AC 2008-861: APPLIED INDUSTRIAL ROBOTICS: A PARADIGM SHIFT

Adam Stienecker, Ohio Northern University
Adam Stienecker teaches electronics and applied control systems courses at Ohio Northern University in the Department of Technological Studies. He holds undergraduate and doctorate degrees in Electrical Engineering from the University of Toledo in Ohio. His areas of research include 2.5D and 3D robotic vision.

Applied Industrial Robotics: A Paradigm Shift

Background

Since the introduction of industrial robots in the 1960's, [1] the industry has grown in leaps and bounds, similar to many other technology fields. According to statistics released by the Robotic Industry Associates (RIA), the robotics industries' only trade group[2], the industry has doubled since 1996 [2]. When one reviews [3, 4, 5] the instructional materials currently available to the robotics student she or he will find an assortment of old applied industrial robotics material published in the mid to late 1990s with a plethora of robot design and kinematics texts that were published after 1999. This represents the traditional and current approach to the robotics education at many institutions. In the last four decades the student that took a robotics class was typically a mechanical or electrical engineer and the course likely focused around robot kinematics and design as the industry was in need of engineers to design the robotic manipulators and their control systems. Today, industry is much less in need of robot designers and much more in need of experts in the application of robots and the design of the systems that work with the robots such as end-of-arm-tooling and vision systems. It is the author's opinion that while kinematics and design are necessary areas for some students, the majority of industry bound undergraduate students in all degree options within engineering will likely find it more useful to study the application of the equipment rather than its design.

The chart below indicates the number of robots in operation in America since their introduction. Data were obtained from Keramas before 2000 and from the World Robotics 2006: Exectutive Summary for the remainder of the data. Years not represented in the data were linearly interpolated. Data obtained between the years 2006-2009 are estimates.

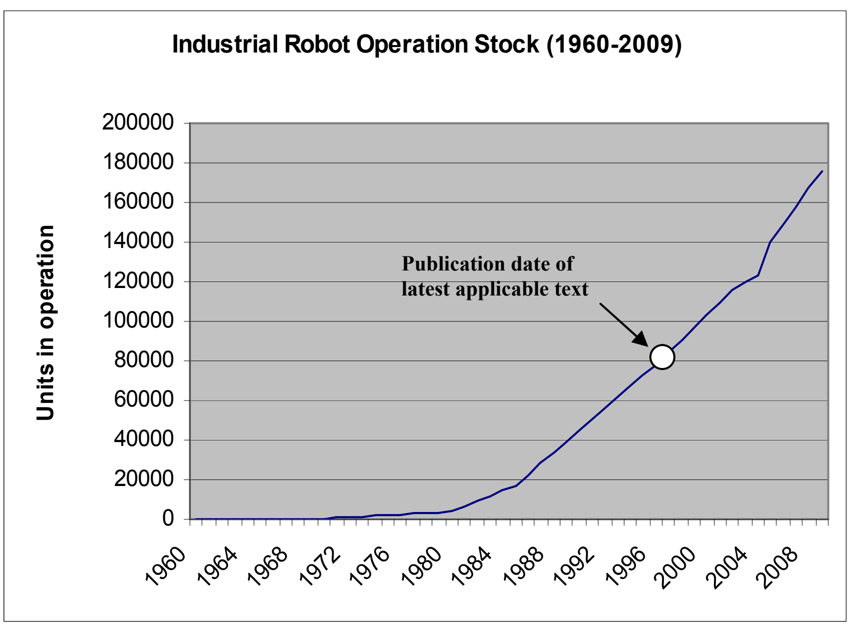

Figure 1: Industrial Robot Operation Stock from 1960 through 2009

The most current text's [1] (with industrial application focus) publication date, 1999, is indicated in Figure 1. Since the date of publication of [1] the industry has almost doubled in size. This says nothing regarding the advance in technology in the machines and peripherals. Since then, drastic advancements in End-of-Arm-Tooling (EOAT), vision systems, robot programming, and overall capability have been made. Other items such as network communications and interface with other devices have since come into view and are not included in this latest text. It can be said that if a student learns the industry based on the most up to date text that she or he would likely be only familiar with the terminology and be lost when it came to the application or troubleshooting of a current machine. According to Faculty Center [5], a textbook adoption data warehouse among other things, 16 major universities are making do with a book [7] that was published in 1996 and is now out of print. This is the most used book in applied robotics according to Faculty Center [5]. Several other universities, including the author's university, aren't using textbooks for their applied robotics courses, according to their websites. There are assuredly many reasons for this, but a lack of up-to-date selections is likely at the top.

