An Effective Learning Approach for Industrial Robot Programming

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Abstract

Programming an industrial robot by using a teach pendant is a tedious and time-consuming task that requires a considerable amount of work-related skills, robotics knowledge and experience. Robot applications design also requires a tremendous amount of programming skills and input/output controls to make them useful. Obviously, a good robot programmer is a key factor of successful robot applications. In order to teach manufacturing engineering technology (MET) students to program industrial robots, we propose an effective learning approach for industrial robot programming in our curriculum. Research indicates that the use of off-line programming (OLP) method for learning industrial robot programming has a positive impact on reducing the robotics lab programming time (Ex. only two robots are available for 20 students), reducing the downtime of equipment when programming new work pieces/variants, and accelerating programming complex paths. This paper describes the development of off-line programming method to help students learn industrial robot programming. The off-line programming method is based on examples from industry and illustrates several good robot program designs. Overall, The OLP method provides not only our students an excellent learning environment but also a powerful teaching tool for MET instructors. Our results indicate that the students have the following competence to: 1) study multiple scenarios of a robotic workcell before any decision is committed, 2) determine the cycle time for a sequence of manufacturing operations, 3) Use libraries of pre-defined high-level commands for certain types of robotic applications, 4) minimize production interruption and help meet flexible automation goals, and 5) ensure that a robotic system will do the functions that an end-user needs it to do. We also recognize that the students who understand both robotics hardware and offline programming (OLP) software in combination is a challenge for many other colleges and universities. Not many students are proficient at both, but our students are.

1. Introduction

Today's industries use various types of industrial robots to manufacture parts and products [1]. Many college students misunderstand what an industrial robot is. They confuse the terms automation, remote-controlled, and numerical-controlled. Obviously, the most generally accepted definition for the industrial robot in the United States has been published by the Robotics Industries Association (RIA) as follows [2]: An industrial robot can be defined as

"A programmable, multifunction manipulator designed to move materials, parts, tools or special devices through programmed motion for the performance of variety of tasks".

As new parts or new products are needed, industrial robots can be reprogrammed to build the parts or products required. This flexibility saves money because the equipment does not have to be discarded or rebuilt. In addition, it takes much less time to reprogram the same industrial robots than to install new ones. In the last twenty years, the advances in robot hardware and
software design have made it possible for bringing industrial robots into the classroom, especially for Manufacturing Engineering Technology (MET) students [4]. The introduction of industrial robots into MET program at Minnesota State University, Mankato (MnSU) not only has the opportunity to enhance students’ hands-on practices and real world experiences, but also motives them for pursuing advances research and education in robotic vision, simulation and offline programming. Actually, robot hands-on experience plays a key role in engineering education. It is an effective tool for student learning, as well as for encouraging participation in class learning and in research outside the classroom. In general, industrial robot programming subject can be integrated with the MET curriculum in three different ways: (1) for manufacturing automation class that is specifically designed to teach students how to program different industrial robots; (2) for Computer Integrated Manufacturing (CIM) class that is designed to teach students how to integrate industrial robots into a production system; (3) for advanced level programming classes or other specific topics such as robotic simulation, and OLP, where robotic projects can be used to facilitate real world experience for the students and motivate their interests in the various topics. Offline programming is the technique of generating a robot program with using a real robot machine. This OLP method presents many advantages over the on-line method (Physically use a robot teach pendant to generate a robot program): (1) robot programs are generated without interruptions of robot operation, (2) removal of the students from the potentially dangerous environment, (3) there is a greater possibility for optimization of system layout and the planning of robot motions. We teach our MET students offline programming software to emulate the robot motions, generate program instructions, and determine whether each movement can be successfully executed by repeatedly checking.

2. Background

Robotics courses are commonly found in many Manufacturing Engineering Technology programs in the USA. They include coverage of robot programming and often utilize robot motion simulation software such as WORKSPACE 4.0. Many Manufacturing Engineering Technology curricula include both Computer Aided Design and Computer aided Manufacturing (CAD/CAM) and Robotics courses. These courses may focus on different robotic workcell designs and manufacturing process analysis, which often involve a lot of design and manufacturing issues and theoretical concepts. At MnSU many design and manufacturing projects attempt to provide the students opportunities to practice their CAD/CAM knowledge and promote creativity and innovation. In the last two years, almost 40 students in our program were involved robotic workcell design projects. In general, all of the students are given foundational manufacturing and design concepts, principles, and methodologies of the engineering disciplines during their first two years. MET students have to finish their study of Material Processing I (MET 177), Computer Aided Drafting (MET 142), and product development and design (MET 144) courses before they are accepted by the program (see Figure 1).
In order to verify that the students meet the program outcomes, a robotic workcell design project has been utilized to help them practice their robot programming knowledge and continuously improve the student learning environment. The supporting evidence in table 1 shows the relationship between ABET criterion 2 outcomes a-k and the robot programming learning outcomes. As we continue to use and improve this model, we expect that the robotics learning outcomes will eventually meet ABET criterion 2 perfectly. Additionally, we will utilize more surveys to assess the effectiveness of the model.

