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An Industrial Robotics Course for Manufacturing Engineers

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For many years the automobile industry was the home to more than half of the robots used in U.S. manufacturing. Recently, however, many other industries have been or are planning to introduce robots into their manufacturing processes.[1] In the Pacific Northwest region several companies in aerospace, electronics, apparel, and commercial cookware have either introduced robots or expanded their use in recent years. As such, an introduction to robotics in the context of manufacturing is becoming more important for students pursuing degrees in Manufacturing Engineering. There is, however, always a challenge when teaching robotics to find the correct balance between application and modeling. Many robotics courses taught in Electrical or Mechanical Engineering Departments have a tendency to emphasize modeling over application, but a well-prepared Manufacturing Engineer needs to understand where the challenges in robotics applications lie as well as understanding what is going on 'under the hood'. A quick survey of the 21 ABET accredited Manufacturing Engineering programs indicates that only five have a manufacturing specific robotics course, and three of those are special topics courses that are not offered consistently.[2] Other programs have robotics integrated into a general automation class, have cross-listed classes with other programs, or have graduate classes on robotics that are available to seniors, so there are not the same opportunities for depth or focus on manufacturing applications. Most of the recent work that has been done in the development of lab intensive robotics courses has been done for engineering technology programs,[3-6] with only one being specific to Manufacturing Engineering.[7]

This paper describes a new Industrial Robotics course for Manufacturing Engineering students at Western Washington University. The new course is based upon a course that had been part of a Manufacturing Engineering Technology program that has recently transitioned to Manufacturing Engineering. The goals of the new course are to both find the right balance between modeling and application and be true to the applied nature of the new Manufacturing Engineering program. Therefore, the course is lab intensive to provide students with multiple opportunities to work with industrial robots. Students complete eleven structured and semi-structured lab activities that introduce them to different aspects of applied robotics, including the design of end-effector tooling and fixtures for different tasks. Students work with three different robot configurations and two different operating systems, so they are exposed to some of the different options available and get experience with different interfaces and design philosophies. Students also get a brief introduction to machine vision systems through lab activities. The lab experience culminates in an open-ended, industry-sponsored project that requires students to apply their knowledge from the lab activities to solve a real robotic automation problem, including the design of the appropriate fixtures and specification of the necessary equipment for a production cell. In addition to lab experiences that emphasize applications, the course covers the fundamentals of robotic modeling, including kinematics, inverse kinematics, trajectory planning, and vision systems, with activities and exercises designed to tie the modeling to the applications, and important aspects of applied robots including ANSI/RIA safety standards, sensors, and actuators.

Course overview

Part of the stated Mission of the Engineering & Design Department at Western Washington University is to prepare industry-ready graduates. The goal is to have graduates have a proper mix of theoretical foundation and practical experience. The latter is achieved through a combination of lab and CAD-based design activities. Correspondingly, the new Industrial Robotics course is lab intensive. Western Washington University is on the quarter system, so there are only ten weeks of class. The Industrial Robotics course has two 2-hour laboratory meetings and one 2-hour lecture session each week. The four hours of lab/week for each student provides the students with meaningful exposure to the robots. Students generally work in lab and on their project in teams of three, although often one team of four is necessary due to the number of students in the class. Each lab period there are up to four different labs occurring simultaneously during a lab session.

The learning outcomes for the class are that by the end of it students will be able to:

- Do basic robot modeling and motion planning,
- Program robots to complete manufacturing-related tasks,
- Design fixtures and end-of-arm tooling for robotic applications, and
- Design or select and implement an appropriate robotic system for a specific manufacturing task.

The first outcome is primarily achieved through traditional lecture and homework activities, including some computer modeling using a combination of Excel, CATIA, and MATLAB. Lectures are structured so that the modeling intensive topics – kinematics, inverse kinematics, and trajectory planning – are spread across the entire quarter. These topics are covered in the first hour of lecture meetings. The second hour of lecture meetings is used for more applied topics such as ANSI/RIA safety standards, vision system concepts, sensors (focusing on optical encoders), and actuators (focusing on pneumatic peripherals). Each lecture includes one or two think-pair-share exercises during the first half, so sometimes the first half topic requires part of the second half to complete.

