Agile Robotic Work Cells for Teaching Manufacturing Engineering

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Background

Robots have become commonplace in industry. This is due in part to dramatic improvements in robot programming tools[1] and improved systems integration. The same technology improvements that have made it easier for industry to implement robots make it more feasible for universities to develop robotics laboratories and therefore better prepare students for the manufacturing workplace. It is the authors' contention, as expressed by Stienecker[2], that industry today needs experts in the application of robots using modern controllers and other integrated hardware, rather than robot designers. Stienecker[2] states "undergraduate robotics courses need to become applied robotics courses in which students get real world experience with real hardware."

A major concern, however, with implementing a curriculum that contains modern industrial robots is the cost to purchase and install such systems. Other robotic laboratory developers have outlined cost effective means to implement a robot-based curriculum. Anderson[3] discusses the universal programming language that Microsoft has developed and outlines how basic articulated arm robots can be built from components for around $15,000. This approach is somewhat less expensive than purchasing a branded-name robot product but it will not provide students with the experience of working with industry-grade hardware and software. This paper describes how advancements in digital interfacing technology facilitate the implementation of robotic work cells in educational settings. Further, this paper outlines how the development of offline robot programming and simulation software facilitates instruction.

Agile work cells

Recent advances in robot technology are enabling more educators to implement a curriculum with industry-caliber robotic technology. The technology advancements having the greatest potential benefits to academia fall into two categories: digital interface technology and virtual interface technology. By our definition, digital interface technology includes the tools and techniques that facilitate the installation of safeguarding equipment, sensors, and actuators needed make robots interact with their environment. Virtual interface technology refers primarily to a robust set of offline robot programming and simulation tools that better enables student-centered learning and allows a school to leverage the purchase of one robot to teach dozens of students.

The agile nature of contemporary industrial robots are well suited to the diverse needs of an educational setting. The term agile in this paper refers to a flexible configuration of industry-grade robotic technology. The availability of off-the-shelf components that can be readily integrated into flexible robotic work cells makes it possible to depart from the traditional pre-configured automation cell.

Figure 1 illustrates schematically the central themes of this paper. First there will be a discussion of how the adoption of the modern digital interface technology simplifies the installation of agile robot work cells. Next, it will be shown how the use of virtual interfacing technology facilitates teacher-led instruction and enables student-centered learning. Finally specific examples of agile work cells implemented at Illinois State University will be discussed to illustrate alternative work cell configurations.

