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Playful Learning: Robotics and Mechatronics Projects for Innovative Engineering Education

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Abstract

The knowledge in the field of engineering is growing at an exponential rate. With only four years available for studying undergraduate engineering disciplines, this leaves many emerging and even established sub-fields and courses beyond the reach of students. This is particularly the case with universities offering predominantly undergraduate programs in engineering with a limited number of faculty. Robotics and mechatronics are among the frontier areas of electrical, mechanical, and computer engineering. Project-based learning experiences for undergraduate students in these disciplines can provide valuable real-world problem solving experience, expose them to new or established courses that students are not formally being taught, serve community outreach, and potentially produce innovative technologies and products for entrepreneurship by graduates. This paper discusses the project-based learning experiences of the author's undergraduate engineering students at the University of Michigan-Flint, in the fields of robotics and mechatronics.

Introduction

Ever since the Industrial Revolution, technological development has been at the heart of socio-economic growth of developed countries such as the United States. Many of the symbols of national achievement in the US are engineering projects[1]. A strong university system focused on producing engineers and technologists well trained in the various engineering disciplines has been the basic infrastructure underlying this development.

Sound training in engineering requires a strong background in mathematics and sciences. As technology-driven affluence is taken for granted among the younger generation, the perceived “difficulty” of math and science drives away many youth and school children from pursuit of science and math, and eventually of engineering. As a result, compared to the post-Sputnik era when the challenges of space exploration attracted vast numbers of talented youth to pursue engineering careers, in recent years there has been a significant plateau or even decline in the numbers of engineering students graduates.

This decline so far has mainly been offset by an influx of immigrant engineers and technologists, particularly at the graduate and doctoral levels. For example, nearly 70 percent of Ph.D. degrees in engineering in the US are awarded to graduate students of foreign origin. Many of these graduates have in the past tended to stay back in the US. However, the globalization of economic development and the resulting higher standards of economic and educational systems in their home countries are increasingly attracting many of these well-trained engineers, scientists, and educators to return home.

In many high-tech industries in the US, ranging from autos to space, there has been a sharp "greying" of the workforce: many of the engineers who entered their fields in the post-Sputnik era are nearing the retiring age, while there are not enough young engineers to take up their place. For example, at the National Aeronautics and Space Administration (NASA), the engineers and scientists over sixty outnumber those in their thirties by a factor of nearly three to one. Such generational imbalances would seriously affect the smooth development of these industries in future.

There are undoubted economic benefits to the pursuit of a career in engineering, such as higher starting and average pay, better job security, and so on. However, many of the high school students who enter undergraduate engineering programs soon discover that they are inadequately prepared in basic math and science to deal with the rigorous coursework that engineering programs require. Partly as a result, high dropout rates are a common occurrence in many engineering programs. As many as 39 to 61 percent of male and 54 to 70 percent of female students entering engineering programs do not graduate. Retention is especially a serious problem in the freshman and sophomore years, and in smaller engineering programs.

Due to a variety of socio-cultural factors, female students are increasingly outperforming their male counterparts at all levels of school education. Yet engineering education and the engineering profession in the US remain predominantly a male domain: 20 percent of students enrolled in our engineering programs are women, while only 8.5 percent of the country's engineers are women. Moreover, about 70 percent of women entering engineering programs do not graduate. By contrast, women constitute about 46% of the national work force.

Similarly, minorities – especially, African-Americans and Hispanic Americans – continue to be underrepresented both in the engineering profession and in engineering education. By the year 2008, about 29 percent of the work force are expected to be minorities. Therefore, for reasons of equity, diversity, and competitiveness it is necessary to attract more women and minority students to university engineering programs.

At another level, the exponential growth of the knowledge base in various engineering disciplines poses a pedagogical challenge for the engineering educators. With only four years available for studying undergraduate engineering disciplines, this leaves many emerging and even established sub-fields and courses beyond the reach of students. This is particularly the case with universities offering mainly undergraduate programs in engineering with a limited number of faculty.