The remaining outcomes are primarily achieved through lab and project activities, which are described in more detail below. The prerequisites for the course are Introduction to Automation and Control and Introduction to CAM and CNC. The former prerequisite course introduces students to feedback systems, DC servo and stepper motor control, PLCs, and microcontrollers. Students must complete a course in Linear Algebra and a course in Ordinary Differential Equations before they take the Introduction to Automation and Control course. The latter prerequisite course is intended to make sure that students are prepared to fabricate tooling for lab and project work. However, more often than not, today's students fabricate tooling using rapid prototyping (RP) technology instead of CNC, so in the near future this prerequisite will change to a co-requisite Design of Tooling class. Students will still have the CAM and CNC course as a foundation, for it is a prerequisite for Design of Tooling, and they will have been introduced to and had the chance to apply the principles of good fixture design by the time they need to apply them for the Industrial Robotics class.

Lab equipment and labs

One of the things that has enabled the development of many lab activities for the Industrial Robotics course is the accumulation of robots over time. Through a combination of grants, industrial donations (gifts-in-kind), horse trading, and internal support from the Dean and Provost, we have managed to accumulate seven working industrial robots, and we are currently working on getting an eight on line as well. The current equipment for labs includes:

- Two Denso HS-45552E/GM 4-axis SCARA robot arms,
- Two Denso VS-6577GM-B 6-axis articulated robot arms,
- One Fanuc LR Mate 200i 6-axis articulated robot arm,
- One FANUC CERT Cart with M-1iA 6-axis parallel-link robot with vision system,
- A manufacturing cell with a FANUC M-6i 6-axis articulated robot arm, a HAAS SL10 CNC lathe, and a HAAS VF2 mill, and
- A variety of pneumatic components and proximity sensors.

Aside from the cell, all of the equipment is in the same lab, so many activities can take place simultaneously. The cell, due to the size and weight of the equipment, is awkwardly located on the ground floor of the Engineering building, while the rest of the equipment is in a lab on an upper floor. Unfortunately, only the parallel link robot can be moved, so it is difficult to support multiple labs when students are working with the cell.

One of the best things about having robots from two different manufacturers is that FANUC and Denso have very different approaches to programming their robots. FANUC's approach is driven by teach pendant (TP) programming, combines motion specification with point definition, and uses local variables. Denso's approach is more focused on off-line programming (we use WinCaps III), separates motion specification from point definition, and uses global variables. They have many things in common of course, but the differences allow the students to apply principles on different robot systems, so they can separate what they are trying to accomplish from how they need to write a program or define a frame on the specific robot system. It also helps them quickly realize that they can adapt to virtually any robot if they know how to apply the principles.

Labs are organized into rotations. Each rotation includes two to five labs of roughly equal challenge. Because the cell is isolated from the rest of the robots, students complete that lab at the end of the third rotation, but it really is conceptually part of the third rotation. The first rotation is introductory and contains two labs. The second rotation includes semi-structured applications and contains five labs. The third and final rotation includes semi-structured applications that require the design and fabrication of support tooling to complete or are open-ended experiments. The third rotation currently contains four labs, but there are plans to increase this number by adding two new labs next year. One of the goals of this structure is that the second and third rotations reinforce concepts and approaches learned in the first and second rotations respectively by requiring students to use them for more complex scenarios.

The first rotation is designed to introduce students to: 1) Tool and User/Work frames and how to set them, 2) TP programming, 3) proper structure of a pick and place program, 4) path following, and 5) off-line programming. The first task is accomplished using the FANUC LR Mate 200i articulated robot and the FANUC M-1iA parallel link robot, and the other four tasks are accomplished using the Denso HS-45552E/GM SCARA robots. Each of the two labs can easily be accomplished in two hours, and they can be run in parallel, with two teams working on each lab simultaneously. The result is that the first rotation only takes a week, and it sets students up for beginning the more interesting second rotation quickly.

The introduction to Tool and User/Work frames lab requires students to explore different methods of create Tool and User/Work frames. One team starts on each FANUC and uses three different methods (three point, six point, and direct entry) to create a Tool frame and two different methods (three point and four point) to create a User/Work frame. At the end of each step, students demonstrate that they have successfully defined the frame. Once they have completed the definitions for all five frames the two teams switch robots and repeat one Tool frame and one User/Work frame, both using a three point method, on the other robot. The principles are the same, but the M-1iA parallel link robot has such a small envelope that it often takes students a few tries to find a way to allow the robot to access all three of the necessary points for the Tool frame.

