Surgical Robot Competition – Introducing Engineering in Medicine to Pre-college Students

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Abstract

Robotics is a multidisciplinary field that holds great potential for hands-on education throughout a student’s school career. However, making technology accessible for learning is challenging due to cost, safety and implementation concerns. This paper describes a method for drawing on current, real life challenges faced by researchers in the field and translating such experiences into a secondary school level program. The concept of the competition, application of LEGO Mindstorms® robotics platform, methods of organization and expansion, past experiences and future plans are presented. Our goal is to show an example of how to integrate off-the-shelf robotic technology with current real-world engineering challenges and to engage students in the fields of engineering, robotics, and medicine in a fun and exciting atmosphere.

Introduction and Background

Modern medical practice relies on innovation and technology to provide better solutions in the operating room. Doctors, scientists and engineers work together to improve current surgical care by designing tools and machines to overcome human limitations, namely precision, control, reliability, patience and memory. Computers and robots do not have these restrictions. Computers have had such an impact on surgery that many current procedures would be impossible or significantly more difficult without them. Computers aid surgeons by displaying images of internal organs through computed tomography (CT) and magnetic resonance imaging (MRI) or exposing brain function through electroencephalographic analysis. Robots can function as surgical assistants [1] or even substitute for the surgeon on location (e.g. telesurgery).

Robotics is a popular tool for science and engineering education on various levels because of its multidisciplinary nature. The development of a successful robot incorporates knowledge from a variety of disciplines such as physics, math, mechanical engineering, materials science, electrical engineering, and computer science as well as a variety of skills gained through practical experience. There is also a need for equipment: raw building materials and shop tools, wires and a soldering iron, a variety of computers and, often, complicated programming interfaces. A complete engineering education is founded on the acquisition of these skills, yet the time and...
experience needed to be successful with them prevents the use of robotics for education and recruitment at younger levels. With the recent arrival of LEGO’s Mindstorms Robotics Invention System (RIS), students with a minimal robotics or engineering background could sit down and instantly begin to develop an understanding of and practice with the core issues and challenges of robotic development without being busy with the machining and precision control aspects required for real-world robots. The recent surge in pre-college robotics programs illustrates the impact this has had on exposing future engineers to the excitement of the field such as the FIRST Robotics competition [2].

While robots on the assembly floor are now ubiquitous, robots in the operating room are just starting to move from the research bench to the hospitals. Indications of the immersgence of robotics in the medical environment are shown by the formation of the NSF-funded Engineering Research Center for Computer Integrated Surgical Systems and Technology (CISST) [3] as well as by the increasing success of commercial systems such as Integrated Surgical Systems’ ROBODOC® [4], Computer Motion’s® Zeus® [5] and Intuitive Surgical’s® DaVinci™ [6]. Utilizing the advantages of machines to overcome human limitations, these robots promise to make surgery faster, safer, and more efficient. These tools also open a wide variety of new surgical solutions to doctors, increasing their ability to treat their patients. Research in this field brings biology, anatomy, surgery, and biomedical engineering together with a variety of disciplines already present in general robotics. One way of involving students in computer-integrated surgery is a surgical robot competition used as a practical educational tool that is enjoyable for the students.

The CISST ERC is a multi-university, multidisciplinary center whose focus is on the development of computer-integrated systems that can work cooperatively with surgeons to significantly improve quality and cost-effectiveness of surgical procedures and to enable research into new treatment procedures that would otherwise be impossible or impractical. The core institutional members of the CISST ERC include Johns Hopkins University, Carnegie-Mellon University, Massachusetts Institute of Technology, and Brigham and Women’s Hospital, and we have a number of academic and industrial collaborations with other institutions. Like all NSF ERCs, our Center’s strategy combines systems-oriented research on the underlying science and technology base of our field with development of systems testbeds and applications to drive research and demonstrate concepts. One unusual aspect of our Center is the extent to which we engage clinicians in all aspects of our activities. Our strategy also emphasizes close interactions with industry and integration of education with everything we do.