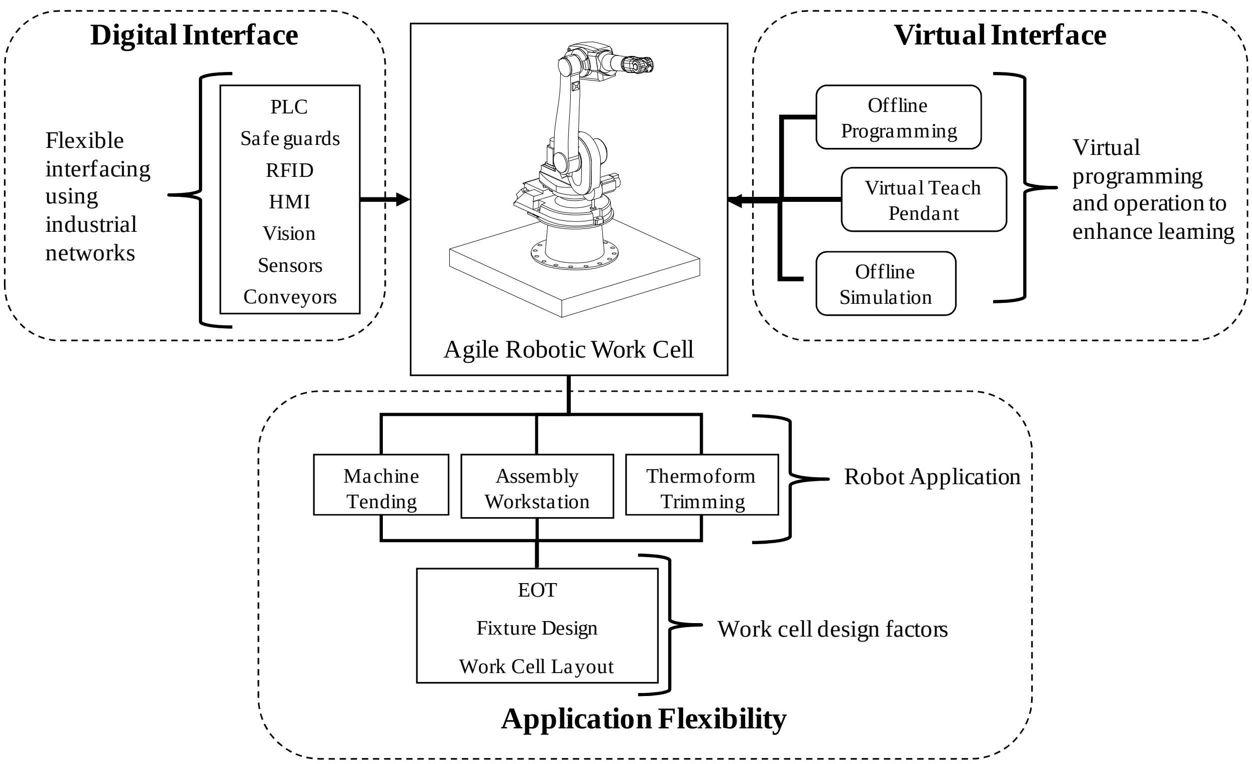

Figure 1. Elements of agile robot technology for education

Digital interface

Robots seldom work alone. Rather, they are usually interfaced with other devices such as PLCs, sensors, conveyors, safety devices, and the like. The traditional interfacing technology used to create an interface between an industrial robot and peripheral devices involves the use of discrete inputs and outputs (I/O). Essentially this means that devices are hard wired together using an individual wire for each communication input or output. A robot having 32 inputs and outputs, for example, would have up to 64 individual wires connected to various devices in the work cell. Likewise, a PLC with 64 inputs and outputs would potentially add an additional 128 wires to the work cell. When using traditional discrete I/O, even modestly-complex work cells can require hundreds of individual wires. This has made the systems integration task time consuming and tedious for industry and academia alike. Furthermore, changes to an existing work cell often require physical wiring to be redone, creating a significant deterrent to making even minor work cell changes in the academic environment.

Industrial networks are now frequently used in place of discrete I/O, relieving much of the tedium and expense of electrical interfacing. Industrial networks are similar to office computer networks in that many devices can be connected to the same physical media[4]. In a work cell interfaced with an industrial network, only a single cable is run rather than the hundreds of individual wires required with discrete I/O. A wide array of devices are available that plug directly into industrial networks. Many of these devices have undergone extensive network compliance testing by independent groups. After a device is physically connected to the network, a network port address is assigned and an electronic data sheet (EDS) is downloaded from the internet. The newly connected device is then visible to other devices on the network. Figure 2 shows a variety of sensors and a network connection block used with the DeviceNet industrial network.

Figure 2. Sensors and Network Connections

The use of industrial networks in an academic setting is beneficial in many ways. One obvious benefit is that the initial effort required to integrate a robotic work cell is greatly reduced. The use of a single network cable rather than many individual wires greatly simplifies the integration process. A second benefit is that a significant deterrent to changing a work cell has been virtually eliminated. Sensors can be added, components moved, and new equipment added to the work cell with minimal impact on physical wiring. This increased flexibility makes it possible to reconfigure an existing work cell with relative ease, making it more attractive to conduct a greater variety of projects and learning activities using the same primary work cell components. A supply of standard sensors, actuators, and other peripheral devices can be kept on-hand and added to the network with ease when needed. Finally, the use of plug-and-play sensors can be of great value when teaching students about different types of sensors. Even students in introductory courses can easily connect sensors during lab activities, thus facilitating a series of hands-on experiments with sensors. Because the sensors are so easy to install, students do not need to worry about wiring and can focus on learning about the applications and limitations of the sensors.