The introductory Denso lab starts by having students run through an on-line tutorial provided by Denso. This introduces students to the Denso TP interface, and steps them through writing and running a simple program. For the program students are required to move an imaginary object from one point to another with good program structure, so it introduces them to the most basic robot commands in the Denso language. Once they have completed this first program, students use the robot manual to set up and learn the WinCaps III off-line programming software and write a simple program to follow given straight line and curved paths. As with the FANUC frames lab, students must demonstrate the successful completion of both the first and second program to the instructor. The labs in the first rotation are very simple, but they give students a good foundation in frames and robot programming quickly, which prepares them well for the second rotation.

The second rotation contains five labs that use the principles students learned in the first rotation while expanding upon them. The labs are semi-structured in that the task is specified, but students are not provided with step by step instructions on how to accomplish the tasks. All five of the labs require complete programs, so it is during this rotation that students begin to really have fun with the robots. Up to four labs are run simultaneously depending upon enrollment, so the labs are designed to all be independent of each other so that the order in which students do them does not matter. The five labs of the second rotation are: 1) palletize using a Denso HS-45552E/GM SCARA robot, 2) complete a small assembly using a Denso HS-45552E/GM SCARA robot, 3) 'weld' (the welder is a focused LED) using the FANUC LR Mate 200i articulated robot, 4) pick up a pile of randomly located and oriented parts using the FANUC M-1iA parallel link robot and its vision system, and 5) complete an arrayed task using a Denso VS-6577GM-B articulated robot by using a User/Work frame and then relocate the task by redefining the frame. The first three of these labs have near 100% success rates, but the last two require careful attention to detail, so some teams end up with final programs that do not successfully complete the tasks. For these labs students must successfully incorporate all of the given requirements into their programs to receive full credit for the lab. These labs are worth twice as much as the labs in the first rotation.

The palletize using a Denso HS-45552E/GM SCARA robot lab introduces or reinforces switching on and off external devices, introduces or reinforces loops and position variables in programs, and introduces stack up issues. The requirements of the lab are to pick up ½" square chips from a magazine feeder and successfully place them into the compartments of a tray with a 5 x 5 array using only two defined points. The students are required to try using both a mechanical gripper and a vacuum gripper and also to use a corner cell and the center cell as reference points. Students end up writing a program with one gripper and one reference point, switching to the second reference point, and then redefining the points to use the other gripper and the center reference point, so it ends up being one relatively short program that is modified twice. The programming efficiency is achieved through the use of loops (FOR-NEXT are recommended) and position variables inside the program. Students are told what commands they need to use, but they have to figure out how to use them from the Denso programming manual. Students inevitably find that the center cell of the tray is a much better reference point because it has half of the stack-up error a corner point does. To get full credit for the lab students must develop at least one solution that successfully places all twenty five chips into the array. Teams that take the time to carefully locate the chip in the center cell by both centering it and squaring it to the edges of the cell generally successfully complete this lab.

The small assembly using a Denso HS-45552E/GM SCARA robot lab reinforces good assembly program structure and the use of the WinCaps III off-line programming software. The requirements of the lab are to assembly a six-piece stopwatch that is roughly 2” in diameter. The original stopwatch was redesigned to incorporate DFAA principles, but it still has three small pieces, an LCD and two buttons, and a circuit board that must be located on four very small pins. The LCD screen was too fragile for novice robot programmers, so it was replaced with piece of aluminum, and the body and buttons of the stopwatch are made using an RP machine, so they can be replaced quickly when they are broken, which happens at least once during the rotation. The small parts can be placed in any order, but the other parts must be placed in a specific order. Students are required to use the off-line programming tool to write the program, and they must use both a mechanical and a vacuum gripper to complete the task. Their grade is based upon whether or not their program can be run successfully at a reasonably high (at least 80%) speed.