Table 1 - Student project learning outcomes, program outcomes and ABET criterion 2 mapping

<table>
<thead>
<tr>
<th>Student Project Learning Outcomes</th>
<th>ABET Criterion 2 Outcomes a-k</th>
<th>*MET Program Outcomes</th>
<th>Learning Outcomes</th>
<th>ABET Criterion 2 Outcomes a-k</th>
<th>*MET Program Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analytical Ability</td>
<td>a,c,f</td>
<td>1,2,4</td>
<td>Oral Communication</td>
<td>e,g</td>
<td>6</td>
</tr>
<tr>
<td>Teamwork</td>
<td>e,f</td>
<td>6,7</td>
<td>Written Communication</td>
<td>e,g</td>
<td>6</td>
</tr>
<tr>
<td>Project Management</td>
<td>b,c,e</td>
<td>6,7</td>
<td>Visual Communication</td>
<td>e,g</td>
<td>6</td>
</tr>
<tr>
<td>Math Skills</td>
<td>b</td>
<td>3</td>
<td>Creative Problem Solving</td>
<td>d</td>
<td>1,2</td>
</tr>
<tr>
<td>System Thinking</td>
<td>d,e</td>
<td>4</td>
<td>Ethics and Professionalism</td>
<td>a,i</td>
<td>8</td>
</tr>
<tr>
<td>Self-Learning</td>
<td>b</td>
<td>5</td>
<td>Technology Skills</td>
<td>a,f</td>
<td>1,2</td>
</tr>
<tr>
<td>Respect for diversity</td>
<td>j</td>
<td>8</td>
<td>Continuous improvement</td>
<td>k</td>
<td>4</td>
</tr>
</tbody>
</table>

Note: ABET Criterion 2 Program Outcomes - Students will have:
- a. an appropriate mastery of the knowledge, techniques, skills and modern tools of their disciplines;
- b. an ability to apply current knowledge and adapt to emerging applications of mathematics, science, engineering and technology;
- c. an ability to conduct, analyze and interpret experiments and apply experimental results to improve processes;
- d. an ability to apply creativity in the design of systems, components or appropriate to program objectives;
- e. an ability to function effectively on teams;
- f. an ability to identify, analyze, and solve technical problems;
- g. an ability to communicate effectively;
- h. a recognition of the need for, and an ability to engage in lifelong learning;
- i. an ability to understand professional, ethical and social responsibility;
- j. a respect for diversity and knowledge of contemporary professional, societal and global issues; and
- k. a commitment to quality, timeliness, and continuous improvement.

*MET program outcomes: [http://cset.mnsu.edu/met/about/outcomes.html](http://cset.mnsu.edu/met/about/outcomes.html)

Although robotics topics can be possibly integrated into MET 347 and MET 448 courses, there are still many challenging issues we need to face and solve. In the world market for industrial robots, there are so many hardware and software platforms available for developing robot programming. What is the appropriate choice? These are the factors that need to consider when selecting the right platform. There are many tradeoffs when selecting the appropriate
programming platform for learning purposes. Robotic Simulation enables a fast learning cycle (programming, debugging, and testing) by assuming that robot work in an ideal environment.

3. Methods

Research has shown that project-based learning is an extremely effective learning activity. Many university professors today accept this learning environment to help students make the transition from passive learning to active learning learners in their classrooms [8]. In order to find better ways of involving the students in this learning process, we introduced Offline Programming (OLP) Project into our MET 347 Manufacturing Automation course. With the successful OLP design project (see Table 2), the students learn more materials, retain the information longer, and enjoy the class activities more. The OLP design project allows the students to learn many OLP concepts, principles, and guidelines in the classroom with the help of the instructor and other classmates, rather than on their own. The OLP design project consists of project-based learning activities to encourage students to do more than simply listen to a lecture. They are able to evaluate and redesign their own robotic workcells to prove their ideas and what they have learned from MET 347 course. After learning, processing, and applying information from OLP (WORKSPACE 4.0) software, the students are ready to share their ideas with team members (3-4 students/per team). By dividing students into different roles and working cooperatively, the whole class will be able to work together to design their own robotic workcells.