The Computer-Integrated Surgery Student Research Society (CISSRS) is a group of undergraduate and graduate students involved in community education and outreach as part of the CISST. The CISSRS Surgical LEGO Robot Competition balances the increasingly multidisciplinary field of surgical robotics and the versatile but easy to learn Mindstorms system to provide the participants an introduction to CIS by giving them hands-on experience in solving real-world, cutting edge science and engineering challenges in a fun and exciting environment. During the course of a “long” weekend, participants with no or little computer or engineering experience can learn the necessary skills to design, build, program, test, and demonstrate a functional robot that performs a simulated surgery.
Robotic Challenge

It was our goal to establish a development framework that would closely approximate real-world engineering scenario in a context of a competition. We wanted to take the students through an accelerated version of a full-scale implementation of a robotic system that would include as many realistic components as possible balancing with the students’ limited knowledge of advanced engineering concepts. Therefore, we designed the competition that would give an opportunity to all teams to build a working robot that could complete at least one of required elements.

We had two competition concepts in the past. The first was started in 1999 with a trial competition for three teams of high school students from the same school. In 2001, we introduced a new concept that we would like to run several times. Refer to Table 1 for past competition history.

In the first challenge, the students were provided two sets of Mindstorms and several light sensors to design, build, program and demonstrate a functional robot that can perform a simulated tumor biopsy. This task involved localizing the tumor in a simulated environment as well as accurate insertion of the needle into the tumor. The “patient” was modeled as a transparent box of JELL-O with a grape suspended in the middle (Fig. 1), which is very similar to research models (Fig. 2).¹

This setup is an approximation of a percutaneous procedure routinely used for cancer diagnosis and treatment. Preoperative imaging is used to study the location of the tumor, note important landmarks and plan the insertion trajectory. During the procedure, live intraoperative imaging such as a portable X-ray machine is used to aid the surgeon in reaching the objective. However, major consideration must be given to targeting, minimizing damage to internal structures and reducing exposure of the patient and the surgical team to radiation. In this context, robots are more useful as they are much more precise, reliable and able to sustain extensive radiation exposure than humans. Integration with target tracking systems allows for precise needle insertion, which is especially important for soft tissues when tissue motion due to the insertion is a concern. In this challenge, much attention was paid to proper design of hardware components because the robot had to be able to cover a wide range of motion, bear significant loads and move at good speed. The system was to be designed to be semi-automatic, with limited user input, thereby placing emphasis on effective search pattern and sensor readout.

For the second challenge, students were given two sets of Mindstorms and a LEGO Vision Command set, which includes a programmable camera that can be interfaced to the RCX (a programmable LEGO “brick”). Students were required to build a robot that performs a simulated telesurgery with the camera used as the surgeon interface. The task involves designing an effective method of recognizing the surgeon’s motion and interpreting it into proper robot movements. The robot was to simulate a cutting procedure.

¹ This competition is described in greater detail in “From Science Projects to Engineering Bench: High School Surgical Robot Competition” by Gerovichev, O., et.al. (under review in IEEE Robotics and Automation Magazine Robotics in Education: An Integrated Systems Approach to Teaching).

Telesurgery is an important facet of advanced surgical technology. It refers to a method of surgery when the surgeon is either operating through an input interface in the same room as the patient or if the surgeon is located elsewhere and his input is relayed electronically. In most cases, the tools contacting the patient are held and manipulated by a robot. It is imperative that the robot follows the control mechanisms without endangering the patient. Fast response time, good range of motion and sterility are also important. On the surgeon’s side, the input stage must be comfortable and intuitive to the user. Systems like the da Vinci use special joysticks that let the surgeon manipulate remotely a set of robotic arms for minimally invasive surgery (MIS).