The ‘weld’ using the FANUC LR Mate 200i articulated robot lab reinforces the creation of Tool and User/Work frames from the first rotation, introduces or reinforces switching on and off external devices, introduces or reinforces specifying frames in a program, and introduces students to the creation of straight line and arced paths and how to specify speed and continuation of robot motions on the FANUCs. The first requirements of the lab are to create a Tool frame for the LED ‘welder’ and then a User/Work frame on the workpiece. The workpiece is a pillow block bearing that is roughly 6” by 4” and has two straight edges and two edges that are made up of two small straight segments with an arced segment between them. The students’ program must clamp the workpiece, move the robot to a corner of it with the LED tool off from vertical in a specified angular range and with the offset from the workpiece in a specified range, turn on the LED and move along the edge at a specified rate. At the end of each edge the program must turn off the LED and reorient the robot to meet the angular specification before ‘welding’ the next edge. The LED works very well because it lets the students see how well they are following the edges of the workpiece, and lets the instructor see how carefully the students defined their points. The only place where students get in trouble with this lab is, if they are not paying attention, the fourth joint of the robot will reach its motion limit before the whole edge of the workpiece is completed. When this happens it usually requires redefining most, if not all, of the program points. Otherwise the only challenge for the students is remembering to include all of the details that are required.

The pick up a pile of randomly located and oriented objects and put them in a bin using the FANUC M-1iA parallel link robot lab introduces students to vision systems and reinforces creating User/Work frames and programming on the FANUCs. The object is a 1.5” long square peg (so that it has distinct edges) made on an RP machine. The lab requires students to set up and calibrate the camera and create two User/Work frames before training the vision system to recognize the object. The program to pick up the object is small and simple, but the training of the object and the original pick location requires careful attention to detail, so students are given step by step instructions for the three steps that require the vision system. Even with these instructions, however, many teams miss a detail and have to repeat part of the training and programming before their programs are successful. Students first write a program to pick up a single object. Once that proves itself to run successfully, they modify the program to include a loop so that it can pick up a pile. The only drawback of this lab is that teams that successfully write a working program still often encounter joint limit errors due to the small size of the robot's envelope. The lab would probably work better with the 4-axis version of the robot than the 6-axis version that we have.

The program a task using a User/Work frame using a Denso VS-6577GM-B articulated robot and then move it lab introduces students to defining Tool and User/Work frames on the Denso robots, introduces or reinforces loops and program variables, introduces a motion command, ROTATE, that exists on the Densos but not on the FANUCs, and introduces the use of relative locations for future flexibility. The lab is set up to mimic something like a deburring operation on nine holes in a 3 x 3 array, but the deburring tool is an unbent paper clip (which is often re-bent as this is students' first experience with the 6-axis Denso robots). The students must first define a Tool frame, which uses a different Tool Center-Point (TCP) method than FANUC does, then define the User/Work frame on the fixture with the array, and then write a the program to trace all nine holes. It uses the same basic program structure as the palletize lab, but requires students to learn to define and use a vector variable to use the ROTATE command. Once students have demonstrated that their program is fully functional, they have to move the fixture with the array and redefine their User/Work frame for it. If they do this part carefully, which includes remembering to define it the User/Work frame relative to the World frame, their program will successfully run for the new location without needing to be modified or having any of the points retrained. This last step must work for students to receive full credit on the lab.

The third rotation contains four labs that use the principles students learned in the second rotation while expanding upon them and requiring them to design and fabricate or RP tooling to complete the labs. Because one of the labs uses the cell, the students are currently completing that lab last, so it can take advantage of the third rotation lab on the FANUC LR Mate 200i articulated robot, and I will discuss it last. The split in this rotation of labs currently means that four teams are working at a time for two weeks and then two team are working at a time for two weeks. The remaining teams are given the time to work on their design project when they have a lab period without a required lab. The four labs of the third rotation are: 1) load an object, add a design to it, and unload it using the FANUC LR Mate 200i articulated robot, 2) propose and run a three factor, full factorial designed experiment for one of the Denso VS-6577GM-B articulated robots to learn more about its capabilities, 3) propose and run a three factor, full factorial designed experiment for the vision system with the FANUC M-1iA parallel link robot, and 4) use the FANUC M-6i articulated robot to load and unload the HAAS SL10 CNC lathe in the cell. The two FANUC articulated robot based labs require students to design fixture inserts and gripper fingers, and the Denso articulated robot and FANUC parallel-link robot labs require them to conduct some background research to justify their proposed experiments. The first three of these labs are worth twice as much as the labs of the second rotation, and the lab that uses the cell is worth three times as much. There are also plans to add two labs to this rotation for next year's class. These are briefly outlined at the end of this section.