Table 2 – learning modules and lessons of Industrial Robot Programming

<table>
<thead>
<tr>
<th>Module</th>
<th>Lesson</th>
<th>Learning Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fundamentals of Robotics</td>
<td>1. What is an Industrial Robot?</td>
<td>1. Define an Industrial Robot</td>
</tr>
<tr>
<td></td>
<td>2. Characteristics of an Industrial Robot</td>
<td>2. Identify robot configurations</td>
</tr>
<tr>
<td></td>
<td>3. Manipulator Configurations (number of Axes)</td>
<td>3. Describe the operating principles of an Industrial Robot</td>
</tr>
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<td></td>
<td>4. Robot Coordinates</td>
<td>4. Recognize Robot degrees of freedom</td>
</tr>
<tr>
<td></td>
<td>5. Repeatability, Precision, and Accuracy</td>
<td>5. Identify six factors which should be considered when selecting an Industrial Robot</td>
</tr>
<tr>
<td></td>
<td>6. Industrial Applications of Robotics</td>
<td>6. Differentiate between robot links and joints</td>
</tr>
<tr>
<td></td>
<td>7. Advantages and Disadvantages of Robots</td>
<td></td>
</tr>
<tr>
<td>Components of an Industrial Robot</td>
<td>1. General components of an Industrial Robot</td>
<td>1. List the main components of an industrial robot</td>
</tr>
<tr>
<td></td>
<td>2. Types of Actuator Drive</td>
<td>2. Identify four types of actuators</td>
</tr>
<tr>
<td></td>
<td>3. Tool Orientation</td>
<td>3. Name two types of robot arms</td>
</tr>
<tr>
<td></td>
<td>4. Work-Envelope Geometries</td>
<td>4. Name the two most popular types of drive systems used in Industrial Robots</td>
</tr>
<tr>
<td></td>
<td>5. Sensor Areas for Robots</td>
<td>5. Define point-to-point control</td>
</tr>
<tr>
<td></td>
<td>6. Motion Control Methods</td>
<td>6. Describe three characteristics of a continuous path robot</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7. Differentiate between servo and non-serve control systems</td>
</tr>
<tr>
<td>Manipulators and End-of-Tooling</td>
<td>1. Characteristics of End-of-Arm Tooling</td>
<td>1. Determine tool length using a tool center point (TCP)</td>
</tr>
<tr>
<td></td>
<td>2. Calculating Gripper Payload and Gripper Force</td>
<td>2. Name the most common type of manipulator</td>
</tr>
<tr>
<td></td>
<td>3. Manipulator Power Supplies</td>
<td>3. List six end effectors used in Industrial Robotics</td>
</tr>
<tr>
<td></td>
<td>4. End Effectors and Grippers Design</td>
<td>4. Name the three types of revolute joints</td>
</tr>
<tr>
<td>Robot Programming</td>
<td>1. Robot Programming Methods</td>
<td>1. Name the two major categories of robot programming</td>
</tr>
<tr>
<td></td>
<td>2. Online and Offline Programming</td>
<td>2. Differentiate between manual and automatic programming</td>
</tr>
<tr>
<td></td>
<td>3. Programming Languages</td>
<td>3. Identify five different types of motion instructions</td>
</tr>
<tr>
<td></td>
<td>4. Types of Programming</td>
<td>4. Describe the most popular type of robot programming language</td>
</tr>
<tr>
<td></td>
<td>5. Voice Recognition</td>
<td>5. Explain how program touch-up is used when programming</td>
</tr>
<tr>
<td>Robot Applications</td>
<td>1. Integrating Industrial Robots into the</td>
<td>1. Describe the most Common Application for Industrial Robots</td>
</tr>
<tr>
<td></td>
<td>Manufacturing Process</td>
<td>2. List eight Applications for Industrial Robots</td>
</tr>
<tr>
<td></td>
<td>2. Industrial Applications of Robotics</td>
<td>3. Identify the three most common functions performed by inspection robots</td>
</tr>
<tr>
<td></td>
<td>3. Justifying the Cost of Robots</td>
<td>4. Differentiate between robot handling and assembly</td>
</tr>
<tr>
<td></td>
<td>4. Robot Safety and Maintenance</td>
<td>5. Define the term Palletizing</td>
</tr>
</tbody>
</table>
Evolution of Robotic Simulation Technology and Off-line Programming  
Robotics Workcell Design  
Robot Calibration

1. Analyze Collision Situation  
2. Create and Generate Automatic Path Generation  
3. Evaluate and Visualize Manufacturing Process  
4. Optimize Cycle time  
5. Design appropriate Robotic Workcells for different manufacturing processes