In view of the above factors, it is imperative for engineering educators – especially, in smaller predominantly undergraduate universities serving underrepresented regions and minorities and women – to focus on innovations in engineering education that would help them attract, retain, and graduate high-quality engineers trained in emerging fields[2].

Robotics and mechatronics are among the frontier areas of electrical, mechanical, and computer engineering. Project-based learning experiences for undergraduate students in these disciplines can provide valuable real-world problem solving experience, expose them to new or established courses that students are not formally being taught, motivate them to continue engineering education, serve community outreach, and potentially produce innovative technologies and products for entrepreneurship by graduates. This paper discusses the project-based learning experiences of the author's undergraduate engineering students at the University of Michigan-Flint, in the fields of robotics and mechatronics.

Robotics and Mechatronics

The field of robotics came into prominence in the 1950s with automation of assembly operations. Lately, robots have been finding major applications in other fields such as space, defense, healthcare, entertainment, and so on. *Mechatronics* is an interdisciplinary field encompassing machines, electronics, and computers, and has attracted much attention over the past decade. In a sense, robotics may be considered a sub-discipline of mechatronics.

Robotics and mechatronics technologies lie at the heart of the major technological and industrial achievements of the twentieth and early twenty-first centuries. The decreasing cost and size on the one hand, and increasing power and versatility on the other, of electrical machines, sensors, controllers, and computers have resulted in the incorporation of computer control methodology in many technological systems. Incorporation of computer control results in increased economic competitiveness, due to *innovation* and *value added* in terms of energy efficiency, safety, comfort, novelty, environment-friendliness, etc.

Some examples are modern automobiles with enhanced safety, fuel efficiency, and comfort due to use of on-board computers, industrial automation, microelectromechanical systems, consumer appliances, healthcare and assistive technologies, environmental monitoring, and defense applications such as surveillance and missiles.

Thus, robotics and mechatronics have become a major frontier of engineering and technology, with wide-ranging applications in a variety of disciplines. Some of the most outstanding technological achievements of recent years, e.g., Mars Rover, Space Shuttles, unmanned aerial vehicles, hybrid/fuel-cell cars, AbioCor artificial heart, Aibo robot, iBot wheelchair, and Segway personal transporter, are all good examples of robotic and mechatronic systems.

The study of robotics and mechatronics has therefore become central to the study of mechanical, electrical, aerospace, and computer science and engineering disciplines. In recent years there has been a tremendous growth in their applications to practical systems, in other engineering disciplines: e.g., agricultural engineering (heavy equipment control), civil engineering (intelligent buildings and transportation systems), chemical engineering (intelligent process control), environmental engineering (monitoring and control), and biomedical engineering (microelectromechanical systems or MEMS, and assistive technologies)[3-5].

Robotics and mechatronics are also spawning newer disciplines like intelligent systems, embedded systems, and hybrid systems.

Project-based Learning

The recent revolutionary, rather than evolutionary, changes in the engineering education accreditation criteria by the ABET show that acquisition of technical knowledge alone is not sufficient for graduating engineers in the globalized workplace today. The students further need training and experience in the areas of technical communication, ethics, team work, economics and ergonomics of system/product design, relationship between technology and society, civic engagement, sensitivity to cultural diversity, and so on.

The half-life of knowledge gained in many engineering fields is estimated between two-and-a-half and three years[6]. Since engineering students have only four years to study the requisite engineering and non-engineering courses, they necessarily need to learn many important newer fields on their own by way of “learning by doing” projects.

Several leading universities have emphasized innovative approaches to engineering education, such as “hands-on learning”, “learning by/while doing”, and “project-based learning”. The tangible and intangible benefits of such *active learning* approaches are most widely gained through practical laboratory and project-based instruction[7, 8].