The load an object, add a design to it, and unload it using the FANUC LR Mate 200i articulated robot lab introduces students to using subroutines in programs, including standard subroutines, and precise specification of points. The object is a piece of aluminum that has one flat end and one curved end (it resembles a tombstone in its basic shape, so this has become known as the "tombstone lab"). As with all of the labs currently in the third rotation, this lab requires students to complete design and fabrication tasks before coming to lab. They have to design and fabricate fixture inserts to hold the object in a precise location, design and fabricate gripper fingers to attach to a specified mechanical gripper in order to load and unload the object, and come up with a design to place on the object including the precise location of the points of the design relative to a reference point on the object. Most students elect to RP their parts for the fixture inserts and the gripper fingers, but some teams do machine them instead. The lab uses two grippers, and students are provided with the subroutines to complete the gripper exchanges. The designs are added with felt tip pens because they are cheap, pose no safety risks when they are destroyed, and their ink wipes off of aluminum with a damp towel. In general the pen tips get mashed at the rate of about one per team, but sometimes the destruction of the pens is more spectacular, say if the team means to program a low speed, linear motion but accidently specifies a high speed, point to point motion. The basic structure of the students' master program is to: 1) pick up the workpiece from the feeder and place it in the fixture (which has a pneumatic clamping mechanism), 2) exchange gripper 1 for gripper 2, 3) pick up the pen and approach the object, 4) add the design to the object and put the pen away, 5) exchange gripper 2 for gripper 1, and 6) unload the fixture and move the object to the completed part bin. As part of the programming, students must create a User/Work frame with its origin at the point on the object that is the reference point for their design. The efficiency of this lab is influenced by two factors: students' design work for their fixture inserts and finger, and the complexity of their design. I strongly encourage students to fabricate and test their fixture inserts and fingers early enough to make corrections or improvements, but only some teams do so. As a result, I have a small collection of fixture inserts and fingers that can be used if a team's design cannot. I also strongly encourage teams to come up with a design that requires roughly two dozen points. Because the x, y, and z coordinates of each point must be entered on the TP, overly complex designs become very tedious to complete and sometimes need to be simplified. To receive full credit for this lab teams must both design and fabricate successful fixture inserts and fingers before their scheduled lab day and complete all of the programming steps.

The two labs that require students to design, complete, and analyze three factor, full factorial experiments on one of the Denso VS-6577GM-B articulated robots and on the vision system with the FANUC M-1iA parallel link robot are very open-ended. The goal of both labs is to have students explore the capabilities and limits of the technology a little bit, and to see if they can learn about what factors can improve or degrade performance. The Denso lab also gives students a bit more time to work on the robots that many of them will use for their design project, and the FANUC lab gives students another chance to work with the vision system, which is especially good for those teams who did not successfully complete the first vision task during the second rotation. Because there is space in the lab schedule for two labs that are still under development, students in the first class were given two lab sessions on each of the robots so that they could refine and improve their experiments or conduct a second experiment on each robot if they preferred.

For the Denso lab it is common for students to want to test factors that might have an effect on the robot's precision or cycle time, including speed, location, payload, and motion type. Teams that test cycle time generally find some interesting results, but teams that test precision find it difficult to measure location accurately enough. Of the four teams in the first class, two initially tested cycle time and two initially tested precision. Three of the four teams refined their experiments in the second lab session, but the fourth team, one of the original precision teams, elected to test noise levels during the second lab session, and they did find some correlations.

For the FANUC vision lab it is common for teams to explore what improves the reliability of the program successfully locating and grabbing a part, including its shape, location, and orientation, and factors such as lighting, contrast between the part and the background, and camera settings. For the most part these experiments were challenging as many of the factor levels resulted in failure of the robot to successfully locate and grab the part, and the teams determined more about what does not work than what leads to process optimization. Even with the second lab session for both experiments, these labs are just scratching the surface, but they do help the students to understand the robots a bit better. These are the only labs that require student to turn in reports, and their grades on these labs are based upon the design, conduct, and analysis of the experiments.

