLC logic Forcing function).

*Lab 5.* PLC Time Delay Functions (This lab is about how to generate time delays using the Timer function, and how to use of data monitor screens).

*Lab 6.* Traffic Light Control (The students develop and test programs utilizing PLC instructions up to comparison instructions).

*Lab 7.* PLC Adjustable Time Delay and Counter Functions (This lab is to let the student get familiar with the application of the combination of time delay and counter functions).

*Lab 8.* Digital Clock and Traffic Light Control (As the final lab, the students develop and test programs utilizing PLC Timer and Counter functions. They also use 7-segment LED displays to indicate related values from the timer and/or counter. Finally, they use program control instructions for conditional execution of a set of rungs).

With the great investment from the school for PLC education, there are 20 Allen Bradly PLC lab stations to maximally accommodate 20 students per lab section. Without professional PLC programming skill as a beginner, one can barely contribute in a big team on technical aspect. Therefore, the students were highly encouraged to conduct all the labs from the beginning to the end individually. Eventually, with the constant encouragement from the lab instructor of PLC, almost every student who attended the lab would like to perform the lab in person. Besides, because for a programming problem of PLC the answer is not limited to one, the beginners were suggested to creatively design and solve a given programming problem based on their own experiences and thoughts. If the students would like to search for a novel solution but could not finish it with the assistance or hint from the lab instructor, the lab instructor should approach the student and have a brain storming with the student to help dig out the interesting solution. On the other side, the students were also recommended to seek alternative solution or optimal solution. By doing

so, bonus mark could be added for their initiative work. Besides, the lab module and lecture module were mixed and coupled, which means in the lecture module, the instructor explored further about the most recently lab work and guided the students to analysis the lab problem in a deeper manner. Sometimes, the given problem in the lab would be re-designed in the lecture module so that the students were requested to solve it with the emulator in the classroom. Through this way, the idea of hands-on and minds-on learning would be fully integrated and conducted to achieve the optimal teaching and learning effectiveness.

This integration can also be realized in the other approach. For example, when the new instructions or functions were delivered and covered in the lecture module, in the forthcoming lab, the students utilized what they just learnt about the new instructions or functions to conduct the lab. Thus, the theoretical knowledge points were well absorbed by the students via performing the lab. Although lecture module was not mandatory, for the students who regularly attended the classes, they usually did better than those who did not attend the class regularly because of the fully integration of lab and lecture. That is the main reason why the developed experiments in this course are hands-on and minds-on.

For example, to solidify their understanding of the Timer concept, Traffic Light Control lab was designed. The students were requested to develop a ladder diagram to control repeat time sequence using either pilot light or light stack if the lab instructor provides some assistance on DeviceNet.

The students were asked to add a toggle switch as an external input. Once the toggle switch was turned on, a pedestrian signal would be automatically added into the sequence of operation. This pedestrian signal works in the following way: once a green light in one direction is on, a pedestrian light in that direction will be illuminated for a certain number of seconds then automatically off. Once the toggle switch is turned off, the program functions without pedestrian signal. Such kind of lab problem can well integrate the lecture portion and lab portion. Besides, the students enjoyed the process of 3 hours experiments per week. The instructor designed a motto for this course called as “Learn by curiosity, learn for innovation, and learn by thinking and doing”. According to the class observation and feedback from students and colleagues, the students actually did what the instructor expected in the motto.

The instructor should collect and analysis all the problems that rose in the lab portion and then discuss/address these common problems either in the next lecture hour or lab hour. The students were

suggested to do the prelab based on the emulator. When they tried to solve the problem in the emulator, they were expected to dig the problem deeply by individual work and team work.

Typically, for the lab report, there are three parts, namely the prelab, the ladder logic program, and the discussion. As said in the above paragraph, prelab was conducted in the emulator; however, the ladder logic program is based on RsLogix 5000. During this process, the students can comprehend the program skills at least in two PLC languages.

In addition to perform the ladder diagram programming in the emulator and the real PLC equipment, each student was requested to write the detailed technical discussion after completing each lab. There are several reasons by doing so:

*Reason 1.* It helps them recall what they exactly did in the lab to improve the experience.

*Reason 2.* It consolidates their technical writing skills in the aspect of PLC.