The Caterpillar Integrated Manufacturing Laboratory (IML) at Illinois State University makes extensive use of the DeviceNet industrial network. Figures 3 and 4 illustrate the front and back of one of ten robot workstation in the IML. The DeviceNet network was used to integrate most of the equipment on each workstation. DeviceNet also made it possible to implement a robust safety system in the IML that is controlled by a safety PLC and control panel. The safety system in the IML includes 42 presence sensing mats, 52 emergency stop buttons, 14 safety switches and various key switches and control buttons. All told, there are approximately 300 safety inputs and outputs in the safety system, all running on a single network cable. If these devices were wired individually, there would have been approximately 600 individual wires entering the safety control cabinet. Figure 5 shows two workstations in the IML and illustrates several of the safety devices in the lab.

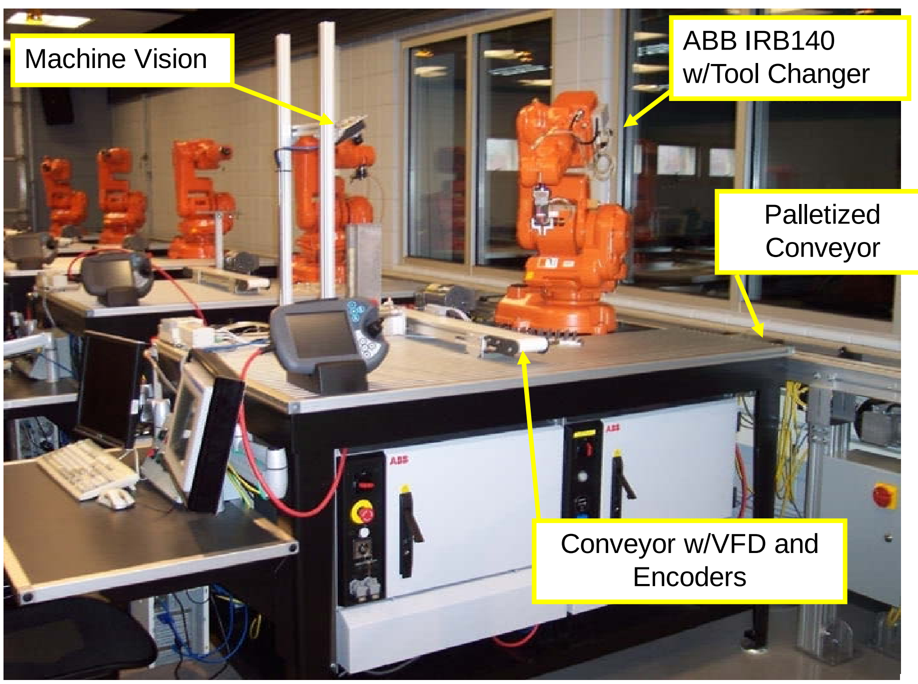

Figure 3. Front of work station in networked robotics lab[5]

