GETTING YOUR ROBOTIC ARMS AROUND COMPUTING CURRICULA

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Abstract

Our academic institution is very fortunate to have a robotics laboratory that houses eight robotic arms as well as other miscellaneous support equipment like camera systems and conveyer belts. The lab is maintained by a computer science department and the students utilizing the lab are primarily Computer Science, Computer Information Systems, and Mathematics majors. We have no engineering department. Over the last several years we have developed a variety of coursework, undergraduate research projects, and other activities to nurture an active learning environment in which undergraduate students not only learn hands-on and theoretical articulated robotics concepts, but are also taught traditional computer science concepts via industrial robotics equipment. A survey of the different facets of this active learning environment is presented in this paper.

Introduction

Unlike mobile robots which are popular in academia [1-6], industrial robotic manipulators (arms) have traditionally been prohibitively expensive for educational environments. Also, industrial robotic equipment that is acquired by an educational institution typically finds its home in the engineering department and is usually utilized as part of a mechanical engineering degree program. Therefore, little work has been published on how to incorporate industrial robotics equipment into a typical ABET (Accreditation Board for Engineering and Technology) accredited computer science curriculum. Kumar and Meeden [7] describe an Artificial Intelligence course based in an industrial robotics laboratory and is one of the few papers we found that is similar to our efforts.

Times they are a changin'… Recent years have seen industrial robotic equipment becoming more available to the world of academia primarily because of two reasons: (1) many U.S. companies are donating their used equipment as they upgrade to current state-of-the-art machines, and (2) many robot arm makers now have special educational packages that make such equipment more attainable. Our robotics laboratory features a total of ten robotic arms, most of which were donated to us by the Stäubli Corporation. The equipment is integrated into our Bachelor of Science in Computer Science and Bachelor of Arts in Computer Information System degree programs.

In recent years we have made great strides in starting to realize the full potential of our robotics facility. In this paper, we outline the several different ways we are utilizing this industrial robotics equipment:

- The equipment serves as the center piece of the following courses Robotics, Artificial Intelligence, and Computer Vision. We have already published detailed papers on specific ways that the equipment has been integrated into the Artificial Intelligence and the Computer Vision courses [8-9].
- Our industrial robotics laboratory is also a hot bed for undergraduate research. Students enroll in independent study courses and work to implement novel visual or voice guided robotic applications. Some of these projects resulted in recent peer-reviewed published articles [10-13] which were co-authored by the students.

- A 24 credit hour focus area in "Automation" is being integrated in the Computer Information Systems degree which will offer a unique combination of robotics, business, manufacturing, and engineering technology management concepts.
- Strong collaborations have been established with Stäubli and SEW Eurodrive which has not only resulted in the placement of student interns at these companies, but also the funding of academic student research in the robotics lab.
- Robotics summer camps are also held each summer and target younger students from 12-16 years of age. An interesting set of industrial robotics activities have been designed that entertain the younger students while challenging them at the same time.

We hope that a reader of this article could use our experiences as a roadmap to fully integrating industrial robotic arms into their computing curricula.

Motivation

Manufacturing environments continue to evolve into sophisticated marriages of robotic equipment, computer technology, and humans. It is clear that the inability to adapt either equipment or human assets will result in the loss of American jobs to international companies. "Automate or Evaporate" is the saying in the manufacturing world. Industrial robotic systems improve productivity by increasing throughput and enhancing the quality of manufactured goods. It is amazing that robotic automation has existed since the early 1960s - long before the age of personal computers, the internet and email.

North America has historically lagged behind many countries in the area of industrial robotics and manufacturing. A recent 2009 report by the International Federation of Robotics [14] compares the number of robots that are being employed by Asia, Europe, and North America. Figure 1 shows how North America has been and is estimated to be behind in this area in the coming years. Although North America lags behind other countries in this area, the integration of robotic technology in North America has historically grown steadily. Even though growth has recently stagnated, the forecast is still expected to continue to trend upward starting in 2010-2012 once the worst of the current economic crisis has abated [14].