To quote Professor Seymour Papert, the creator of the Logo language, “Knowledge is only part of understanding. Genuine understanding comes from hands-on experience”. This is because while the theory, and often lab, courses teach the modeling, analysis, and design techniques to engineering students, projects illustrate to the students how the seemingly abstract techniques which they studied in the “theory” courses are grounded in important practical applications in a variety of fields.

Engineering Science Program at University of Michigan-Flint

The author served as an Assistant Professor in the Engineering Science Program at the University of Michigan-Flint (UMF) during Sept. 2001 – Aug. 2003. UMF is the smallest of the three-campus University of Michigan system, and is ranked in the third-tier of Midwest universities offering programs up to Master's level. It is primarily an undergraduate university, and remains what is called a "commuter campus". A large portion of the students are "non-traditional", in that they are employed in nearby industries or companies, and are married with families. Many of them transfer to the program after a two-year associate degree from neighboring community colleges, while some enroll in university several years after graduation from high school or community college. The retention rates are quite low, especially in the first two years of the engineering science program.

The Engineering Science Program at UMF is rather small in size, graduating about 10 to 12 students a year. Program enrollments start at about 50-60 in the freshman year, but taper off rapidly in the freshman and sophomore years. The program specialization resembles a mix of mechanical and electrical disciplines. The faculty size too is limited, comprising four to five full-time and adjunct faculty members. The teaching load is quite high, comprising three 3-credit courses per semester. Moreover, faculty are also expected to exhibit significant research productivity and to contribute to service.

The situation at UMF is fairly representative of conditions at smaller universities offering predominantly undergraduate engineering programs of limited size.

Robotics and Mechatronics Projects at UM-Flint

The Robotics and Mechatronics Laboratory was started at UMF in fall 2001. The lab provided the resources for a lab course to accompany an introductory senior-level course on robotics and mechatronics. The resources additionally came to be used to support senior capstone engineering design projects, senior/junior Independent Study courses, junior/sophomore Supervised Study courses, as well as faculty research in the areas of control, robotics, and mechatronics. Most of the projects involved teams of three or more students. A summary of the projects and their outcomes is given in Table 1.

Computer hardware and software issues are paramount in the design and operation of robotic and mechatronic systems. Many of the projects discussed here also involved the participation of computer science majors.

Educational outcomes assessment

Most of the students working on these projects were very enthusiastic in their participation. A number of students spent time both inside and outside classroom on these projects, often spending their own resources on some hardware, or collecting them as donations from local industries.

Many of the projects involved "playful learning", both literally and figuratively. Since the UMF engineering science program had only a limited number of lab courses, for many of the students these projects provided their first encounter with understanding topics they had only studied in theory (e.g., real-time computer control), or had not even studied (e.g., pneumatics, computer vision, etc).

Due to ever-decreasing cost of actuators and sensors on the one hand, and the decreasing cost/power size of computers on the other hand, design of "proof of concept prototypes" of innovative engineering products and systems is well within the reach of motivated and ambitious engineering students today. This is illustrated by the range and depth of the projects completed.

Development of a typical robotic/mechatronic project typically involves the use of the following skills:

- Knowledge of mechanical systems (design, materials, mechanisms, etc)
- Knowledge of electrical systems (ac and dc machines, batteries, telecomm, etc)
- Knowledge of electronics (analog and digital, semiconductors and ICs, power electronics)
- Knowledge of computers (*hardware*: computers, microcomputers and microcontrollers, Networks, multimedia; *software*: programming, AI, cognition)
- Knowledge of engineering economics (cost-benefit analysis, ergonomics, quality management)

The project-based approach also offers the following advantages:

- Experience in teamwork, communication, ethics, economics, creative problem solving, and multidisciplinary knowledge
- Scope for future entrepreneurship
- Freshmen-Juniors mentored by Seniors/Graduate Students, increasing recruitment and retention
- Motivation for graduate studies/research and lifelong learning
- Collaboration with faculty in research