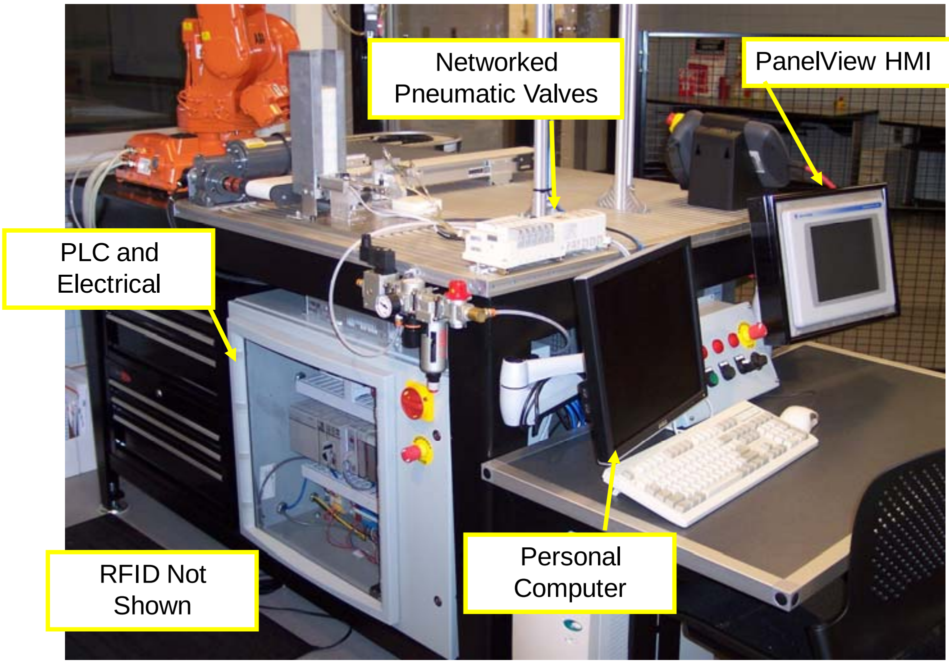

Figure 4. Back view of work station in networked robotics lab[5]

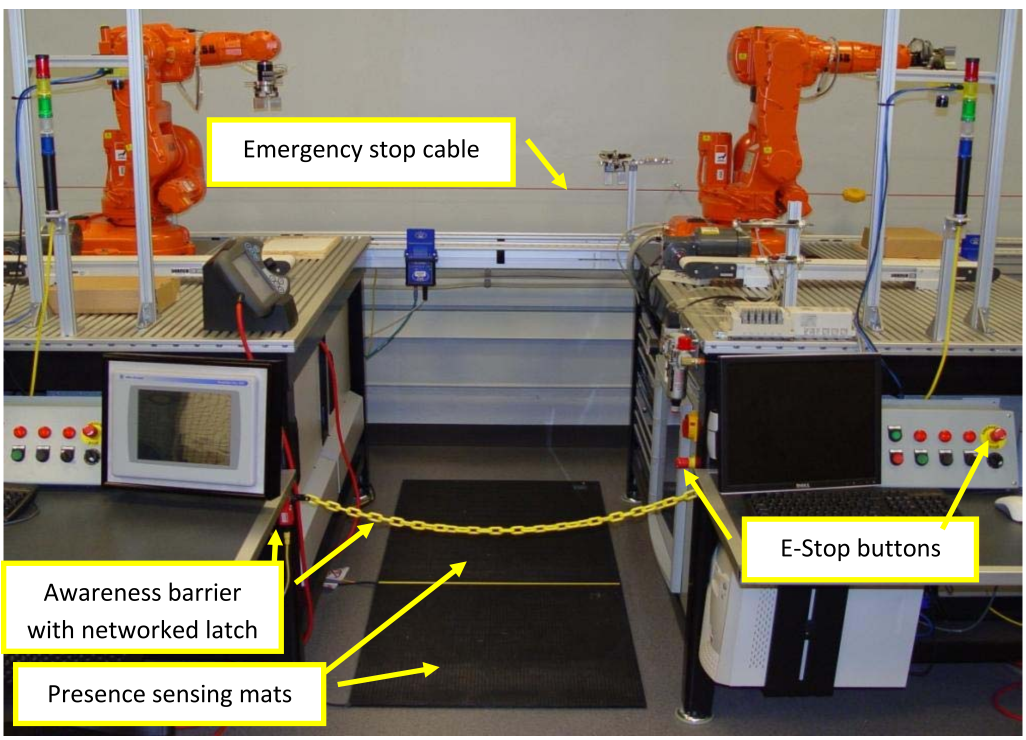

Figure 5. Example of networked safeguarding of multi-station robot lab

Virtual interface

Most industrial robots are programmed and operated 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. Figure 6 shows a teach pendant and industrial robot made by ABB. Because there is no practical way to project a teach pendant, the logistics for demonstrating robot operating and programming procedures to students has long been problematic. Therefore, it was not uncommon for 20 students to circle around an instructor who was describing the screens as they appeared on the teach pendant. Further, due to cost constraints, most engineering technology programs have very few industrial robots available for instruction, making it very difficult to provide students with important hands-on learning experiences. Fortunately, recent advances in offline robot programming and simulation tools now make it possible to augment the limited hands-on instruction with almost unlimited virtual-robot instruction.