*Reason 3.* The discussion part itself serves well as the extension of the rung comments, through which the lab instructor can see what they thought when performing the lab to help improve the lab quality in the future course development process.

## 5. Discussion of innovative projects and advanced experiments

Conducting individual or group based projects for technical courses is an efficient approach to engage the students utilizing the absorbed knowledge and skills to figure out some real world problems [20–24]. The main mission of engineering technology education is to pass the fundamental and cutting-edge technology in a systematic way to the youth generation. Thus, only imparting/conveying knowledge is not sufficient. The students should comprehend the materials of different courses and understand their relationships. They should be able to discover and define a problem in a systematic way. They also need to have a clear and vivid understanding of the design process of a complicated project as well as the related characteristics which affect the process. They should be able to build the model of the system and understand its input and output. The logical relationship between input and output should be analyzed and determined. Besides, they need to understand how to decompose a project into several sub-tasks and then how to integrate those subcomponents. Therefore, the way that assigns the students valuable, interesting, real-life applicable or industrial applicable projects is paramount. In the following sections, four types of PLC projects that were assigned to the students will be discussed here.

### 5.1 Open ended project

The purpose of open ended project is to energize the students' imagination potentials and capabilities. Besides, in most test modules such as quizzes, assignments, lab tests and written tests, the students are always requested to analysis and solve the pre-designed questions. They may well answer those traditional questions. However, engineering technology education in universities normally did not teach imagination. This ignored problem would probably be carried to their upper years studies and affect their future careers. Obviously, the teaching and learning process without the participation of imagination leaves a significant drawback, which makes the students have less psychological motivation and passion to explore a problem spontaneously. It can be anticipated that if the students are accustomed to the instruction-following learning style, their self-carried original motivation and enthusiasm will probably be slowly reduced and finally removed. Therefore, first project is all about imagination based free design. The students were highly recommended to open mind widely to discover and define a problem with the language of PLC. During this process, everything was conducted and implemented by the students themselves from the beginning to the end. They used either the emulator or the real PLC device to finally solve an open-ended engineering problem that they defined.

Open ended project could be conducted either individually or by a group of two students. Typically, in each open ended project, it contains following events.

*Event 1.* Explore and discover a technical related real-life problem or industrial problem.

*Event 2.* Analysis the feasibility to address this problem by PLC.

*Event 3.* Populate the general plan to solve the problem by PLC. Then make a plan as detailed as possible.

*Event 4.* Build the model of the system and find out all the necessary inputs and outputs.

*Event 5.* Conduct deep investigation of the implementation process and thoroughly discuss the results.

*Event 6.* Try to figure out any alternative solution and then fulfill the performance comparison between different methods.

Although this course is about training of PLC beginners, they were treated as responsible and independent engineers. Therefore, they should at least have some sense about discovery, definition, system decomposition and integration, and accomplishment of an engineering problem in a professional way. The students should get systematical

and sufficient training of engineering design abilities throughout many technical courses while not only rely on the functionality and objective of capstone course.

### 5.2 Entry level project

Entry Level Project is a mini project which can be treated as the extension of a 3 hours lab work. Mini project was used to enhance the students PLC programming skill outside of the classroom. Since lab work is very important during the 3 months' PLC study and lab hours are quite limited—3 hours once per week for 8 weeks. Mini project could be assigned to each student as home work to be finished in a week. In this way, it is expected that every week each student can spend at least 6 hours on PLC programming to largely improve their experiences. What kind of mini project can be designed and assigned to the PLC beginners? An example in this level is provided as follows.

Develop a digital clock as a new program. The clock should function as follows:

- A user must be able to enter the current time in hours, minutes and seconds by using the thumbwheels and a set of toggle switches. Limits must be implemented in the program so that only valid entries are accepted (up to 23 hours 59 minutes and 59 seconds).
- As the user enters the values, they must also be able to see their current entries on the 7-segment LED display.
- The clock should only start timing when an 'ON/OFF' toggle switch is activated.
- The user must be able to switch between displaying the current hours, minutes and seconds by using a set of toggle switches while the clock is running.
- While the clock is running, the thumbwheels should *not* be able to change the time.
- The time can only be changed when the 'ON/OFF' toggle switch is in the 'OFF' position.
- Also include a toggle switch that allows the hours to be displayed in 24-hour format or in 12-hour format (AM/PM). If the toggle switch is off, it should be in 24-hour format, otherwise if the toggle switch is on, the hours should be changed to 12-hour format and a light should indicate AM (light off) or PM (light on). Note: This will affect the user input system, so you will need to add the format toggle switch to the input system rungs as well. Following simulator, as shown in Fig. 6, can be used for this project.