Finally, the cell lab using the FANUC M-6i articulated robot and the HAAS SL10 CNC lathe reinforces many of the lessons of the other third rotation FANUC lab (the tombstone lab), it gives the students another opportunity to design gripper fingers, and it lets them work with large machines. The sequence that the students must program the robot to complete is: 1) grab a piece of stock and load it into the lathe, 2) get a second piece of stock, unload the first (now called scrap) and load the second, and 3) remove a part from the lathe's part catcher and place it on a conveyor. The FANUC M-6i articulated robot has a dual gripper on it, so students have to design two sets of fingers for it, one of which must be capable of reaching into the lathe's parts catcher, which is a relatively confined space. The stock is a 2" diameter 4" long aluminum cylinder, so RP fingers are generally not reliable for this lab. Therefore fingers are generally made out of aluminum, but students are required to give their finger designs to a technician for fabrication. Students create and document their designs and then meet with the technician to review them. In a perfect situation this meeting leads to RP prototyping for testing and confirmation, but usually it leads to one or more redesigns first. Once the finger prototypes have been tested for fit and function, students must provide the technician with complete documentation so that he can fabricate the fingers for them. This has shown itself to be a good lesson for students, many of whom have come to think of engineering drawings as the end of a process rather than a step on the way to fabrication. It does, however, mean that I maintain a set of fingers that work in case students' designs do not. The lathe is slaved to the robot, so the robot can order the lathe to open or close its door and open or close its chuck. Students do not turn a part in the lathe because that would add money, time, and noise without adding any educational benefit. Part of the grade for this lab is the efficiency of the finger design process. The remainder of the grade is based upon whether or not the students' designs work and how successfully their program completes the loading and unloading tasks.

Those are the labs currently implemented in the Industrial Robotics course at Western Washington University. Many of the labs have their roots in the old Manufacturing Engineering Technology version of the course, though some have been modified or updated with the new Manufacturing

Engineering version of the course. Only the two designed experiment labs are completely new. There are plans to develop two additional labs for next year's offering of the course. We recently obtained a used FANUC LR Mate 200iC 6-axis articulated robot with force control. Once this robot is properly configured and set up the intent is to develop at least one lab that uses the force control. Another goal is to develop another vision system lab with this robot, but that is a lower priority than a force control lab. Finally, for their senior project, two students are currently working on developing a 3-axis robot that will allow students to derive and test their own inverse kinematic equations. This lab will also be incorporated into the third lab rotation because it takes until about midterm for to get to inverse kinematic equations in lecture, so any earlier would be too early. If the students meet all of their design goals, a second lab to test trajectory planning equations will follow the inverse kinematic equations lab. I am very excited about the potential for this little robot, because it will provide a link between lecture material and lab activities.

Design project

While the labs in this Industrial Robotics class are an end in themselves in terms of student learning goals, they are also a means to prepare students to solve a truly open-ended problem. The project is part proof-of-concept implementation and part design and modeling of a production robot cell. Students are given a task to program that requires them to design and prototype a fixture or fixtures, select and model a robot end effector, and program complex paths to show that their fixture solution is feasible using either one of the Denso VS-6577GM-B articulated robots or the FANUC LR Mate 200i articulated robot. In addition to these tasks, students must also design a complete ANSI/RIA compliant robot cell, specify as many of the components as possible, and model it in CATIA. Students are also required to identify candidate robots from companies other than Denso and FANUC. The proof-of-concept implementation has been added to this project for the new Industrial Robotics version; the old version only included design and modeling of a robot cell.

This year's project was with Sawbones, a company that makes orthopaedic and medical models (http://www.sawbones.com/). Like many companies, Sawbones is interested in exploring robotic automation of processes that are currently completed manually. One of Sawbones' product lines is orthopaedic bone models. For their projects, each team was given one bone or two similar bones and a specific task to try to automate for the bone or bones, so each team had a unique task to try to automate. One of the great things about each team having a unique task is that the teams can communicate and share information with each other, so in some sense it is a collective class project. One challenge, however, is that only the three table-top articulated robots are suitable for the task, so sharing a robot was required for two of the teams, which presented some scheduling difficulties. Given that a lab section will have at most four teams, I hope to solve this problem by getting the FANUC LR Mate 200iC articulated robot working for future offerings of the class.