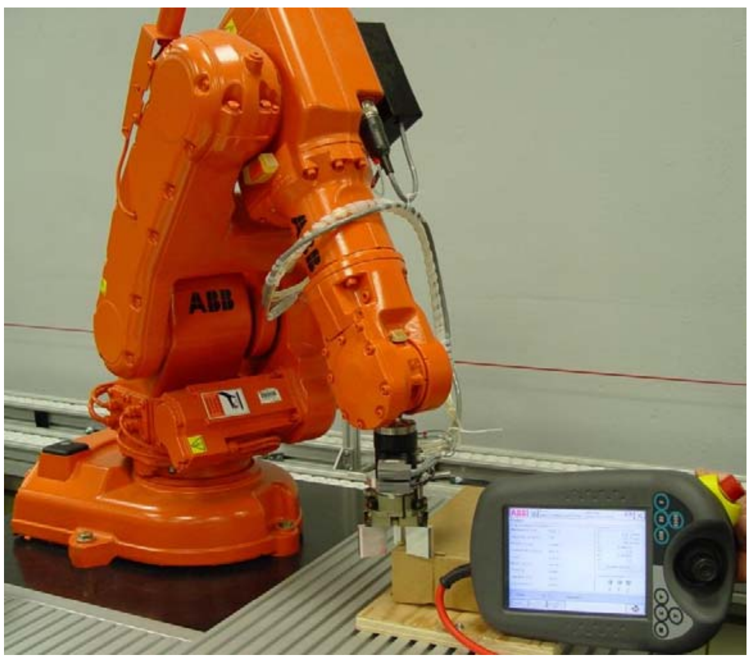

Figure 6. Robot with teach pendant

Driven by the needs of industrial robot users, robot manufacturers and software vendors have developed a new generation of offline robot programming and simulation tools. Unlike CAM packages that have been used to program and simulate CNC machine tools for decades, offline programming and simulation systems for industrial robots were not widely used until recent years[1]. Today's offline programming and simulation tools offer a robust set of tools that provide educators with unlimited potential for instructional innovation.

The offline robot programming and simulation software most familiar to the authors is RobotStudio[6], which was developed by ABB to support their line of industrial robots. At the heart of RobotStudio is a virtual controller equipped with a virtual teach pendant. Figure 7 shows a screen capture of a virtual ABB robot and virtual teach pendant.