This project involves the basic instructions such as Timer, Counter and comparison ones. Every student in the PLC class is expected to conduct such kind of project alone.



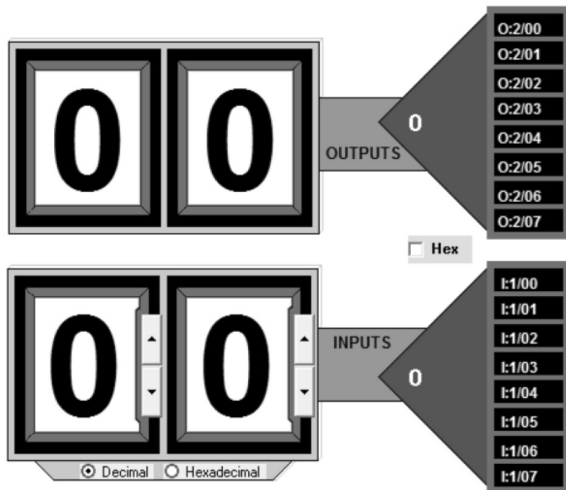


Fig. 6. BCD I/O simulator [in courtesy of TheLeaningPit].

### 5.3 Intermediate level project

Intermediate Level Project could be designed as the course project for group of 3 students. In course project, PLC serves as the major component to drive a controlling system. First of all, it should have user interface which monitors and visualizes the controlling system where PLC serves as the major controller. PLC handles the digital and analog input/output. PLC talks with the sensors and actuators based on these I/O modules with or without interface. Sensors and actuators are associated with the mechanical system. This is the basic structure of a PLC related automation systems from the hardware point of view.

Here, an example of course project about warehouse automation, as shown in following figure, is provided. This automated warehouse project is to provide a robust and interchangeable solution for any current warehouse layout. It is used with the most popular existing PLC's, including ABB, Omron, Siemens, and more. This warehouse solution provides an easy approach to navigate web application, plug/play technology to ensure quick setup, and support for multiple robotic arms to reduce costs for companies which have already put some investment into an automated warehouse. The main function of PLC in this project has two aspects. The first aspect is to start and stop the mini conveyor based on the condition of the proximity sensor. The second aspect is to control the servo motors on a small scale robotic arm. This intermediate level project is doable by average student from PLC class.

### 5.4 High level project

High level project is for the excellent students in the class. Project in this level can be collaborated with

senior undergraduate students or graduate students. At the Process Automation stream in W Booth School of Engineering Practice and Technology at McMaster University, 2 or 3 talented students from the PLC class will be chosen to take part in the students' case competition of International Society of Automation at Calgary, Canada, every year. In this scenario, the instructor/supervisor could assign them some high level project to push them to the limit. Following is an example which is suitable as project in such level.

In this sample project, an autonomous system was designed and built that could be applied as a two degrees-of-freedom translational system. This machine could attempt to score against the opponent and defend against subsequent attempts to score on the robot's goal. A vision system was designed to track the direction of the puck in real time and extrapolate its movement by using two successive points of reference. Once the trajectory is determined, three DC stepper motors were used to control the end effector of the robot, using a belt driven system. The end effector could be positioned to a point that intersects with the disc's trajectory in order to successfully defend the goal. An HMI was developed to set up difficulty levels of game and to track the score. The wireless control method was integrated with mobile phone control add-on feature via the embedded gyroscope. Generally speaking, both PLC and microcontroller can be used in this project. Microcontroller handles the feed signal from the vision sensor, and the decision marking result could be sent to PLC to actuate three motors with proper speed and torque. Compared with projects in other levels, such kind of project is challenging but valuable to inspire the potential of the most talent students in a PLC class.

### 5.5 From PLC to automation

Automation system normally means the integration of electrical, mechanical and computing sub-systems. The nature of automation technology is comprehensive and interdisciplinary since it involves the seamless collaboration and integration of the aforementioned components.