Given the current need in industry of more system designers of robotic workcells and less robot designers it seems necessary to shift the way we teach our undergraduate robotics courses. Undergraduate robotics courses need to become applied robotics courses in which students get real world experience with real hardware. It becomes expensive to make this shift as industrial robotics equipment and peripheral equipment can be expensive, but the switch is necessary to most appropriately serve our students. Additionally, the courses need to be packed with current technology and methods such as interfacing industrial robots with vision systems for bin picking applications, utilizing PLCs and other hardware along side industrial robots, and common industrial communication protocols such as DeviceNet.

Solution

The easy solution to the problem of the lack of a current textbook is to utilize the manuals and datasheets of the equipment used in the laboratory. These are the textbooks that are used in industry. These documents are sometimes inconvenient when used as a teaching textbook, but the solution carries an added benefit that the students are well trained in using technical manuals and sorting their way through datasheets after having gone through the curriculum. In some instances supplemental material must be provided as a datasheet does not give attention to all issues. One such issue is that of EOAT selection. If an angular finger gripper is required what force must be used to maintain hold on the payload? If a vacuum cup is required, how much vacuum is required? Another issue is communication networks. How does DeviceNet work? What are the priority levels in the network? These questions must be answered with supplemental material whether they are generated by the instructor or supplied in an additional text.

Once the content that will be taught in a class has been decided, the selection of manuals and datasheets to use in place of a textbook or to supplement the textbook is fairly straightforward. Unfortunately, the selection of course content is not nearly as simple.

The RIA [2] lists robotic application categories as follows:

1. Arc Welding
2. Assembly
3. Coating
4. Dispensing
5. Inspection
6. Lab/Biotech/Life Sciences
7. Material Handling
8. Material Removal
9. Safety
10. Simulation
11. Spot Welding
12. Other

It can be readily assumed that if the RIA lists the categories as above, that a robotics educational program should somehow address those topics. However, because the RIA is interested only in robots they do not include that equipment which interfaces directly with robots. The author believes that the following additional topics should be required in a good robotics curriculum.

13. End-of-Arm-Tooling (EOAT)
14. Machine Vision Guidance
15. Identification techniques (RFID, Bar Code, Material)
16. Interface to other systems (PLCs, Machining Centers, etc.)
17. Network Communications

Combining the two lists given above leads to a very large and daunting curriculum for both students and instructors. If an instructor is fortunate enough to have a curriculum that is long enough to accommodate the above lists and cover each topic well, then the categories should be maintained. However, for everyone else, there is not enough time to cover the above topics and maintain quality.

In order to accomplish this curriculum in a reasonable time frame, the author recommends the following alterations. Because there are similarities, from the view of the robot, between items 1, 4, 8, and 11 a good treatment of one of these areas (likely item 11 as it is seemingly more common) should suffice. Item 5 can be combined with item 14. In the department in which the author resides, simulation is treated separately and is therefore left out from the remainder of discussion. However, the author would encourage the reader to consider the importance of simulation in her or his curriculum if it is not included elsewhere. Due to the simple rarity and lack of applicability of items 6 and 12, they are also eliminated from further consideration.