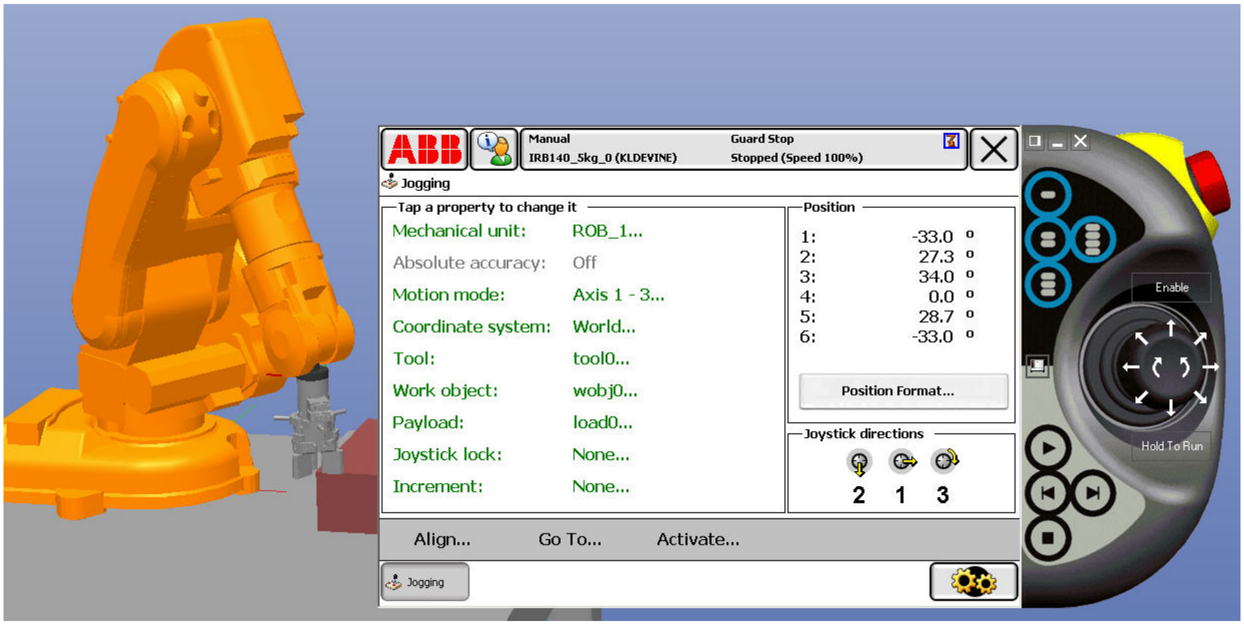

Figure 7. Virtual robot environment with virtual teaching pendant

Because the virtual controller runs the same software as the real controller, the virtual teach pendant is a very accurate replica of the real teach pendant. RobotStudio users working with the virtual teach pendant interact with the virtual robot using the same menus, screens and procedures used on the real robot. The authors have found the virtual teach pendant very helpful for instruction in a number of ways. First, the virtual teach pendant can easily be projected for all students to see, essentially eliminating the need to gather students in a circle around the robot. The virtual teach pendant also makes it possible for instructors to develop customized handout materials with screen captured images that exactly match what is seen on the real teach pendant. Furthermore, the virtual teach pendant allows instructors to create virtual robot lab assignments that allow students to program and operate virtual robots outside of class. The virtual labs can be designed to allow students to practice procedures introduced in class or to introduce new procedures and concepts before coming to class. The homework exercises can be designed in such a way as to allow students to learn though experimentation and discovery, which is sometimes problematic for safety reasons when working with real robots. Experience has shown that using the virtual teach pendant outside of class enables students to work more efficiently when working on the real robots.

In addition to the virtual teach pendant, RobotStudio has a robust set of graphical programming and simulation tools which have proven to be effective teaching tools. For example, novice robot programmers must become familiar with many robot motion control parameters, some of which are difficult to visualize. Program simulations can help students see abstract concepts with clarity. For example, Figure 8 is a screen captured image from RobotStudio that illustrates how program motion parameters can affect the path of the robot. In this example, the student intended to have the robot weld around the perimeter of the block as indicated by the yellow path. The black path is the actual path taken by the robot when the program was simulated. Through experimentation, the student was able to modify a variety of motion parameters to improve the welding process and gain a better understanding of the related parameters.

Finally, novice programmers often have difficulty debugging programs that use counters and if-then loops. User friendly debugging tools such as windows that show the current value of counters and a visible program pointer make it easier for new programmers to understand programming logic.