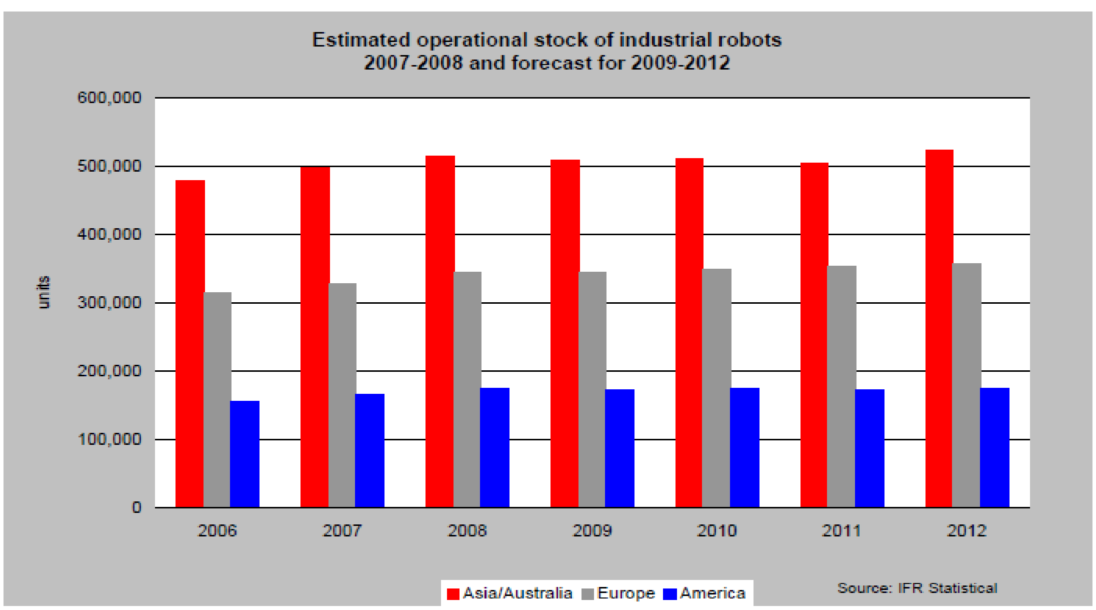

Figure 1. Recent and future lag of North America behind Asia and Europe in the number of industrial robots being used. Source: The IFR Statistical Department.