- Encourages civic engagement and community service
- Encouraged by employers for the qualities they impart to graduates

Some of the above projects (e.g., stand-in box for coma patients and the computer-controlled baseball launcher) are quite comparable in sophistication to the state-of-art products available in their areas. Therefore, such projects can in the long run lead to development of new products and venture businesses. These technologies are knowledge-intensive and do not require a high-tech R&D infrastructure, which is lacking in places like Flint. It is therefore possible for enterprising graduates to start their own industries or venture businesses based on systems and technologies they develop as part of their project/thesis work[9]. At Tulane University, such an initiative is labeled "From Projects to Products". With the coming of the *Ageing Society* in the U.S., Japan, and much of the developed world, assistive and healthcare technologies (such as the motorized wheel chair and the physical therapy machine) will be a major industry in the future[10, 11].

Impact on Quality of Students

In recent years, engineering educators have realized that captivating student attention in the freshmen and sophomore years – when they are busy doing their prerequisite math and science courses – is essential for improving retention and graduation rates. Robotics-based courses and introductory engineering design courses have been found very helpful in this regard[12, 13]. Therefore, it is hoped that sustained project activities would indirectly contribute to increased enrollment, retention, and graduation rates.

Smaller universities often do not have the faculty/staff, space and financial resources to develop and offer new theory and lab courses in emerging fields. Therefore, hands-on projects can be used to teach students selected topics in these fields e.g., machine vision using robot vision system, machine learning using mobile robots, automotive electronics using power devices, and so on.

Robotics incorporates several major disciplines of computer science and engineering. At least 7 out of 14 knowledge areas in the ACM/IEEE Computing Curriculum 2001 Draft (viz., programming, algorithms & complexity, languages, architecture, OS, intelligent systems, net-centric computing) are covered by robotics[3, 4]. Therefore, the participating students of computer science benefited substantially from the pursuit of robotics and mechatronics projects.

Project-based instruction can help faculty teach "theory" courses to establish connections between theory and practice of engineering. This would help their students' motivation and understanding, and also increase student-faculty interactions. Some of the projects can be developed into experimental systems for laboratory instruction (e.g., in the areas of control systems, instrumentation and measurement, robotics, and mechatronics).

Many of the completed projects resulted in hardware and software components and modules that were successfully adapted into experimental modules for the robotics and mechatronics laboratory.

Impact on Faculty Development

An advantage of research in areas such as robotics and mechatronics is that much state-of-art research can be performed on fairly inexpensive systems bought off-the-shelf (OTS) or build-your-own (BYO) type built in-house[14]. This enables the faculty to provide modern yet inexpensive facilities for graduate and undergraduate research, and enable their dual use as instructional resources.

At smaller universities such as UMF offering undergraduate engineering programs with limited number of faculty, the faculty time available for research is very limited due to heavy teaching loads. Therefore, involving undergraduate students in research under faculty supervision is valuable to both the faculty and students.

In fact, for faculty pressed for time and resources, supervision of such projects can be a very useful "learning by teaching" mechanism of diversifying into related new fields: e.g., control systems specialists to diversify into machine vision, intelligent systems, or rehabilitation robotics.

Many of the projects in robotics and mechatronics are highly inter-disciplinary, involving mechanical, electrical, and computer science/engineering disciplines. Therefore, such projects can often be conducted by teams of students from different departments. Over a period of time this can lead to sharing of limited resources, and interdepartmental research collaboration among the faculty, as well to offering new cross-disciplinary courses.

Service Learning and Community Outreach

Faculty can employ project assignments to introduce service learning and community outreach components in their teaching[15]. The completed projects thereby serve not only as learning tools but also double up as a *community resource*.