For the competition the students again have three stages: 2-degree-freedom (DOF) robot control, 2-DOF cutting and 3-DOF cutting. For the first stage, students have to build a robot capable of moving in two-dimensional horizontal space measuring about 20x20 cm. The robot has to move in response to commands received through the camera. The camera is capable of motion and color recognition, so the challenge is to define a set of commands that can be used as visual cues for triggering certain robot motions. For the second stage, a student “surgeon” should control the robot to perform a simulated cut. This time, the “patient” is a flat piece of paper or transparency with a printed path for the cut. The path varied in width between 1 and 2 centimeters and had a combination of right turns, sharp angles and curves. The “cut” was to be done with a fine-tip marker attached to the robot. For the third stage, the robot had to be modified to move the marker vertically, so the cut could be made at different depths. By implementing three stages of increasing difficulty, participants have the opportunity to go through incremental design process, which is commonly used in engineering labs.

Observations

The first challenge had a lot of problems arising from the use of a “soft-tissue patient”. Since consistency of the JELL-O was not uniform, lighting played a crucial role in performance. LEGO software does not allow for dynamic lighting calibration, so the teams had five minutes to calibrate their sensors (by adjusting proper light intensity ranges) before their demonstrations. Variable light reflection, ambient light, peripheral movement, shadows and temperature became a testing point for the robots. Limitations of LEGO software became apparent when several teams were unable to implement their guiding and searching routines that would have been possible in a higher-level language. This drawback necessitated either clever algorithms or rebuilding of the hardware to fit the possible software approaches. This rebuilding reduced available programming time, delaying or preventing some groups from progression to the next stage. This was especially noticeable in automatic systems from the first challenge because only two teams were able to progress past the first stage in each of the JHU competitions. The second challenge was more about controlling the robot with discrete commands, so problems only appeared if the teams were using color input, which is affected by light.

For the second challenge, the most important part of the design process was to transfer the input from the “surgeon” to the robot in a robust and simple manner while enabling precise robot control. The Vision Command camera has a selection of grids that divide the input image into sections that can be assigned specific robot functions. Students used either motion or color detection (which is already programmed in the grid) as triggers, but a surprising outcome was an array of tools created by several teams to simplify the task for the operator. Several teams built
multi-shaped and multi-colored input sticks or wands to be held by the operator, and one team went as far as building an input piano that triggered the camera on motion (Fig. 3).

We decided to allow the students to build mobile robots partly because we were interested how they would fare in comparison with their stationary brethren and partly to tailor to students’ possible previous experience with such machines. For the first challenge, it did not make much of a difference because an overwhelming majority of teams chose to attach the robot to the “patient” by physically building against and around the box (which was allowed by rules), which is a common technique in medical robotics called registration. This greatly reduced the hardware requirements because the robot could use the box as support. For the second challenge the choice of building a mobile or a stationary robot resulted in a rapid divergence of design ideas and quick building process, which left more time for next stage: software development. This stage proved to be the focus of the challenge because the Vision Command software does not have all the capabilities of the Mindstorms software and currently does not interface to it. Most noticeably, there was no way to wirelessly communicate between the RCX’s, which would allow for easier implementation of command transfer from the camera RCX to the robot RCX. Therefore, students had to either use a single RCX or run wires between a pair of RCX’s. Despite the setbacks with the software, the second challenge proved to be a great success as an unprecedented eleven teams completed the first stage, nine completed the second stage, and six completed the third stage.

Another important real-world concept was task management. Successful teams assessed their priorities early on, set their goals and distributed their tasks. The most common division was one person on software development and two people on robot construction. Teams without a dedicated programmer had a difficult time making their robot run because the software has a learning curve as well as limitations in control.