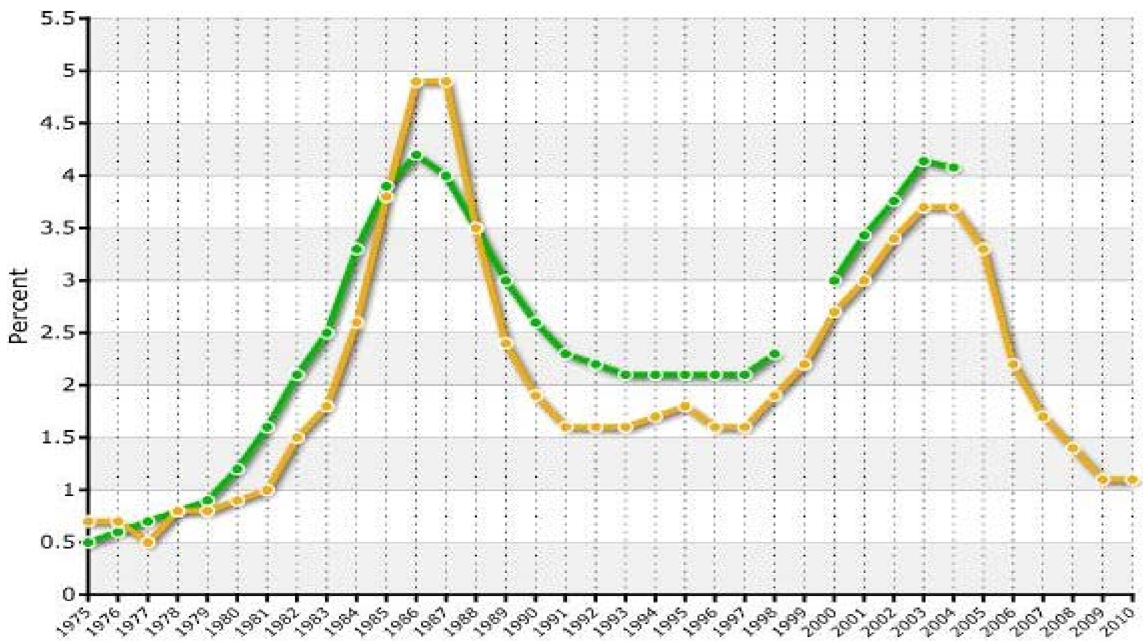

Figure 2. Intention to major in Computer Science compared to degrees granted (which stops at 2004) as a percent of total majors. Source: The Higher Education Research Institute (HERI) at the UCLA.

On the computer science front, it is no secret that the number of students declaring computer science to be a major has decreased steadily since the 2000 bubble. Figure 2 shows the historical trends in computer science majors [15]. It seems as though the decline may perhaps finally be leveling out as it did in the early 1990s after the 1987 bubble.

Manufacturers say that they face a serious shortage of highly skilled workers who can fix and program robots and other equipment in a 21st century factory [16]. The integration of industrial robotics and computer science, and potential job opportunities that come with this marriage, will help to attract more students into the area of computer science and technology. Both industrial robotics and computer science areas of academia and industry will benefit from this marriage.

Coursework

When integrating the robotics equipment into our curricula it was extremely important not to simply introduce new robotics courses – which would require additional resources (instructors to teach the new courses, etc) and also could not be easily assimilated into the existing curricula. Therefore, the goal was to enhance existing courses using this equipment where for the most part: *traditional computer science concepts would be taught via the robotics equipment.*

Theoretical and abstract concepts can be implemented and more easily visualized using industrial robotic equipment. For example, our SCSC 314 Introduction to Robotics course does not simply teach students how to operate and program Stäubli machines. Although such skills are valuable, they do not fall within the scope of a traditional computer science education. In our course, students are first taught the basics of matrix algebra and 3D vectors. This builds the pre-requisite knowledge needed to understand transformation matrices which are 4x4 matrices that represent rotational and translational differences between two coordinate systems. Locations in one system can be mapped to another system by multiplying the transformation with the location: ${}^{A}P = {}^{A}_{B}T\,{}^{B}P$:

$$\begin{bmatrix} {}^{A}P \\ 1 \end{bmatrix} = \begin{bmatrix} {}^{A}_{B}R & {}^{A}P_{BORG} \\ 0\ 0\ 0 & 1 \end{bmatrix} \begin{bmatrix} {}^{B}P \\ 1 \end{bmatrix}$$

where ${}^{A}P$ is a point in coordinate system A, ${}^{B}P$ is a point in coordinate system B and ${}^{A}_{B}T$ is the transformation matrix that maps points in system B to system A. The 3x1 column vector ${}^{A}P_{BORG}$ is the translational difference from A's origin to B's origin, and ${}^{A}_{B}R$ is a 3 x 3 rotation matrix comprised of three orthonormal column vectors that map the orientation of each axis in A with respect to B, ${}^{A}_{B}R$ =

$$\begin{matrix} \cos\alpha\ \cos\beta\cos\gamma - \sin\alpha\sin\gamma & -\cos\alpha\cos\beta\sin\gamma - \sin\alpha\cos\gamma & \cos\alpha\sin\beta \\ \sin\alpha\cos\beta\cos\gamma + \cos\alpha\ \sin\gamma & -\sin\alpha\cos\beta\ \sin\gamma + \cos\alpha\ \cos\gamma & \sin\alpha\sin\beta \\ -\sin\beta\cos\gamma & \sin\beta\sin\gamma & \cos\beta \end{matrix}$$

where α is the rotation around the moving Z in degrees, β is the rotation around the moving Y in degrees, and γ is a second rotation around the moving Z in degrees – i.e. Z-Y-Z Euler angle representation which is the internal representation used on Stäubli machines.