Bloom's cognitive domain vs. OLP learning Objects

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

Table 3 - Bloom's Taxonomy of Cognitive Development vs. OLP Learning Objects

<table>
<thead>
<tr>
<th>Levels of Learning</th>
<th>Bloom's Taxonomy Verbs</th>
<th>OLP Learning Objects</th>
<th>Thinking skills</th>
</tr>
</thead>
</table>
| B1: Knowledge      | Define, list, name (label), count, order, assign, record, recognize ... | Object 1: Define an Industrial Robot  
Object 2: Recognize Robot degrees of freedom  
Object 3: List the main components of an industrial robot  
Object 4: Name two types of robot arms  
Object 5: Name the two major categories of robot programming  
Object 6: Define point-to-point control | B1 - Lower Order Thinking Skills |
| B2: Comprehension  | Identify, indicate, classify, discuss, locate, explain, review ... | Object 1: Identify robot configurations  
Object 2: Identify six factors which should be considered when selecting an Industrial Robot  
Object 3: Identify four types of actuators  
Object 4: Identify five different types of motion instructions  
Object 5: Identify the three most common functions performed by inspection robots  
Object 6: Explain how program touch-up is used when programming | |
| B3: Application    | Determine, apply, construct, operate, select, practice, sketch, use, solve ... | Object 1: Determine tool length using a tool center point (TCP)  
Object 2: Describe three characteristics of a continuous path robot | B1 - Lower Order Thinking Skills |
| B4: Analysis       | Analyze, calculate, categorize, test, examine, inspect, question, differentiate contrast ... | Object 1: Analyze Collision situation  
Object 2: Differentiate between servo and non-servo control systems  
Object 3: Differentiate between manual and automatic programming  
Object 4: Differentiate between robot handling and assembly | |
| B5: Synthesis      | Create, design, develop, collect, formulate, propose, setup, compose ... | Object 1: Create and Generate Automatic Path Generation  
Object 2: Design appropriate Robotic Workcells for different manufacturing processes | B1 - Higher Order Thinking Skills |
| B6: Evaluation     | Evaluate, appraise, assess, judge, justify, value, select, ... | Object 1: Evaluate and Visualize Manufacturing Process  
Object 2: Optimize Cycle time | |

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

4. Results - Student Projects

In the past two years, a number of student projects have been selected to help MET students understand the importance of OLP when the intention is to improve robotics course learning. In general, student design teams are given a small assembly product (25 ± 5 parts) that has not been designed using the principles and then asked to develop a robotic workcell solution that simplify the manufacturing process and also meet the product specification. Obviously, the robotic workcell design projects add the ability for students to not only complete a design cycle, but also to examine product improvement opportunities. Along with giving MET students the opportunity for a complete design experience, these student projects also give them the opportunity to practice their communication skills and to enhance their design learning experience. Below are some of student projects that demonstrate what they have learned from this project (see Figure 2, 3, 4, and 5).

Traditional robot programming methods

Traditionally, most of MET students at Mnsu created their robot programs by using a hand-held
teach pendant attached to the robot controller. The teach pendants are microprocessor-controlled devices that facilitate a wide variety of robot operation and programming functions (see figure 2). Because there is no effective way to learn a teach pendant, the logistics for learning robot operating and programming procedures to students has long been problematic. Minnesota State University has very few industrial robots available for students, making it very difficult to provide students with robot programming learning experiences.

Off-line programming projects

The average students spent 8-10 hours on the design of their robotic workcells, and applied what they have learned from OLP lectures in the classroom. The OLP implementation in the product development and design course provided many benefits. The students were able to incorporate design experience and manufacturing experience early in the design cycle. Teamwork was promoted and communication increased between product design, and manufacturing. A better understanding of the design's impact on manufacturing cost was gained. In addition, students now have a much better sense of product development and design process.

After students created their solution for their products (see Figure 2, 3, and 4) in MET 277 course, each team developed a redesigned case and modeled it in Pro/ENGINEER. These new designs were then built on the robotic assembly workcell and students were able to test how well their new designs worked. Most teams needed at least two different redesign solutions to demonstrate how much they have learned from this project. Figure 8 shows an example of one of the students redesign workcell. This particular redesign increased original design efficiency by 60%.
Lab 3-Pick-and-Place Lab (Using teach pendent to move RV-M2)

Using Action Command to Close RV-M2 Gripper

Place down the top block on the other side of table

Using Simulation Option to record a video for Lab 3 demonstration (Ex. Creating an .AVI video file)

Figure 3 – Student Lab 3 - Sequence of views in WORKSPACE 4.0 offline programming software