Evaluation

The competition is scored by the organizers on a point-based system in the following areas:

- Each demonstrated functional stage at any point throughout the competition – students are allowed to present a stage in up to three consecutive runs once per hour at the demo station. It is possible that the students present a functional robot that incorporates more than one stage, in which case they receive points for all working stages. Since the robots have to be generic and be able to work on any patient, judges used different “patients” for each test to assess the this quality.
- Design notebook – In addition to the building skills, it is important to encourage and assess the creative thinking process by requiring the completion of a “design notebook” developed by CISSRS. First, the students present several possible solutions focusing on mechanical and programming approaches and select the best one. After implementation, the solution is analyzed and described in greater detail. It is not uncommon to see a lot of detail and versatility in student design (Figs. 4a, 4b). Students are awarded points for correctness of the design, creative solutions and versatility of designs.
- Final demonstrations – bonus points are awarded for demo of functional robots on the last day to attending parents, teachers and media. Figures 5, 6, 7, 8, 9 show several robots from the recent JHU competition.
Competition Logistics

The competition is held in a university setting over a four-day weekend without conflicting with school classes. Refer to Table 2 for the full schedule of the competition.

Students participate in the competition in groups with their peers from the same school. Each team is encouraged to use the maximum of three members, although teams with two members or less are not prohibited (although uncommon). Having several students on the same team promotes teamwork and teaches students how to divide tasks between themselves to achieve best results.

Since students may not have an adequate background in design, building and programming LEGO robots, CISSRS provides appropriate tutorials in the beginning of the competition. Important mechanical concepts such as gear trains, weight distribution and balancing, motor control and multi-dimensional mobility are explained in depth with step-by-step example robot construction followed by a tutorial on how to program the robots in the Mindstorms programming environment. With the recent release of RIS 2.0, programming LEGO robots became much easier, thanks to more straightforward control routines and availability of variables.

Besides a tremendous learning experience, students receive a variety of prizes from the organizers. All students receive CISSRS T-shirts and certificates of participation. The top team receives LEGO Mindstorms kits or gift certificates to stores where they can purchase them. Second and third teams receive gift certificates for smaller amounts.

Future Development

So far the competition was run at Johns Hopkins University and Carnegie Mellon University, and proved to be a great deal of success in Baltimore and Pittsburgh areas. Throughout the five competitions that were held, we enjoyed an increased number of schools, teams and students (see Table 1 for participation statistics). We are also strongly increasing the participation of minorities and women as well as public schools (in fact, all schools at the last JHU competition were public). As part of CISST ERC educational initiative, CISSRS plans to organize a competition for Boston area schools in conjunction with Massachusetts Institute of Technology. Furthermore, our positive experience with LEGO Mindstorms as an easy-to-learn platform for engineering prompted organization of a similar competition by the RoboJackets Club at Georgia Institute of Technology for the spring of 2002. CISSRS will serve as a consultant for organization purposes.

Conclusion

The CISSRS High School Surgical Lego Robot Competition is a great opportunity for high school students of different engineering and robotics background to work together in a fast-paced setting that provides exposure to current problems and solutions in medical robotics. Although the robots are made from LEGOos, the students follow the same design and testing process as
their future colleagues in industry and research. The surgical task of placing a needle into a grape suspended in a box of JELL-O or simulating a surgical cut with a telesurgery robot is not unlike real operating room procedures. The students learn something about the task and about some of the key component ideas of real surgical systems, including sensor feedback, mechanisms, and control. Beyond this, they learn important project skills that are very important in industry but are not usually taught within a technical context at the high school level. These include systems design and integration, troubleshooting, project management and development teamwork. These skills are learned “by doing” within the context of a fun task that gives direct and visible feedback to the students involved. It is our hope, of course, that the experience will help attract students to undergraduate study in engineering or (ideally) into Computer-Integrated Surgery. But the basic skills taught and the insights into the engineering development process are universally valuable.

In addition, the competition has a great deal of value for the undergraduate and graduate students who are involved in running it. First, it provides a simple and intuitive framework example for beginning students in much the same way that it does for high school students. Second, organizing and running the competition requires the CISSRS students to practice skills that are essential in many real world pursuits, especially in the area of organizing logistics, setting up kits, and providing “field support”. Also, one of our goals is to teach our own students how to teach others. The competition provides a great practical experience in putting together educational materials and practical exercises. Again, these skills are important in many lifetime pursuits, and not just in classroom or university teaching.