The students implement these equations in a general purpose programming language like Java or C# and then can verify their implementation is correct by running tests using the actual robotic arms which already have these operations built in to the operating system. After that, the students have to figure out how to implement the forward kinematics (given the joint angles of the arm, compute the transformation between the tool and world coordinate systems) of their particular Stäubli robotic arm and verify their program is correct by testing it against the actual machine. The theoretical and programming concepts learned here include: 3D geometry, transformations, matrix algebra, and 2D array multiplication. A typical robotic setup with example transformations that a student must carefully understand is shown in Figure 3.

Here is a video of a student demonstrating the final project that they implemented in this introductory robotics course: Allyson Underwood - http://www.youtube.com/watch?v=VOQpTRZzvrE. These concepts are very important not only in robotics, but several other fields in computer science like graphics, 3D modeling, virtual worlds, and computer vision.

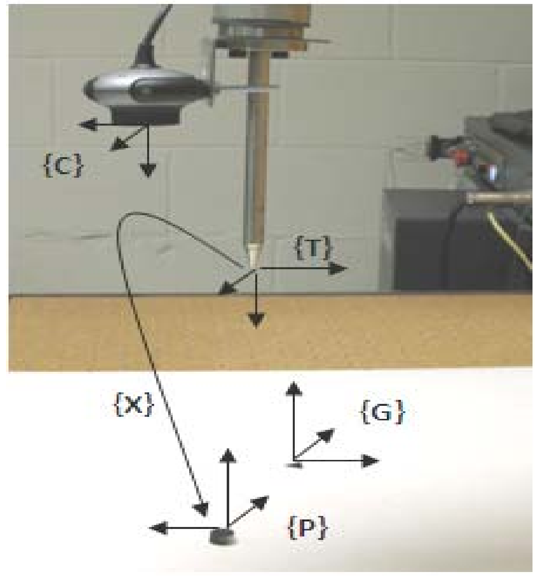

Figure 3. A project work area with several typical transformations that must be well understood by the students. Transformations have been defined for the pointing tool {T}, camera {C}, objects in the scene {P} and {G}, and the movement {X} from {T} to {P}.

Our SCSC 585 Computer Vision and SCSC 580 Introduction to Artificial Intelligence (AI) courses are also based in the robotics laboratory. But again, the equipment is used to solidify traditional topics that are typically taught in these types of courses. We have already produced detailed papers on the integration of robotics equipment into these two courses [8-9], and so the courses are just briefly outlined here.

In the AI course, students group into pairs and are assigned a robotic arm for the semester. The overarching project for the course is to implement a two player board game where all of the pieces are known – for example, chess, checkers, breakthrough, lines-of-action, fox-and-geese, etc. This is a traditional AI topic where concepts would include: searching strategies, the mini-max algorithm with α-β pruning, complexity analysis, heuristic functions, and training an artificial neural network that learns how to play the game without the programmer having to code any rules. All of this gets visualized by the students as they implement the robotic game playing system. A drawback is that some basic robotics concepts and programming must be covered in the class if the students have not yet used the machines – this does cut into the time that could be spent on other AI topics. Videos of actual students demonstrating their programs can be seen online: Andrew Whitaker who implemented Lines of Action - http://www.youtube.com/watch?v=Rt9-4LPSXFc; Jermaine Pinckney who implemented Breakthrough – http://www.youtube.com/watch?v=Eynlnl9T66o.

In the Computer Vision course, thresholding, binary images, segmentation, edge detection, Hough transforms and deformable contour tracking are all implemented for a *visual servoing* project. A Visual Servoing [17] system is a closed loop system where images of the current scene are captured and compared to an image of a target scene after which the robot arm is incrementally moved to minimize the error between the current and target image. Here is a video where two students present their implementation of a visual servoing project in this class: Sebastian Knapp and Samuel Barnet: http://www.youtube.com/watch?v=cmFyNZSmFMo.

Undergraduate Research

Besides the standard coursework described in the previous section, an industrial robotics laboratory could serve as a hot bed for undergraduate research. In the last few years, we have four peer-reviewed publications which were co-authored by undergraduate students [10-13]. One of these projects is a voice guided robotic system [11] that was implemented completely by an undergraduate student, Benjamin Overcash. In this system, Overcash could speak to the machine via a wireless microphone to jog the machine around and teach locations. All of the functionality of the teach pendant was duplicated in this hands-free voice guided system. Overcash demonstrates the system here: http://www.youtube.com/watch?v=dxo1NbBblE4.