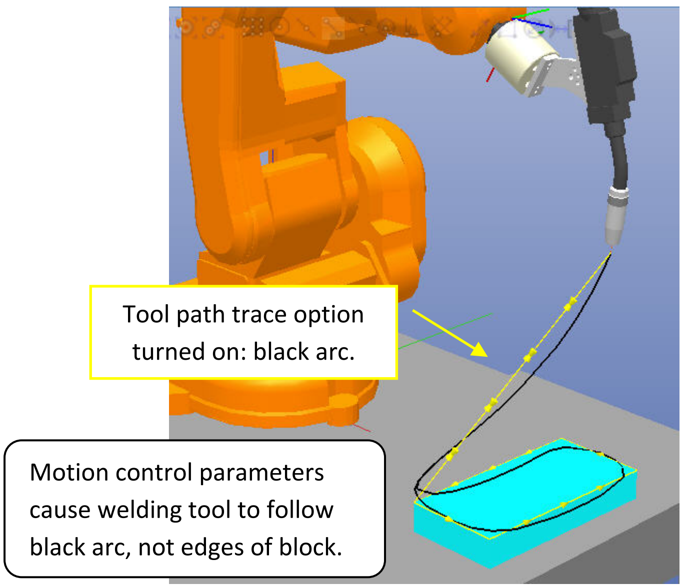

Figure 8. Simulation tools provide resources for student-centered learning

Examples of agile robotic work cells

Two configurations of agile robot work cells have been implemented at Illinois State University. The aforementioned Caterpillar Integrated Manufacturing Laboratory (IML) is an example of a highly networked, multi-station, assembly work cell. The IML is a very agile work cell that has been successfully used to deliver hands-on instruction of introductory automation concepts through advanced systems integration. The second robot work cell is comprised of a stand-alone robot and PLC that is used to perform machine tending and material removal operations. By changing out end-of-arm tooling and fixtures, students from different courses utilize this work cell to perform trimming of thermoformed parts or drilling holes in components for later assembly. Figure 9 illustrates the use of this work cell to perform trimming of a thermoformed part by using an air drill for the end-of-arm tool and a vacuum fixture to hold the work piece. The robotic work cells discussed in this paper are used in several courses throughout the manufacturing technology program including TEC 130 Introduction to Manufacturing Processes, TEC 234 Robotic Systems Integration, TEC 318 Product Modeling and Analysis, TEC 345 Process Control Networks, and TEC 392 Manufacturing Organization and Management.

Figure 9. Agile work cell example: from assembly tasks to material removal applications

The example of a stand-alone robot work cell is used to illustrate how a college program can leverage the purchase of one physical robot to teach numerous students important, non-trivial robotic automation functions. Figure 10 illustrates the use of the work cell by numerous project teams during the TEC 392 capstone manufacturing course. Each team had to employ a robot to perform material removal operations on their unique product. By employing the virtual interface of offline programming and simulation one team is able to design and debug their set-up concurrent with other teams. The process begins by a team importing the three-dimensional CAD models of their product and fixtures into their virtual robot environment. When this project team has successfully developed a program to complete the operations required for their project, they upload the robot program from the virtual work cell to the physical robot work cell. After the program has been uploaded and coordinate systems calibrated, this first team can run their material removal operations in the physical work cell: robot moves, air drill engages, holes are drilled and chips are made. While the first team is using the physical work cell, other teams are developing their unique robot programs in their own virtual robot work cell environments. When these other teams have successfully simulated their programs, they in turn will upload their programs and run them in the physical work cell. The ability to conduct numerous parallel robot programming projects that will ultimately be run on a real robot provides a tremendous cost savings advantage and dramatically increases instructional efficiency.