When designing an automation projects, the students are required to decompose and breakdown the entire system into at least two sub-entities, namely the hardware part and the software part. The hardware part typically includes mechanical body, sensors, actuators, controllers, circuits, human-machine interface tool, component to component interface tool, communication tool/accessory, and power supply component. Here, PLCs were frequently used to design an automation project or to perform the labs of other high level technical courses.

The design of software part should also be decomposed into several levels, such as signal acquisition/conditioning, algorithm design in many scenarios, data analysis and decision making, design of HMI, and design of action taking approach (e.g., command for actuators). It is noticeable that for automation engineering, software design usually is neither independent nor standing alone, because in order to make automation system functional, software must be tailored to meet the various requirements of hardware components in different levels. From this point of view, the implementation of software design process should consider the hardware requirements, conditions, and specifications. Vice versa, when considering designing the hardware, software part should be carefully considered as well, since without either part, an integrated automation system is impossible in most cases. This design paradigm is called “design for automation”. To achieve this goal, there are many control and automation courses were offered at W Booth School of Engineering Practice and Technology of McMaster University. Taking the Process Automation stream as an example, it contains the following technical courses where PLC played an important role for each of them.

PROC TECH 2IC3 Instrumentation & Control.  
 PROC TECH 2PL3 PLCs and Automation 1.  
 PROC TECH 3CT3 Control Theory 1.  
 PROC TECH 3PL3 PLCs and Automation 2.  
 PROC TECH 3SC3 System Control and Data Acquisition 1.  
 PROC TECH 3MC3 Motion Control and Robotics.  
 PROC TECH 3SD3 System Control and Data Acquisition 2.  
 PROC TECH 4CT3 Control Theory 2.

PROC TECH 4IC3 Industrial Networks and Controllers.

Taking the Industrial Networks and Controllers course as an example, this course was offered for the year 4 students in the first semester. Although this course was focused on the fundamentals of communication and industrial networks as well as the theory and practice of implementing sensor, control, and plant level networks, it also covered the concepts of horizontal and vertical industrial systems integration which utilized PLC as the key part. This course has 8 labs and 6 of them are the labs based on different kinds of PLCs, which means the students have to carry their PLC experiences which they obtained from the previous PLC programming courses and also transfer their skills to smoothly conduct labs on new PLC devices and software. Click PLC and Productivity PLC were frequently used in this course for communication such as Modbus RTU, Modbus TCP and TCP/IP. For example, the students obtained the speed of the VFD and then the value was sent from one PLC to another using either Modbus RTU or TCP.

In addition to technical courses, for the capstone course in stream of Process Automation, PLC related systems were utilized often. Fig. 8 shows a XYZ coordinate system for process control. This system was used by many groups of students in previous years to design capstone projects. Basically, these projects were about manipulation and control of a scaled industrial process by PLC. The system contains a couple of robotic manipulators, and all of them were directly controlled through Allen Bradley PLC which they learnt previously.

From PLC to automated system, even with the decomposition of automation systems into the sub-components of hardware and software, the design process of such systems is still a complex task

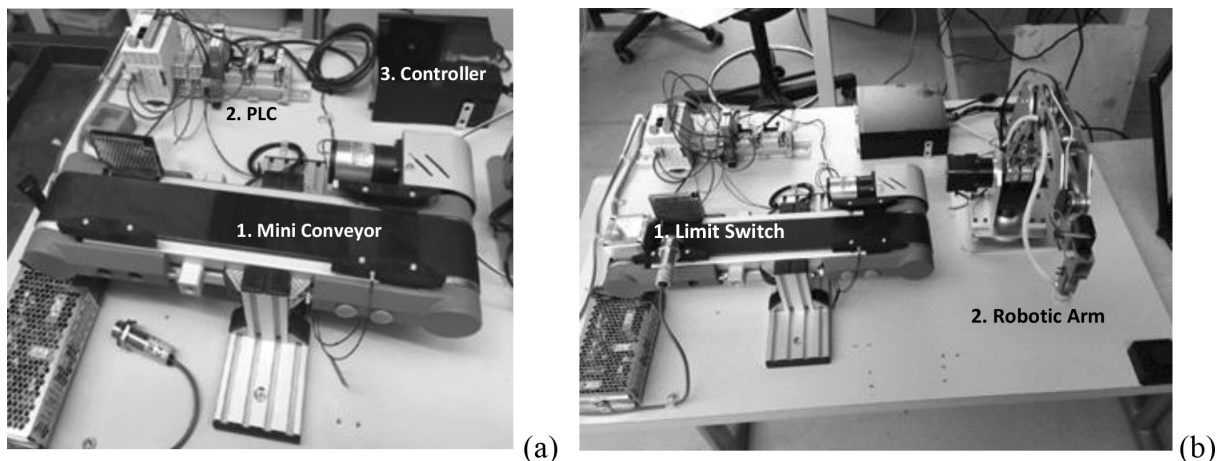


Fig. 7. PLC based automated warehouse project; (a) setup of the conveyor, (b) setup of the robotic arm.