Recently, another student, Nicole Tobias, completed a contour recovery project which uses a laser and camera mounted to the end of the robot arm to recover the 3D model of an unknown surface. The work has been published [13], and a poster of the work was also presented at Discovery Day 2010 (an undergraduate student conference for the USC

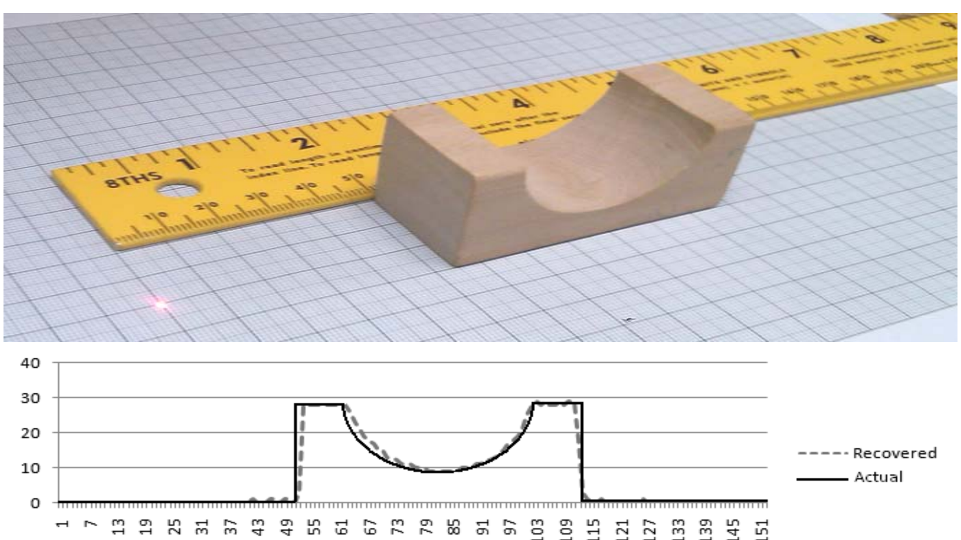

Figure 4. Example contour that was recovered with a laser/camera end-effector attached to a robot arm.

System) and won 1st Place for the Best Poster Award in the *Computer Science and Engineering* category. A demonstration of the project is shown here: http://www.youtube.com/watch?v=5mInN8RIz9o. Figure 4 shows a typical part setup and the contour of the part that was recovered by one of the algorithms.

Automation Focus Area

Based on informal conversations with numerous businesses in the region like Stäubli, SEW Eurodrive, Spartanburg Steel, and others, it is clear that there is a need to produce college graduates who are very good computer scientists and programmers, but also have knowledge of robotics and the manufacturing process and environment. We seek to fill this niche market by introducing an "Automation" focus area in our Computer Information Systems degree program.

This new focus is a unique and collaborative venture between the Computer Science, Engineering Technology Management, and Business departments at our institution. The majority of the coursework in this degree program is computer science related (programming, networking, web development, database, etc); however, 24 credit hours will be robotics and manufacturing related. At the time of this writing, the below focus area has been approved by all parties involved and is in the process of being approved by the university and should appear in our course catalog in 2011:

____ **Automation Focus Area**(24)[1]

______ SCSC 314 Industrial Robotics (3)
______ SCSC 441 Experiential Learning (robot intern) (3) or
SCSC 399 Independent Study (3, in robotics)
______ SCSC 580 Introduction to Artificial Intelligence (3) or
SCSC 585 Introduction to Robot Vision (3)
______ SBAD 372 Operations Management (3)
______ SETM 320 Engineering Cost Analysis (4)
______ SETM 330 Engineering Work Analysis (4)
______ SETM 410 Engineering Teams Theory and Prac (4)

[1] Students focusing in Automation must take SPHS 201/202 General Physics I and II to fulfill their IV Natural Science requirements; and SMTH 202 Elementary Statistics or SMTH 315 Statistical Methods I to fulfill their Core Major requirements

This focus is a collection of existing courses and therefore there is no additional cost or resources needed to implement this focus area. We envision graduates of this program getting jobs at any manufacturing or assembly plants who employ robotics technology or plan to investigate automation solutions. Also, robotics integrators would certainly be interested in this pool of graduates. To provide more details on what these courses entail, here are shortened versions of their course descriptions:

SCSC 314. Industrial Robotics (3) Fundamental concepts of industrial robotics including kinematics, 3D coordinate transformation, robot motion, robot control and sensing, robot programming, and computer vision. Students are required to write programs in order to demonstrate the laboratory projects.