The proof-of-concept demonstration portion of the project went well, and the design and modeling of a complete production cell went reasonably well, but both parts of the project had room for improvement. For the proof-of-concept demonstration portion of the project students had to identify a commercially available tool that could be attached to the robot to complete the task in a production cell, and then model and RP an attachment for the robot that was representative of the size of the actual tool. Instead of modifying the bones, as is needed for the actual products, teams used focused LEDs attached to their RP tools to show that the robot was following the required path at an appropriate angle, as they had for the 'welding' lab. In addition, students had to develop and prototype a fixturing solution to hold their bone or bones for processing. Finally, students had to program one of the 6-axis robots to demonstrate a complete processing cycle for their bone or bones. Ultimately all of the teams had successful demonstrations of their processes, but three of the four had room for improvement. All four teams designed and prototyped workable fixturing solutions, but two of them would need to be modified, one for efficiency and one for locating reliability, before they could be used for a production cell. All four teams also had complete programs, but one required repositioning the bone part way through processing, which would increase cycle time too much for efficient production, and one did not have perfect path following. The former problem was caused by the team with the largest bone selecting the robot with the shortest reach (the FANUC LR Mate 200i). Had the team elected to use one of the Denso VS-6577GM-B robots they likely would have been able to complete the task in a single setup. The latter problem was the result of the team having to share the robot and therefore being rushed to complete their programming in time for the scheduled demo. There are obviously many ways to prevent this, and both an additional robot and an earlier start will be pursued as solutions when the course is next offered.

For the other part of the project, design and modeling of a production work cell, students had to determine everything that would be required to develop an ANSI/RIA compliant cell for production purposes and model it in CATIA. The design had to include a complete parts list and a description of the workflow for production. Three of the four teams developed a reasonable cell design, with the fourth being much too large for production efficiency. All four teams developed feasible workflow plans, although all four had room for improvement for process efficiency. Finally, three of the four teams designed ANSI/RIA compliant solutions in concept, but were missing some of the necessary details such as the location of interlock and emergency stop switches. The fourth team did not complete the guarding solution for their design thoroughly enough to be ANSI/RIA compliant without significant improvements. The modeling portion, however, went more smoothly than the design portion, and all four teams developed complete CATIA models of their designs. Overall three of the four teams met the basic goals of the design and modeling portion of the project, but all of the designs had room for improvement. The students also enjoyed getting to work on an actual product, and they were motivated by the knowledge that Sawbones was interested in their solutions and findings.

Student outcomes

Each of the learning outcomes was assessed by reviewing student performance on specific assignments or parts of assignments. The general target is to get 80% of the designs, students, or teams to be successful, although for the latter the course was intended to have six teams, and the first offering of the course had only four, so in this case one team failure could be acceptable depending upon the degree of failure.

The learning outcome *Students will be able to do basic robot modeling and motion planning* was assessed based on students' performance on two questions on the final exam. For the first question students had to apply the Denavit-Hartenberg model to a 6-axis robot and develop kinematic transformation matrices, and for the second question students had to use the full transformation matrix for a 4-axis robot to find two of the inverse kinematic equations. The first question, the kinematics question, had three parts, and twelve of thirteen students, 92%, got over 80% on the three parts combined. The second question, the inverse kinematics question, also had three parts, and all thirteen students, 100%, got over 80% on the three parts combined. These results indicate that the course is meeting its learning outcome in this area, but it is based upon one event for a small number of students. Next year the intent is that this course will have a new lab set-up where students will be able to derive equations for a 3-axis robot and then implement those equations to drive the robot to specified points, along specified paths, and at specified velocities. When these activities are implemented they will also become part of the assessment process for this learning outcome, and that will provide a more complete assessment of this learning outcome.

The learning outcome *Students will be able to program robots to complete manufacturing-related tasks* was assessed by looking at the successful completion rates for all labs in the second lab rotation, the FANUC labs in the third lab rotation, and the proof-of-concept part of the design project. In the first offering of the class, four lab teams attempted each of these eight robot programming tasks, and thirty of the thirty-two, over 93%, were implemented successfully. Two teams completed all eight tasks successfully, and two teams completed seven of the eight tasks successfully. One team was unable to move the Work/User frame on the Denso VS-6577GM-B articulated robot so that their program automatically shifted to a new fixture location, and one team was unable to get the vision system to successfully guide the FANUC M-1iA parallel link robot to pick up a part with a random orientation and in a random location during their first lab period. Those were, however, the only two instances when the teams did not complete the required lab tasks, so all of the teams were generally very successful at programming the robots for manufacturing tasks. It is clear therefore that the students in the course met this learning outcome.