The following is the resulting list:

1. Spot Welding
2. Assembly
3. Coating

4. Material Handling
5. Safety
6. End-of-Arm-Tooling (EOAT)
7. Machine Vision Guidance and Inspection (2D, 2.5D, and 3D)
8. Identification techniques (Radio Frequency Identification (RFID), Bar Code, Material)
9. Interface to other systems (PLCs, Machining Centers, etc.)
10. Network Communications

Within the region in which a university is located there tends to be a surrounding industry or set of industries. It is these industries that likely hire or will hire the graduates of a program. Because each industry has different needs each university will prepare their students differently; therefore, it is left to the reader to determine which of the categories above deserve priority within a given curriculum. However, all industries have one thing in common, they will benefit from a hands-on curriculum in applied robotics.

The author believes in and is dedicated to a largely hands-on delivery of these topics were possible. It is that reason that the author has built a teaching laboratory around the discipline of applied robotics in order to deliver the curriculum described above. The following will describe the methods of developing the laboratory along with the successes and failures in order to encourage others in their pursuit of the development of a similar space.

The Laboratory

In the summer of 2006, the author began to re-build an applied controls laboratory beginning with the acquisition of a set of industrial robots. Through the course of one year the author acquired equipment that allows the hands-on instruction of the list defined in the previous section. The identity of the products used in the laboratory is offered to the reader in an effort to help the reader understand the laboratory and not to advertise the use of any one brand.

The laboratory was built around the KUKA KR3 Industrial Robot [8]. The university invested in seven units to build an applied robotics laboratory around. KUKA was chosen for three reasons. First, all KUKA robots have identical teach pendants and software so the students would be familiar with at least 50 different robots. Second, an external monitor, keyboard, and mouse can be connected to the robot controller such that multiple students can see and interact with the teach pendant. Third, the cost of the units was relatively less than other solutions.

Failures:

- The teach pendant, as all are, are difficult to see properly if you aren't the individual operating it. For teaching purposes, it is advantageous to have an external monitor, a keyboard, and mouse connected to the robot so that not only can the instructor see what the problem is, the other students working on the team can provide input to the laboratory exercise. During the first year, the external monitor was not installed and this led to teams with one student doing the work and the others watching at best.

- Currently the laboratory uses a simple angular finger gripper, exclusively. It would be advantageous to use a vacuum cup, and other alternatives to give the students an array of experience.

- The KUKA I/O, other than a few discrete points near the tool mounting plate, is brought out of the DeviceNet connection in our particular model. This is unlike some robotic systems made by KUKA and others. This was not necessarily a failure, but an added planning point for the author. Allen-Bradley [9] CompactBlock I/O systems are used to make the discrete I/O accessible to the student via DeviceNet.

Successes

- During the second year of building the laboratory a portable dual monitor tree was installed near the robot, shown in figure 2. One monitor was connected to the robot and another to an additional PC used to display tutorial files or manuals. A single keyboard and mouse controls both the robot and the additional PC via a KVM switch. This was a terrific move as it aids in team building and faster completion of assignments while in the lab.

Figure 2: The dual monitor tree

Another key component to the lab is the vision system. The author has employed both smart camera technology and Firewire camera technology to aid in the fulfillment of number seven in the list above. The DVT-535 from Cognex [10] serves as the smart camera technology and is interfaced to the robot via discrete I/O. This allows for part inspection, bar code reading, part presence, and visual guidance of the robot. The Firewire camera technology that is employed is from Point Grey Research [11] (Flea2, 1024 x 768). Coupled with VisionPro software from Cognex, [10] the camera interfaces directly into a PC via firewire and from the PC to the robot via a serial port. This makes for an unlimited application base to teach upon. Currently the firewire camera is for use in special projects only as time does not permit the covering of this system within the confines of the current curriculum. However, it still provides very useful and creates excitement in students and their projects.

Failures

- A critical part of any machine vision system is the lighting. Although the cameras work without any extra ambient light it is difficult to teach concepts in vision with AC lighting. The author relied upon the optional DC ring lighting kit that can be ordered with the DVT-535 model cameras. While this lighting helps it isn't sufficient for the high reliability that is needed in a teaching lab. High quality and high quantity DC lighting is a must for machine vision in the lab.