Robotic Workcell Design – Box Palletizing

System Equipment Layout (Ex. Conveyor, Pallets, and IRB 200 Robot . . .)
Creating Robot Motion path and Pallet pattern

Using "Simulation Option" function to Record Palletizing Process

Figure 4 – Sample student projects (Robotic workcell Design for Box Palletizing)

Robotic Workcell Design – Painting operation

Manual Spray Painting Layout- Simulation View

System Equipment Layout (Ex. Waterfall screen, two slide tracks, and GMC Robot …)

Using "Simulation Option" function to Record Spray Painting Process

Figure 5 – Sample student projects (Robotic workcell Design for bamboo box painting)
Using OLP simulation software to teach students in MET 347 course is a significant improvement to the class. Without the addition of OLP course project to the curriculum, students would not have been able to understand how to apply OLP concepts to robot programming phase and they would not have had access to real-world design experience. The OLP course project has the potential to positively affect student learning outcomes in the area of robotic workcell design. It allows students to simplify product structure and close the loop on design process that have traditionally been taught through lecture and homework. The additional learning and resulting student confidence is both noteworthy and exciting, and can be also easily accomplished through the choice of an appropriate OLP project.

**Course Outcome Evaluation**

Course outcome evaluation is a key factor for recognizing the benefits, identifying the deficiencies, and improving course contents. Through the evaluation, we should be able to assess students' attitudes towards using offline programming software in class, whether it is a source of motivation, or it does not improve their learning process. Typical evaluation process includes assessing students' labs, projects, and exams. In addition, we can also get feedback from students through the use of SurveyMonkey™ questionnaires. These outcomes can be compared with the outcomes in the previous classes to see the differences. There are a number of approaches to assessing student learning outcomes. Each assessment method has different advantages and disadvantages and yields only partial insight into student learning and teaching effectiveness. However, a combination of direct and indirect outcome measures can provide valuable information that can be used to address students' problems and enhance instructional organization and delivery. In order to measure OLP learning outcomes, we used the following methods to assess the outcomes and collect necessary data:

1. **Course-based tests and examinations** - What knowledge and abilities have students acquired from our lectures and project activities (see Figure 5),
2. **In-class observation** - Many student skills are demonstrated by performing product disassembly and assembly in the classroom (see Figure 5 and Table 3),
3. **Student survey** - according to our university policy, we have to collect and conduct student surveys (at least two courses/per semester) at the end of each semester,
4. **Project presentation** - Students present their results and findings to the class (peer evaluations 50% + instructor grading 50%),
5. **Project report** - Normally prepared outside of class, students report include written assignment, designs, analysis worksheets, portfolios, or redesign drawings.

When employed carefully and thoughtfully, the OLP learning outcomes may highly contribute to judgments of teaching. Apparently, we will continuously use the above student outcome
information to support and improve instructor teaching styles and/or student learning, not contribute to instructors' fear, stress and alienation.

After the OLP curriculum was developed through the cooperative effects of two MET courses, a number of student assessment and feedback was collected in Manufacturing Automation classes at the end of semester 2009 and 2010. The population size was 30 students (22 undergraduate
students and 8 graduate students) and the total number of responses was 28. Some of the results from these student assessments present as follows:

1. Most (90%) of the students had strong confidence in their ability to apply OLP knowledge and correctly solve a similar problem in the future.
2. Almost (85%) of the students were able to examine and analyze existing designs, identify assembly difficulties, and create alternative designs.
3. 22 students ranked robotic workcell design project experience in the top two activities they liked overall.
4. 23 students agreed that are more likely to remember the content delivered in these courses because of this new curriculum.
5. When compared to a traditionally-taught course, 24 students preferred this approach over the traditional one.

The result of the evaluation also indicated improvement in robot programming skills and techniques among students. These findings suggest that students learn robot programming better from coursework that incorporates content knowledge and practical, real case examples.

**Conclusion**

This study investigated a new model of teaching MET students robot programming knowledge and skills that they need for a successful future. We also examined our curricula to ensure our students are familiar with the trends in manufacturing technology. This robotic workcell design project challenged our MET students to practice robot programming skills. It also helped our students to better understand OLP principles and guidelines. In addition, it allows our students to strengthen their design and manufacturing technology skills, exercise their creativity, and practice their research capabilities. The student project is a motivational, fun, and enlightening project that provides students a hands-on opportunity while combining and practicing manufacturing, design, and project management skills. Finally, they demonstrated their fundamental knowledge and insight by redesigning their robotic workcells and then estimating cycle time and operational costs. They understood how this might be helpful to them in their design and manufacturing learning.

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