Understanding, mastery, and application of technology have been at the root of prosperity of developed countries such as the United States. However, the emergence of the technological society is accompanied paradoxically by a decrease in the level of *technological literacy* in society[16]. This problem must be tackled to solve major socio-economic challenges such as successful competition in the global economy, the *digital divide*, disappearance of high-paying blue/white collar jobs due to globalization and outsourcing, equalization of opportunities for women and minorities, equitable regional and socio-economic development, etc.

A hopeful trend in this context is the increasing popularity of robots and high-tech toys among children and school students. Machines in general and robots in particular, have strong appeal to the "playful learning" dimension of children and youth (witness the popularity of LEGO robots and FIRST competitions among school children). By nurturing this appeal, in the long run we can motivate children and students to study emerging areas of advanced science and engineering, such as information technology, software, life sciences, energy and environmental technologies, and so on[2]. This will ensure their educational success, thereby giving them access to well-paying jobs and improving their economic well-being.

Some of the projects discussed in this paper were conducted in collaboration with the Sloan Museum in Flint, MI. For example, during robotics and other hands-on exhibits at the museum, some of the robots developed by the students were also on display (Figure 1). Some of the students in the freshman introductory engineering class moreover volunteered with teaching robotics to middle school children in the neighborhood.

A few of the student projects are shown below in Figures 2 – 4.

Figure 1. Mobile robot at Sloan Museum

Figure 2. Motorized wheelchair

Figure 3. Standing box for coma therapy

Figure 5. Automated projectile launcher

Table 1: Summary of Robotics and Mechatronics Projects

Project	*Course*	*No. of students*	*Funding*	*Outcomes*
Radio-controlled mobile robot	Freshman introductory engineering/ sophomore supervised study	Three	Undergraduate research	Mechanical design, motor control
Vision-based air hockey playing robot	Senior independent study	Four	Undergraduate research	Robot vision, distributed computing, robot design and control
Pneumatic cylinder control system	Senior independent study	Two	Faculty research start-up	Pneumatics, motion control experiment system, PC-based data acquisition, learning control research
Microhydro electric power generator design	Senior capstone design course	Four	Department, undergraduate research	Design, renewable energy, campus energy initiative
Motorized wheelchair design	Senior capstone design course	Four	Department	Assistive technology, mechanical design, control electronics
Underwater robot control	Work study	One	Faculty research	Control, Web-centric computing, community outreach, faculty research
Thermal energy conversion	Independent study	Two	Service learning	Design, embedded control, community outreach
Stand-in box for coma therapy	Senior capstone design course	Four	Faculty research	Design, pneumatics, physical therapy
PC-based baseball launcher	Senior capstone design course	Four	Department	Mechanical design, embedded systems, software

Figure 5 shows a schematic of the research project on underwater robotics for environmental monitoring that was also used by local school children to control a prototype robot, known as University of Michigan-Flint Underwater Robotic Device (UMFURD), remotely over the Internet[17]. This project is an example of the trend called Engineering Projects in Community Service (EPICS) encouraged at various engineering schools[18].