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Legal

LEGO and Mindstorms are registered trademarks of The LEGO Group. JELL-O is a registered trademark of Kraft Foods Holdings.

Bibliography

2. URL: http://www.usfirst.org/robotics/index.html
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Table 1. Participation statistics in the competition

<table>
<thead>
<tr>
<th>Date</th>
<th>Challenge Type</th>
<th>Location</th>
<th>Number of Schools</th>
<th>Number of Teams</th>
<th>Number of Students</th>
</tr>
</thead>
<tbody>
<tr>
<td>October 1-3, 1999</td>
<td>Tumor biopsy</td>
<td>JHU</td>
<td>1</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>June 1-4, 2000</td>
<td>Tumor biopsy</td>
<td>JHU</td>
<td>6</td>
<td>7</td>
<td>19</td>
</tr>
<tr>
<td>November 16-19, 2000</td>
<td>Tumor biopsy</td>
<td>JHU</td>
<td>6</td>
<td>9</td>
<td>23</td>
</tr>
<tr>
<td>April 26-29, 2001</td>
<td>Tumor biopsy</td>
<td>CMU</td>
<td>5</td>
<td>7</td>
<td>20</td>
</tr>
<tr>
<td>November 15-18, 2001</td>
<td>Telesurgery</td>
<td>JHU</td>
<td>11</td>
<td>11</td>
<td>31</td>
</tr>
<tr>
<td>March 14-17, 2002</td>
<td>Telesurgery</td>
<td>CMU</td>
<td>10</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>March 28-30, 2002</td>
<td>TBD</td>
<td>GT</td>
<td>6</td>
<td>6</td>
<td>18</td>
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Table 2. Competition Schedule

<table>
<thead>
<tr>
<th>Time</th>
<th>Events</th>
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</thead>
<tbody>
<tr>
<td>Thursday 4-8 pm</td>
<td>Introduction to Computer-Integrated Surgery, tutorials</td>
</tr>
<tr>
<td></td>
<td>Dinner provided</td>
</tr>
<tr>
<td>Friday 4-8 pm</td>
<td>Tutorials (if necessary), begin construction</td>
</tr>
<tr>
<td></td>
<td>Dinner provided</td>
</tr>
<tr>
<td>Saturday 9 am – 8 pm</td>
<td>Continue construction</td>
</tr>
<tr>
<td></td>
<td>2 pm: Part 1 of design notebook due</td>
</tr>
<tr>
<td></td>
<td>Breakfast, lunch, dinner provided</td>
</tr>
<tr>
<td>Sunday 9 am – 6:30 pm</td>
<td>Finish construction</td>
</tr>
<tr>
<td></td>
<td>12 pm: Part 2 of design packet due</td>
</tr>
<tr>
<td></td>
<td>2 pm: demonstrations begin</td>
</tr>
<tr>
<td></td>
<td>4 pm: award ceremony</td>
</tr>
<tr>
<td></td>
<td>Breakfast, lunch provided</td>
</tr>
</tbody>
</table>
Figure 1. JELL-O/grape phantom.

Figure 2. Research phantom.
Figure 3. Input piano: the operator presses a key corresponding to a robot motion; the Vision Command camera detects the motion of the key and sends the command to the RCX.

Figure 4a. Student design notebook shows a great deal of detail.

Figure 4b. Student implementation from Fig. 4a for the first challenge.
Figure 5. A fixed-base robot performs a simulated cut.

Figure 6. A mobile robot with a mechanized arm.

Figure 7. A moving platform robot with a scanning arm.
Figure 8. A car robot with a scanning tool holder follows a curved path.

Figure 9. A 2D wheelbase robot with a scanning tool holder follows a path.