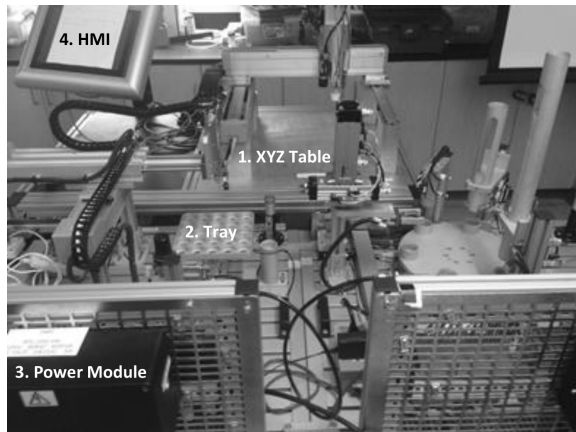


Fig. 8. XYZ coordinate system for process control.

especially if a robot in the system is not fully integrated with the PLC controlling systems. As shown in Fig. 9, when an industrial robot is used for complicated assembly work, the PLC can assist to handle the I/O and synchronize the conveyor.

Taking the SCARA robot for assembly as example, the scope of this PLC related capstone project involves developing a MELFA BASIC V program for a Mitsubishi RH-6FH-D robot to pick, place and maneuver several parts to construct basic linear pneumatic actuators. Various commands and types of motion are required to precisely align and fit the components together. Components including springs, nuts and bolts require additional consideration during assembly. A conveyor belt system which also includes a slot sensor and light stack is used to deliver each part in assembly. An Allen Bradley micrologix 800 series PLC is used to control the conveyer components and signal to the robot when a part is in position to be picked up. PLC programming is performed using Rockwell Automation's Connected Components Workbench

software. A specialized gripper needs to be designed and created to handle the various size parts, in addition to tool modules in order to tighten the nuts and bolts. Two different designs/sizes of actuators are targeted for assembly during this project to demonstrate versatility. The physical digital I/O connections need to be made between the PLC and the conveyer components. The PLC is wired to an I/O board to simplify making the connections. One of the PLC outputs is also wired to one of the robot's digital inputs. This allows the PLC to signify the robot that a part is ready to be picked up.

## 6. Course evaluation

Course evaluation is an indicator to check the teaching effectiveness [25–28]. At W Booth School of Engineering Practice and Technology of McMaster University, the course evaluation was based on three parts, namely a course was evaluated by students, colleagues, and program. The evaluation conducted by the students' has the most important weight. On the questionnaire for the Course Evaluation, the Q1 question checks the overall quality of the course.

The Q1 question and the students' input are given as follows:

*Overall for this course, what is your opinion of the effectiveness of the instructor?*

(Scale: 1 Very Poor to 10 Excellent)

1 student (2.17%) said: 5  
 1 student (2.17%) said: 6  
 2 students (4.35%) said: 7  
 6 students (13.04%) said: 8  
 7 students (15.22%) said: 9  
 29 students (63.04%) said: 10