SCSC 441. Experiential Learning in Computer Science (3) Experience in a business, educational, or non-profit computing environment.

SCSC 580. Introduction to Artificial Intelligence (3) Intelligent agents, expert systems, heuristic searching, knowledge representation and reasoning, artificial neural networks, ontologies, and natural language processing.

SCSC 585. Introduction to Robot Vision (3) Processing and analyzing features in still digital images, camera calibration, stereopsis, object recognition, the processing of edges, regions, shading and texture, and introductory video processing techniques.

SBAD 372. Operations Management (3) Managing the direct resources required by the firm to create value through the production of goods, services and information. There is a strong emphasis on supporting the decision-making process throughout organizations with quantitative tools and techniques. Topics include process selection, quality tools, inventory management techniques and supply chain management.

SETM 320. Engineering Cost Analysis (4) Engineering economics and financial analysis of prospective alternatives. Lab includes analysis techniques, use of modeling tools, and applications of techniques toward real-world problems.

SETM 330. Engineering Work Analysis (4) Techniques for operation analysis, work measurement, and work sampling. Major topics include human factors, work design principles, work environment, economic justification, work measurement and the design process. Predetermined basic motion-time systems and standard data development are introduced.

SETM 410. Engineering Teams Theory and Practice (4) Methods of understanding, planning, and presenting information in oral and written formats while working in an engineering team setting.

Industry Collaboration

Because of the commitment to undergraduate research and integration of the industrial robotics equipment in our curricula, we have been able to establish strong partnerships with some nearby industries: Stäubli and SEW Eurodrive. Both companies offer our robotics students paid internships. The students work with technicians and applications engineers on real-world problems in industry. Both companies provide us both technical and financial support of our robotics efforts. As an example of the latter, SEW Eurodrive is providing us financial support each semester so that a research assistant can be hired in our robotics laboratory who will be working on research projects with the robotics faculty. SEW Eurodrive also provides financial support each summer to sponsor Robotics Summer Camps for younger kids around the ages of 12-16 years old.

Our experience of putting computer science students in industrial robotics internships has been very positive so far. The students have the programming skills to be able to work with the applications engineers to trouble shoot problems on the line with existing applications, or to help develop new applications. One intern developed a C# application for Stäubli which allows engineers to quickly swap in and out robotic manipulator emulators in one of their software development environments. The application is now being used regularly by Stäubli engineers.

Summer Camps

Steering students into the field of computer science, technology and robotics needs to happen before the kids make it to the college age. As an outreach program, each year SEW Eurodrive sponsors robotics summer camps for younger kids around the ages of 12-16 years old. Over the duration of a summer, any where from 50 to 100 young students come to the lab to interact with the robotic equipment. Summer robotics camps that use mobile robots like the LEGO Mindstorms or VEX kits are common and very different from our approach of using industrial robotic arms. Designing appropriate activities for kids as young as 12 is challenging because the activity needs to be fun, not extremely complicated and, most importantly, educational. The kids pair up into groups of two and compete against other groups. In one of the first activities, the kids learn how to manually operate the machine, the difference between positive and negative rotations, and other basic robotics concepts. In a timed competition, they must position the arm in different joint configurations in order to shoot Nerf bullets at targets using the robot’s compressed air. Figure 5 shows an example of a Nerf gun that taps into the machine’s pneumatics. It has been fashioned out of simple materials and attached to a metal pointing tool. Total cost under $10.

Figure 5. Example Nerf gun that was constructed for camp activity.

The activity is thoroughly enjoyed by the students, and by the end of the competition, they are very comfortable with the process of manually jogging the arm.