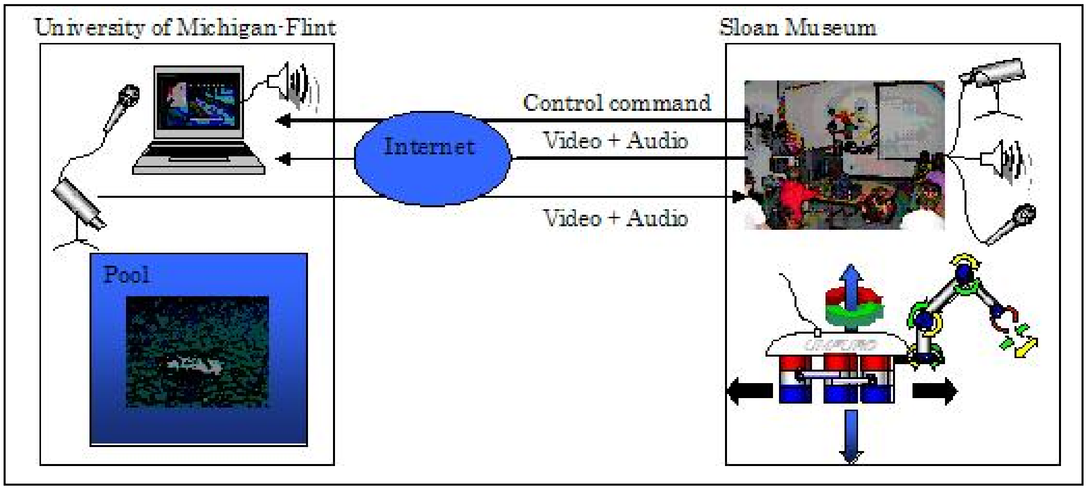

Figure 5. Internet-based Teleoperation of UMFURD

Lessons Learned

Several valuable lessons were learnt from the hands-on projects carried out at UM-Flint:

1. Outstanding student projects with potential for commercialization can be conducted by undergraduate engineering students, in fields like robotics and mechatronics. This is facilitated by the availability of low-cost, off-the-shelf hardware and software components, such as actuators, sensors, controllers, and computers.
2. Participation in these projects provides valuable experience to the students in team work, technical communication, engineering economics, and ethics. This experience will prepare them well for their future workplace, and motivate them to pursue graduate studies in specialized areas.
3. The hands-on experiences help students in better understanding of the topics studied in their courses, thereby increasing their classroom motivation and retention.
4. Supervision of these projects needs a supportive infrastructure in the university/school, in terms of provision of lab space, workshop facilities, and funds to acquire hardware/software.
5. The resources (components, systems, and software) developed as part of the completed projects can be adapted as part of laboratory experiments in related fields. This considerably reduces the load on the faculty involved in developing

new laboratory facilities.

6. Supervision of the projects as independent/supervisory study courses, however, needs significant time and efforts on the part of the faculty. Therefore, departments and universities would do well to compensate faculty efforts in this direction, by reducing their regular coursework in an appropriate manner. For example, at UMF faculty supervision of independent/supervisory courses is counted as voluntary. At Tulane University, guiding a total of six independent study students is treated as equivalent to a regular three-credit course.
7. The completed projects – especially in popular areas like robotics and mechatronics – can be used as a cultural or community resource that would encourage local children and youth to pursue high technologies, such as robots, computers, energy, and environment.
8. The collaboration of faculty and students with local institutions such as K-12 schools and museums provides the engineering students with valuable insights into the relations between technology and society. Moreover, the publicity for such efforts is valuable to universities in marketing themselves among local youth and attracting talented local youth to pursue their engineering programs.
9. Some of the more enterprising student projects can be used to establish collaboration with local industry in the form of student internships. They can also be used in offering short-term and online workshops to local and regional engineers, thereby creating additional finances for the department to improve its curricular and research facilities. Moreover, such liaison between practicing engineers and faculty can help the faculty make continuous improvements in their undergraduate and graduate curricula based on feedback from the engineers. It can further bring to the attention of the faculty real-world problems in industry needing research solutions, thereby facilitating tie-ups with industry.
10. The funding and resource requirements placed on the department/university in the pursuit of the hands-on projects can be reduced by soliciting the support of local institutions such as foundations and endowments, and donations of relevant hardware and software from local and national companies that manufacture these products. Organizations such as the National Science Foundation too provide significant funding for such educational endeavors.

Conclusions

This paper has discussed the experiences of innovative hands-on student projects in the fields of robotics and mechatronics at the University of Michigan-Flint. Such projects provide valuable engineering problem-solving experience to the students involved, and the resources developed can be adapted to promote new laboratory facilities, support faculty research, and serve also as a community resource by promoting the interest of local children and youth in science and engineering. The importance of the project-based learning efforts to small engineering programs cannot be overstated.

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