- The smart camera technology is capable of being interfaced via serial communications. However, it requires a disconnection between the programming PC and a connection to the serial port of the robot. Due to the installation it is inconvenient if not impossible to accomplish this and therefore the only interface to the robot is through discrete I/O. This does not allow the data encoded in the bar code to be translated to the robot only whether the bar code matches a predefined code.

- The optical lens that is attached to the camera is typically a fixed focal length lens in industry. The author selected a fixed focal length lens and is now stuck with the focal length unless a budget comes available to purchase another lens. The initial investment of a variable focal length lens would have proven useful.

Successes

- The software available to program the DVT-535 smart cameras is user friendly and students can program it with minimal assistance from the start. This aids in the teaching of concepts rather than the teaching of a software package.

- After the point in which the author realized that lighting was an issue, Advanced Illumination [12] was able to provide a very effective and wide array of products to allow the students to experiment with different colors of lights, light intensity, and lighting angles.

- The continuous connection of the smart camera to the PC allows the student to see what the camera sees and to more readily understand what the camera is doing and how it is doing it. The student can see why a part didn't pass inspection by simply watching the monitor. The continuous computer connection has proven very valuable.

Identification techniques have been touched on briefly in the previous section as it applies to bar code reading, but this area encompasses much more. The author has implemented the Pepperl+Fuchs IDENT RFID system [13] which communicates via DeviceNet to the robot. This allows passive RFID chips to be read and written through the robot and is a powerful introduction to RFID for the students. Small RFID tags are located in wooden blocks which are manipulated with the robot and can be sorted based on the data available on the RFID tag.

Additionally the laboratory has the ability to sort based on material using an inductive proximity sensor. In a very simple exercise the student can write a program that inspects a product for ferromagnetic part presence as well as part placement verification.

Failures

- The IDENT RFID system has proven possible although challenging to implement into the KUKA robot due to the IDENT requirement for serial DeviceNet communications.

- The inductive proximity sensor is a valuable asset to the teaching environment, but a wide array of proximity sensing technologies would be an improvement.

Successes

- The IDENT RFID system consists of the control interface unit and up to four read/write heads. Although the author has implemented only one read head per control interface there is plenty of room to expand when new technologies in reading and writing RFID tags emerge.

- The non-direct connection of the inductive proximity sensors have provided useful. Because the author had available in the lab, several AC inductive proximity sensors, they were used in conjunction with a relay to interface to the DC system of a PLC which is interfaced to the robot. This simple relay gives an audible indication of the part being detected and aids greatly in troubleshooting. The connection through the I/O of a PLC and then into the robot's CompactBlock I/O module also provides a complicated and educational route that the student must take to accomplish the task.

The interface that a robot makes to other systems is sometimes the most important because it rarely operates in industry without a direct interface with another machine. The most important thing that can, in general, be taught other than programming the robot is to interface it with another machine. The author employs several routes to accomplish the task of educating the students in this area. An EMCO [14] CNC machine with a Fanuc 21 controller is interfaced with one robot. An Allen-Bradley [9] Micrologix 1500 PLC is interfaced to each of the other robots allowing the data to be used by the robot from the aforementioned smart cameras and a series of eight photoelectric sensors as well the inductive proximity sensors. The sensors allow an interface with a large conveyor belt that was purchased through a used automation equipment dealer. A note should be made that PLC and CNC programming is accomplished elsewhere and the students are expected to have the respective skills before interfacing a robot with the systems.

Failures

- The laboratory operated for a year without the new CNC machine. An educational style CNC machine had been used in the department for a while but was shortchanging the students due to the lack of industry style controllers and functionality. The new CNC machine has addressed the issue.

- Because the conveyor was purchased second hand it required a paint job, but even worse safety was compromised for a period of time due to missing guards. These issues have been remedied, but required more work than if a new machine was purchased.

- The PLCs that have been interfaced into the system have no DeviceNet communication interface built in to them. This is not a problem but limits the likeness to industry we could have in that area. A high level PLC with a DeviceNet connection and analog inputs would drastically improve the level of work that is accomplished by the students.