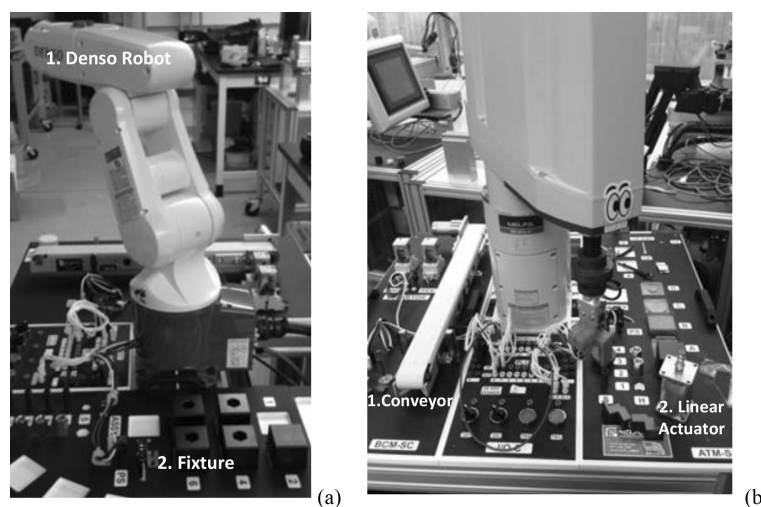


Fig. 9. Experimental setup of Denso robot, (a) Denso robot for assembly; (b) SCARA robot for assembly.

Students' comments about labs and projects are listed as follows:

"Feedback during labs helped us improve for next time.—Every aspect of the course was taught extremely well. I was given help whenever I needed it and labs and tests were graded very quickly so we could see what we did wrong before the next test or lab."

"I love how the prof always encourages his students and how the lab portion of the course is 50% which is great since it is easier to do labs rather than lecture."

"I really liked the labs and found them interesting. Especially because we can see what we learn in class in the industry."

"The course is a perfect representation of what attracted me to this program in the first place hands on work with a solid base in theory. The emphasis on application is excellent."

Students' feedbacks about lectures are listed as follows:

"Prof was very motivational, always encouraged everyone to try their best and helped as much as he could."

"Direct application of lecture to lab is very beneficial."

"Everything, unique teaching style. Very different from others."

"The in class examples were helpful when completing the labs Practice labs were helpful"

"The in-class demonstrations of the PLC code and uses and applications of the PLC code."

"The quizzes were helpful to see how well you knew the material and should be continued"

The overall comments from the students are listed as follows:

"This entire course was very valuable. PLC's were taught in an effective way and I have learned a lot. Great class."

"Great Instructor. Very approachable and easy to talk to. Very helpful. Easily one of my favorite courses and favorite instructors that I have had in my undergrad so far."

"The prof is very interested in the topic and wants to make sure everyone understands the material. He is always encouraging students to keep practicing and he does his best to explain any unfamiliar topics. I look forward to having him as an instructor again in the future! Thanks for being you!"

"This instructor was very understanding and just an amazing person! The material was delivered well in the lecture and lab portions"

The results of peer review of this course is 4.65 (excellent = 5, very good = 4). Here, 'excellent' means 'exhibits target behavior consistently in a highly skilled manner'. 'Very good' means exhibits target behavior most of the time in an effective manner'.

## 7. Conclusions

This work thoroughly investigates every aspect of a newly designed PLC course which applied Practice-

Intensive Learning as a methodology to enhance the programming skills and project design skill of PLC beginners in an effective and efficient approach. This course put the emphasis on the hands-on and minds-on learning through the fully integration of all learning modules including interactive lectures, individual laboratory and innovative projects. For the future development of this course, to fully implement the idea of Practice-Intensive Learning, all of the labs have to be conducted individually. All the students have to purchase the PLC simulator and perform the entry level project individually as a mini project for homework. Besides, each group of 3 students will be considered to assign an intermediate course project based on the availability of more technical support. The teaching effectiveness of the designed course was verified by the evaluation results. The proposed methodology actually can be applied for other engineering and technology courses.

*Acknowledgements*—The authors would like to thank the great support and the instructors and students who helped improve the quality of this course based on the idea of Practice-Intensive Learning. The authors appreciate the valuable support from the administration and technical team of our department.