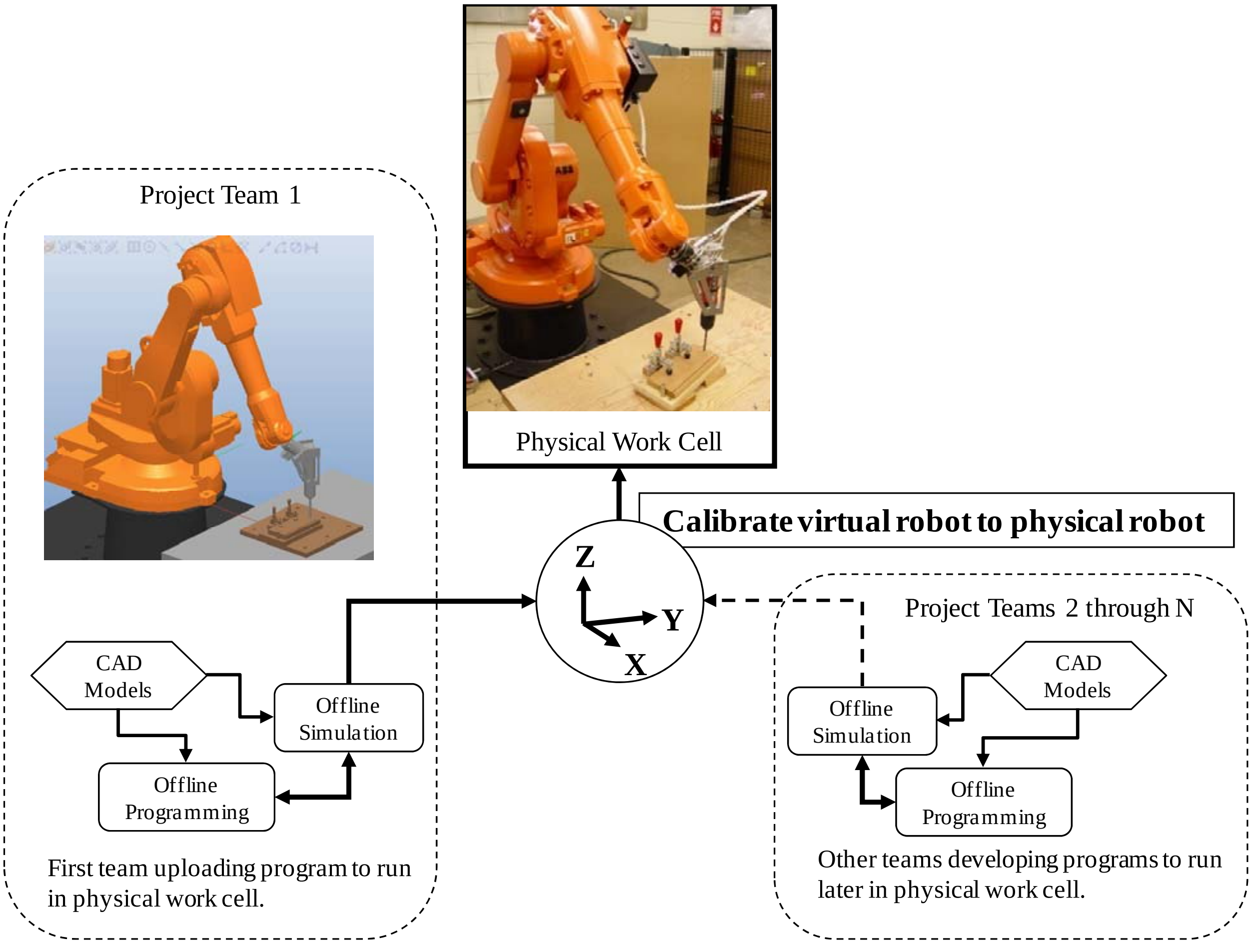

Figure 10. Leveraging robotic hardware with offline virtual robot environment

Two important lessons have been learned by incorporating robot technology in the capstone manufacturing course at ISU. The first lesson supports the age-old adage about keeping things as simple as possible. In an effort to demonstrate the flexibility and potential productivity improvements of robotic technology, students were required to design and fabricate work holding fixtures capable of holding multiple parts. A robot was then used to drill holes in the parts that were later manually assembled. Unfortunately, the fixtures proved to be much more difficult for the students to design and fabricate than anticipated. Furthermore, because of reach limitations of the robot, the parts needed to be grouped closely together on the fixture making the robot programming task much more difficult. The aforementioned reach limitations also left little room for error when it came to locating the fixture within the robot's physical work envelope.

The second lesson learned was that offline robot programming and simulation should be employed very early in the planning stages of the projects. The first time the robot technology was used in the capstone class, students had little prior exposure to the offline programming and simulation tools. Thus, much tedious and slow manual teaching had to be performed online. This on-machine programming created a bottle neck as several groups had to perform similar tasks during class time. Access to offline programming and simulation now permits students to evaluate their set-up without using the physical work cell. Once they have a workable solution in the virtual space they can readily download their program and validate their work on the real robot.

Conclusion

Due to the growth of robot applications in industry, there is a need for applied robotics courses in which university students get practical experience working with industry-grade robot technology. The authors acknowledge that it is not practical for many schools to implement a robot laboratory on the scale of the Caterpillar IML mentioned earlier in this paper which was the result of a generous 1.2 million dollar donation from the Caterpillar Foundation. However, this paper illustrates that much can be done with one industrial-grade robot equipped with digital interfacing technology, offline programming, and simulation software. The educational discounted price of an ABB IRB140 (see Figures 3, 5, and 6) with twenty seats of Robot Studio simulation software is $32,000. The technological advances outlined in this paper not only lead to improved student centered learning and greater instructional efficiency; they also allow a university to leverage their capital investment in robotic technology.

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