Successes

- Because the conveyor was purchased second hand, no options were available. Fortunately, the conveyor had a variable speed/reversible drive attached to it. This has been a remarkable tool to test student code in robotic conveyor following projects and machine vision inspection.

- Another feature of the conveyor was its adjustable height. This has aided greatly in the installation of the system.

- The series of photoelectric sensors mounted along the conveyor are coupled with long mirrors on the opposite side of the conveyor. The sensors are on din rail mounts (see figure 3) and can slide back and forth several inches so that the students can position them wherever they like. A simple bracket was made that converted a din rail mountable relay socket into a connection to the sensor.

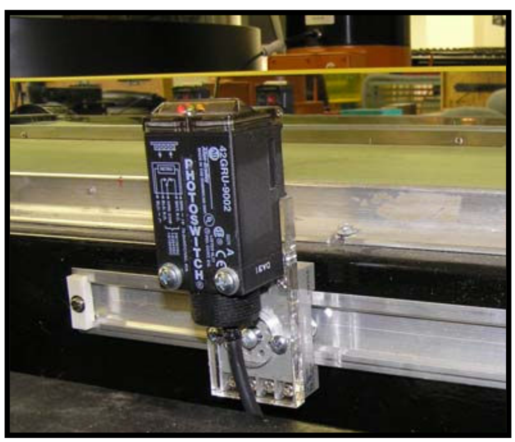

Figure 3: Moveable Photoelectric sensors mounted along the conveyor

An overall picture of a part of the lab in shown in figure 4. An attempt has been made to show the general layout of the components of the system.

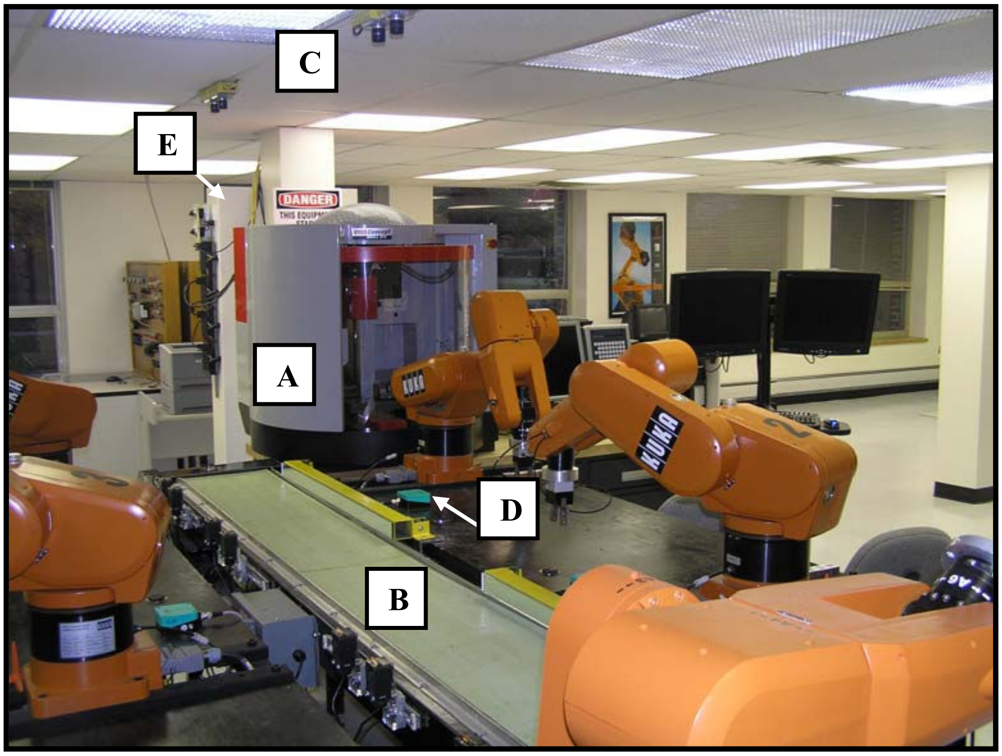

Figure 4: Overall layout of the laboratory

A. The CNC Mill.
B. The variable speed, reversible conveyor with eight photoelectric sensors located along one side with two mirrors located along the other.
C. Smart cameras mounted above the conveyor.
D. RFID read/write head. The IDENT controller is not visible in this picture.
E. The student built PLC control cabinet.