## References

1. E. Hofmann and M. Rüsç, Industry 4.0 and the current status as well as future prospects on logistics, *Computers in Industry*, **89**(8), 2017, pp. 23–34
2. N. C. Batista, R. Melício and V. M. F. Mendes, Services enabler architecture for smart grid and smart living services providers under industry 4.0, *Energy and Buildings*, **141**(4), 2017, pp. 16–27
3. T. H. Uhlemann, C. Lehmann and R. Steinhilper, The Digital Twin: Realizing the Cyber-Physical Production System for Industry 4.0, *Procedia CIRP*, **61**, 2017, pp. 335–340
4. D. Mourtzis, E. Vlachou and N. Milas, Industrial Big Data as a Result of IoT Adoption in Manufacturing, *Procedia CIRP*, **55**, 2016, pp. 290–295
5. D. Golightly, S. Sharples, H. Patel and S. Ratchev, Manufacturing in the cloud: A human factors perspective, *International Journal of Industrial Ergonomics*, **55**, 2016, pp. 12–21
6. A. Schumacher, S. Erol and W. Siñh, A Maturity Model for Assessing Industry 4.0 Readiness and Maturity of Manufacturing Enterprises, *Procedia CIRP*, **52**, 2016, pp. 161–166
7. A. L. Sangeetha, B. Naveenkumar, A. B. Ganesh and N. Bharathi, Experimental validation of PID based cascade control system through SCADA-PLC-OPC and internet architectures, *Measurement*, **45**(4), 2012, pp. 643–649
8. G. Gelen and M. Uzam, The synthesis and PLC implementation of hybrid modular supervisors for real time control of an experimental manufacturing system, *Journal of Manufacturing Systems*, **33**(4), 2014, pp. 535–550
9. S. Jung, J. Yoo and Y. Lee, A PLC platform-independent structural analysis on FBD programs for digital reactor protection systems, *Annals of Nuclear Energy*, **103**(5), 2017, pp. 454–469
10. S. Rösç and B. Vogel-Heuser, A Light-Weight Fault Injection Approach to Test Automated Production System PLC Software in Industrial Practice, *Control Engineering Practice*, **58**(1), 2017, pp. 12–23
11. P. Panchal, G. Mahesuria, R. Panchal, R. Patel, D. Sonara, D. Pitroda, H. Nimavat, V. Tanna and S. Pradhan, Upgradation in SCADA and PLC of existing LN2 control system

- for SST-1, *Fusion Engineering and Design*, **112**(11), 2016, pp. 883–887
12. M. Chmiel, J. Kulisz, R. Czerwinski, A. Krzyzyk, M. Rosol and P. Smolarek, An IEC 61131-3-based PLC implemented by means of an FPGA, *Microprocessors and Microsystems*, **44**(7), 2016, pp. 28–37
  13. Z. Wu, R. Sekar and S. Hsieh, Study of factors impacting remote diagnosis performance on a PLC based automated system, *Journal of Manufacturing Systems*, **33**(4), 2014, pp. 589–603
  14. E. R. Alphonsus and M. O. Abdullah, A review on the applications of programmable logic controllers (PLCs), *Renewable and Sustainable Energy Reviews*, **60**(7), 2016, pp. 1185–1205
  15. P. Mazur, M. Chmiel and R. Czerwinski, Central processing unit of IEC 61131-3-based PLC, *IFAC-PapersOnLine*, **49**(25), 2016, pp. 454–459
  16. C. A. Friesen, The Dietary Guidelines for Americans, *Journal of Nutrition Education and Behavior*, **48**(6), 2016, p. 432
  17. R. Nissi and E. Lehtinen, Negotiation of expertise and multifunctionality: PowerPoint presentations as interactional activity types in workplace meetings, *Language & Communication*, **48**(5), 2016, pp. 1–17
  18. A. Pate and S. Posey, Effects of applying multimedia design principles in PowerPoint lecture redesign, *Currents in Pharmacy Teaching and Learning*, **8**(2), 2016, pp. 235–239
  19. F.C. Hoh, Beyond the Bullet Points: Creating Memorable PowerPoint Presentations, *Pain Management Nursing*, **17**(2), 2016, p. 94
  20. J. Urquiza-Fuentes and Maximiliano Paredes-Velasco, Investigating the effect of realistic projects on students' motivation, the case of Human-Computer interaction course, *Computers in Human Behavior*, **72**(7), 2017, pp. 692–700
  21. E. Starkey, C. A. Toh and S. R. Miller, Abandoning creativity: The evolution of creative ideas in engineering design course projects, *Design Studies*, **47**(11), 2016, pp. 47–72
  22. S. W. Hong, D. Schaumann and Y. E. Kalay, Human behavior simulation in architectural design projects: An observational study in an academic course, *Computers, Environment and Urban Systems*, **60**(11), 2016, pp. 1–11
  23. C. García, Project-based Learning in Virtual Groups—Collaboration and Learning Outcomes in a Virtual Training Course for Teachers, *Procedia—Social and Behavioral Sciences*, **228**(7), 2016, pp. 100–105
  24. Y. T. Bergeon, V. Křivánek and J. Motsch, Proactive Teaching of Mechatronics in Master Courses – Project Case Study, *IFAC-PapersOnLine*, **49**(6), 2016, pp. 291–296
  25. D. Brossier, A. Bellot, F. Villedieu, L. Fazilleau, J. Brouard and B. Guillois, Implementation and assessment of a training course for residents in neonatology and pediatric emergency medicine, *Archives de Pédiatrie*, **24**(5), 2017, pp. 432–438
  26. D. Gorry, The impact of grade ceilings on student grades and course evaluations: Evidence from a policy change, *Economics of Education Review*, **56**(2), 2017, pp. 133–140
  27. B. Sharma, B. Steward, S. K. Ong and F. E. Miguez, Evaluation of teaching approach and student learning in a multidisciplinary sustainable engineering course, *Journal of Cleaner Production*, **142**(4), 2017, pp. 4032–4040
  28. T. Kifle and M. Alauddin, What determines students' perceptions in course evaluation rating in higher education? An econometric exploration, *Economic Analysis and Policy*, **52**(12), 2016, pp. 123–130