The learning outcome *Students will be able to design fixtures and end-of-arm tooling for robotic applications* was assessed by looking at the success of the fixture inserts and fingers that students designed for the FANUC labs in the third lab rotation and their end-of-arm tooling and fixture design for the proof-of-concept part of the design project. For the tombstone lab students had to design both fingers and fixture inserts, for the cell lab they had to design two sets of fingers, and for the project they had to design a fixture or fixture inserts and end-of-arm tooling. Thus there were six design requirements undertaken by each of the four teams. At one level all of the students' designs were successful in that they produced tooling that allowed them to successfully complete the labs or project. However, at another level there were five instances where the tooling had to be modified in the lab for it to be useable for completing the lab. Two of these five instances were caused by the use of RP tooling, which in one case was out of tolerance and in the other case was too fragile. The remaining three instances were caused by design errors or oversights. So by that metric, twenty-one of twenty-four designs, over 87%, were successful. Two teams made no design errors, one team made one design error, and the remaining team made the same design error on both sets of fingers for the cell lab. It is clear therefore that the students in the course also met this learning outcome, although not as well as the previous one.

Finally, the learning outcome *Students will be able to design or select and implement an appropriate robotic system for a specific manufacturing task* was assessed by looking at students' work on both the proof-of-concept implementation, and cell design and modeling parts of the design project. This was a tougher outcome to assess than the others with only four teams in the class. At one level all four of the teams, 100%, were able to develop an effective demonstration to show the potential of using a robot to complete the Sawbones process, although two of the four had room for improvement. At another level, however, only three of the four teams, 75%, turned in a design for a full production cell that could be implemented, and all three had room for improvement, mostly in the details related to the safety systems needed to meet the ANSI/RIA standard. So while one could argue that the learning outcome was met, it was marginal, and improvements are warranted. For the next offering of the class teams will be required to submit a preliminary design report so that they get some feedback on their cell design, and they will be required to prototype and test their fixturing solution earlier as well. It is hoped that with the ability to test things for themselves and some feedback on their designs, including the completeness of them, that the results in this area will be better in the future.

Based upon these findings the course is meeting its learning outcomes, but there is room for improvement – so improvements will be made. Two of the learning outcomes that were met were assessed using multiple samples of student work, so there is good reason to be confident in the results of the assessment. Two of the learning outcomes, however, were met, but in one case that conclusion was based upon a small sample and in the other case the learning outcome was barely met. As a result changes are already planned to improve the situation for these learning outcomes for the next offering of the course so that there are more measurements and more structure to support student learning and to hopefully help them more clearly meet the learning outcomes.

Conclusions and future work

This paper has described a new Industrial Robotics course for students in the Manufacturing Engineering program at Western Washington University. The course is designed to balance application and modeling, and to be focused on manufacturing applications. As such, the course covers the basics of robotic modeling, such as inverse kinematics, covers applied topics, such as vision system concepts, and also provides students with significant opportunities to use robots in the lab. Students complete three lab rotations, which introduce them to two different robot brands and three different robot configurations. The lab rotations go from simple and structured, to semi-structured, to semi-structured and requiring design of physical parts or experiments. These lab experiences help prepare students for the open-ended, industrial sponsored design project for which they must both demonstrate a proof-of-concept of their solution and complete a full robotic cell design. This year's project was with Sawbones, and involved robotic cell design and proof-of-concept demonstrations to automate processes involving products in their orthopaedic bone models line.

Overall the course has gotten off to a good start. Assessment of students' work indicated that two of the four learning outcomes were clearly met, and the other two were apparently met. Of the latter two, one learning outcome was met, but the evidence is thin, so the plan is to also get additional evidence from a new lab next year to complement the evidence from the final exam. The final learning outcome was arguably met, but barely, so there are improvements planned for the project for the next offering of the course to provide a bit more structure and feedback. In addition to these, the current plans for course improvements are to change the prerequisite of Introduction to CAM and CNC to a co-requisite of Design of Tooling, and to develop two additional labs for the third lab rotation. The goal is to develop one lab using force control on a 6-axis articulated industrial robot and one lab to allow students to derive and test inverse kinematic equations for a 3-axis, home built robot that is currently being designed by two students for their senior project.

The intent moving forward is to add and amend labs both as new equipment becomes available and as needs and applications in regional industry change. The area that needs the most improvement at this time is the use of vision systems, which is currently limited to two labs on a single type of robot.

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