A summary in chart form of the successes and failures are given in chart 1.

System	**Successes**	**Failures**
Robot	The dual monitor tree	Teach pendant is too small to be viewed by more than one student
		Use of a single gripper technology
		Lack of planning for DeviceNet I/O
Vision Systems	Programming software	Lack of lighting options
	Wide array of lighting obtained after the fact	Serial / Ethernet communications
	Continuous PC to camera connection	Fixed length lens
Identification	RFID expandability	IDENT RFID challenging to implement
	Indirect access to sensing data	Limited array of proximity sensing technologies
Other systems	Variable speed conveyor	Educational CNC machine
	Variable height conveyor	Conveyor safety compromised
	The ability to position the photoelectric sensors	PLCs lack DeviceNet communication abilities

Chart 1: Successes and failures summary

Creative Methods

Over the course of the last two years, the author has built a $0.5M applied robotics teaching laboratory on a budget of less than half of $0.5M. In order to accomplish this, creativity is required. Some of these creative methods are described below.

1. The biggest and most obvious is educational discounts. Some manufacturers will give you up to 70% off but not just by asking or even begging. These businesses are typically not non-profit. They exist to make money on the products they sell. Most companies need to be sold on the idea that their product will be in the hands of their future customers and that this will impact their future business. Many companies don't get this and need to be given an elaborate proposal detailing numbers of students that will be impacted and the types of employers the students work for after graduation. These companies don't typically know that they want these elaborate proposals, but the author has found success in the justification of a significant discount from a business standpoint. There were several times along the path that competitors were competing to award a discount or even donate a product to the laboratory after their management understood the position that this put them in with our students.

2. Repurposing equipment is an important lesson. One electrical control box in the laboratory would have cost $12,000 - $15,000 if it was purchased from a supplier. Instead an old robot control cabinet was stripped and PLCs, a power supply, terminal strips, and wire guides were installed at very low cost. See figure 5 for the PLC control cabinet. Old metal tables were painted and a plywood cover installed to serve as the base for the robots. All hookup wire was obtained by stripping out old robots that were being scrapped. The computers that interface to the smart cameras were being replaced in a computer lab adjacent to the robotics lab and were brought in to run simple camera software.

3. Donated equipment from local industries is a valuable opportunity. Many companies have old equipment and sometimes new equipment they wish to get rid of. The author obtained 2000 feet of 9 conductor, shielded, communication cable from a local company that had ordered the wrong product several months earlier and could not use it in their application. Additionally, two brand new touch-panel graphical user interfaces were obtained because a local company didn't need them any longer. Likewise, old equipment can be pieced out and re-used. Items as simple as relays and hookup wire provide a money savings compared to purchasing new.

4. Time can be the most precious and lacking resource in this uphill battle. The author found that since teaching was his job, teaching students to commission robots and build electrical panels was just an extension of his job. Several students were instrumental in the construction and testing of the system. Some weren't even paid for their time; they felt that it was a valuable experience to have the opportunity to wire photoelectric sensors into a junction box or make cables for the system. Likewise, when the seven KUKA robots came in, the students downloaded the datasheets and determined how they

mounted and made it happen as part of the class. They drilled holes, ran air lines, and machined and mounted adapters for the end-effectors.

5. Stay involved in industry in general and build relationships with local industries that haven't yet fully embraced many of these technologies. Offer to do a "proof-of-concept" project for them if they fund the purchase of some of the equipment. Many companies are willing to spend some R&D funds on a university if they get something for it. A positive side-effect is the practical experience you will be able to bring into the classroom.