**Zhen Gao** is an assistant professor in the School of Engineering Practice and Technology (SEPT) at McMaster University which he joined in July 2014. He has published over 80 journal and conference papers, 1 book, and 4 book chapters in areas of robotics and control. Dr. Gao served as the Program Committee Member for World Congress on Intelligent Control and Automation, International Conference on Information and Automation, IEEE Conference on Robotics and Biomimetics, IEEE International Conference on Real-time Computing and Robotics, IEEE International Conference on Automation and Logistics, and International Conference on Intelligent Robotics and Applications, and IEEE Canadian Conference on Electrical and Computer Engineering. Recently, he was invited as a keynote speaker with the topic of 'Innovation of Education, Technology and Applications of Intelligent Machines and Robotics' in the International Conference of Robotics and Intelligent Equipment in 2017. He was also invited in the round table discussion about 'Frontier and Interdisciplinary Research with Machine Learning' in Global Machine Intelligence Summit in 2017. His current research interests include industrial controllers, advanced robotics and automation, artificial intelligence, neural network and pattern recognition. He serves as the Editor-in-Chief of International Journal of Intelligent Machines and Robotics; he is also the Editor-in-Chief of Journal of Robotic and Mechatronic Systems.

**Tom Wanyama** is an assistant professor in the School of Engineering Practice (SEPT) at McMaster University which he joined in May 2012. Wanyama has over 20 years of university teaching experience; teaching a wide range of undergraduate and post graduate courses, including: digital electronics and systems, electricity and magnetism, power electronics, power systems, electrical machines, microwave engineering, data communication and computer networks, software architecture, software design process and metrics, industrial networks and controllers, and software requirements and specification. Before joining SEPT, he led the team that developed, built and maintained packaging equipment for DuPont Canada at its Calgary distribution centre. At DuPont, he carried out simultaneous design of mechanical, electronic and software systems of packaging equipment (Nanomates, Fleximates, automated scales for the Form Fill and Seal (FFS) machines, and Tablemates). Moreover, he designed industrial Control Area Networks (CAN) based on TCP/IP, CsCAN, and Profinet. Wanyama has wide experience in the design and installation of electrical systems in commercial and industrial buildings, and he continues to consult in the area of packaging systems automation. His research work falls in three areas, namely: system composition and integration, use of artificial intelligence in systems control, monitoring and maintenance, and development computer based tools for personnel training.

**Ishwar Singh** is an adjunct professor in the School of Engineering Practice and Technology at McMaster University since 2010. Prior to that he was the founding Associate Director of the 4-year B.Tech programs, a joint venture between McMaster University & Mohawk College, programs and Chair of the process automation program within this stream. He coordinated the curriculum design, development and implementation of the process automation, automotive and vehicle technology program, and biotechnology programs in addition to his contribution for the establishment of the energy

engineering technology degree completion B.Tech program. Prior to these roles he was the Chair of several programs at Mohawk College, where he taught for more than 35 years and held many other positions as well. He has many publications to his credit and has done basic and applied research in many fields such organic chemistry, X-ray crystallography, educational technology, software development, process and manufacturing automation.