A typical second activity, which is more low-key, is aimed towards introducing programming as well as the concept of *re-gripping*. The students must implement a program which slides a cylinder off of a rod and places it into a hole on a pallet. The idea is simple, but the problem is complicated by wedging the pallet in between two surfaces so that it is impossible to do a simple *pick and place*. As the students develop the program and think about the problem, they must discover on their own that they must put the cylinder down and then grip it once again from a different angle in order to slide it into the pallet. This concept of re-gripping is a typical process in real-world applications, and the students really feel a sense of accomplishment once they solve this problem. The project setup is shown in Figure 6.

Besides activities in the laboratory, each day the students in the camp visit a nearby industry to see robots in action. BMW Manufacturing, for example, is approximately 20 miles away and offers a wonderful tour. In addition to BMW, Stäubli and SEW Eurodrive, we also visit the Spartanburg Regional Hospital System. Many kids (and adults) do not realize how big of a role robotics plays in the healthcare environment. In particular, at Spartanburg Regional, the Davinci system which has 5 robotic arms is used by surgeons to perform heart, prostate and other types of surgeries. Using the system dramatically reduces recovery time. There is also a robotic system in the pharmacy which fills prescriptions. And, finally, several mobile robots, nicknamed the "tug" machines, autonomously deliver medication throughout the hospital. They even communicate with the elevator system to get from floor to floor. A recent press release from Spartanburg Regional indicated that in 2009, the machines travelled over 5000 miles delivering medicines throughout the hospital that otherwise would have to be transported by people.

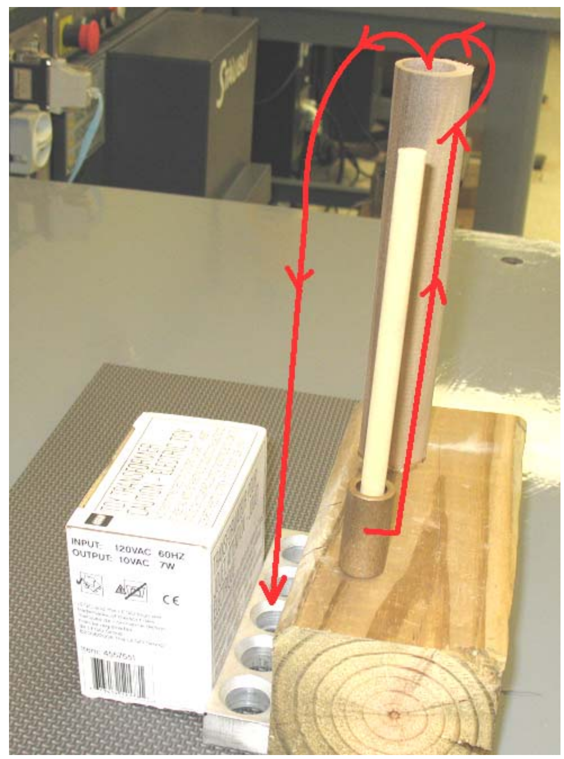

Figure 6. Example camp activity. Students must figure out on their own that after sliding the cylinder off of the rod, it must first be placed down and re-gripped in order to slide it into the hole on the pallet.

Conclusions and Future Work

This paper has described several approaches to integrating industrial robotic arms into computing curricula, including:

- Several existing courses where the robotic arms are used to solidify traditional computer science concepts.
- Undergraduate research where students develop novel robotic applications which have resulted in peer-reviewed publications.
- Industry collaborations, including internships and sponsorships of academic research in the lab.
- Summer camps featuring fun but educational activities for kids as young as 12.
- A focus area in "Automation" where a breadth of computer science coursework is augmented with a concentration of robotics and manufacturing concepts.

We have come a long way at our institution in the last few years; however, we are just scratching the surface of how this equipment can be further utilized. For example, such a lab is ideal for applying for federal funding to establish a REU (Research Experience for Undergraduates) site which supports undergraduate research over the summer. Also, the lab could be used as a training facility for *non-traditional* (older, working) students, offering certificates and other types of training programs for regional manufacturing companies. We hope to pursue these initiatives in the near future in addition to a set of new undergraduate research projects that are currently underway.

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Biographical Information

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