Future Directions

Throughout the past two years, many new technologies have been integrated into the laboratory and new technologies will continue to be integrated. Current plans include widening the array of EOAT technologies that are available in the laboratory. The major component of this will be vacuum technology and differing sizes of vacuum cups. Ideally a customizable vacuum cup system will be designed and built or purchased that would allow the students to build a custom multi-vacuum cup gripper as a laboratory exercise. Additionally, the industry is continually moving forward in 3D vision, namely in bin picking. Another intent is to obtain a series of laser lines that can be used as segmented light to build a 3D vision system using a single camera.

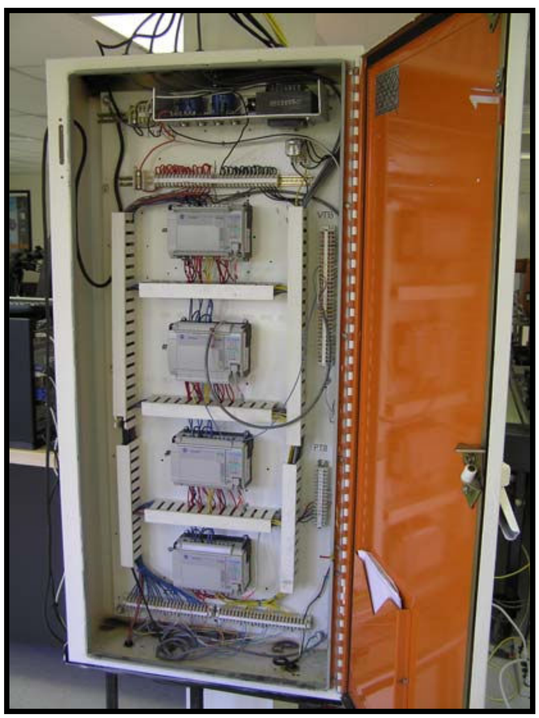

Figure 5: Student built PLC control cabinet

Conclusion

The above paper has described, what the author believes to be, an improvement in the curriculum of an applied robotics course. The topics covered in the curriculum allow the students to have an experience that would assist them whether they went into the automotive industry or the medical industry. In fact, one particular student was able to demonstrate more knowledge of programming robots than the engineers he was working under. He showed a mastery of the skill and has been successful because of it. Additionally, the laboratory setup and equipment contained within have benefited the students beyond imagination, giving them real world experience in many areas of applied controls. This experience has begun to leak into other areas of the curriculum and has produced more advanced senior capstone projects and enabled the interface of robots to a plastic injection molding machine in a course on plastic technology.

The laboratory has also benefited externally. Because of the efforts described above, world class manufacturing facilities 100 miles away are paying our internship students twice the average internship pay in our area. One local industry, just in the past six months, has funded research in 3D vision guided robotics through the laboratory which provided the author and two undergraduate students an opportunity to develop new technology for industry.

Ultimately, the laboratory is at a place that could remain unchanged for a period of four or so years before things start to become outdated. However, to remain unchanged would be to lose a momentum of forward movement and ramping-up a laboratory to an up-to-date condition is not something you want to do every four years. The author is set on keeping the momentum going by continually integrating small amounts of new technology into the laboratory while carefully maintaining the systems that are there now.

References

1. Keramas, J., "Robot Technology Fundamentals", Delmar, Albany, NY, 1999.

2. Robotic Industry Associates, www.roboticsonline.com.

3. Ohiolink, www.ohiolink.edu.

4. Barnes & Noble, www.bn.com.

5. MBS Textbook Exchange database, www.facultycenter.net.

6. www.worldrobotics.org, "World Robotics 2006: Executive Summary", 2006.

7. Masterson, J., Towers, R., Fardo, S., "Robotics Technology", Goodheart-Wilcox, 1996.

8. KUKA Robotics, www.kuka.com.

9. Allen-Bradley, www.ab.com.

10. Cognex, www.cognex.com.

11. Point Grey Research, www.ptgrey.com.

12. Advanced Illumination, www.advancedillumination.com.

13. Pepperl + Fuchs, www.pepperl-fuchs.com.

14. EMCO, www.emco.co.uk.