Creative Learning in School with LEGO® Programmable Robotics Products

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Abstract *- The work in this paper involves exploring the potential of using the LEGO programmable robotics products in school to instill engineering skills, scientific interests, computer acquisition, general ideas and creativity among students. The second objective is to propose a curricular program that covers guidelines for educators, scope of activities to be organized and how to relate the curricular program to machinery and automation in real life. Further to the second objective, the paper also discusses the possible interaction and collaboration between schools and the technological establishments for such a program.*

Learning technology the traditional classroom way could be dull and less appealing to students. Adding some interactive methods in the teaching process can be as fun as a field trip to nuclear plant and fruitful too. LEGO Mindstorms™ is a range of revolutionary programmable robotics products that opens up a whole new perspective in bringing affordable, motivational and interactive learning to adults and children. Mindstorms is so versatile that the limit to what can be done with the robotics kit is only limited by the creativity of the user.

Part of the paper will include work reports. The reports include:

- *Survey on students and teachers regarding their interest in robotics, preference in alternative learning methods, and understanding of robotics at school level.*
- *Observation of past robotics events*
- *Feedback from an ongoing pilot program based on the proposed model.*

1. Introduction

As modern technology advances in an ever-accelerating pace, especially in the crucial fields such as computer and automation, there is a continuous demand for skilled and highly motivated workers. To ensure that this demand could be met, technology curriculum is needed at the school level to give students insight into engineering fields and attract students to technology studies. As opposed to the traditional vocational education approach, technology curriculum at the school level should discard the confined professional bias and provide an insight into engineering science [11]. Therefore, new approaches are needed to design an appropriate modern strategy for implementing high quality technology program at school level. Robotics, being a multifaceted representation of modern science and technology, fits into this planning perfectly.

Realizing the potential and importance of robotics, the LEGO group has launched a range of programmable robotics products called Mindstorms in September 1998. The Mindstorms robotics base set consists of touch sensors, light sensors, rotational motors and a main building block that houses a microprocessor, which is programmable via an infrared communications port, linked to a PC.

2. Robotics in School

Robotics is an engineering art combing electrical and mechanical technologies. It is widely used nowadays and has been part of our daily life. In the industrial area, robots are widely use to increase productivity and hence production capacity. However, due to the complexity of robotics studies, it is hard to attract and pass the knowledge to students. This can be overcome by developing interest in students at younger years by introducing the simplest robotics knowledge to them. To date, many methods have been adopted by institutions around the world to teach and develop interest in robotics among the students.

However, a robotics program at school level should not only focus on the introduction of engineering skills, but should also aim to bring out the best of scientific concepts and technological principles through active, creative and meaningful learning. Robotics projects should also be able to stimulate critical thinking, communications and teamwork among students.

Robotics is fundamentally an applied field and its applications affect everyday life. Focus on robotics can be an effective and exciting way for students to learn about the problem-solving strategies used by engineers in practice. In this context, the LEGO Mindstorms robotics system poses a model for creative and innovative problem solving to the complex problems attuned to contemporary industrial approaches of computer system, automation, machinery and general engineering.

The potential application of Mindstorms is unlimited, as it is open-ended. To successfully manipulate the various functions of the robotics set, users need to possess integrated skills e.g.

- Computer Acquisition – Programming the robot with modern computer software to achieve an assigned task, while addressing issues of object components interface, addressing modes, handling events, and communications.
- Internet Usage – using the internet to participate in online Mindstorms activities
- Structuring Skill – materials, robot frames loads and stability, robot motion and collision worthiness.
- Mechanics Understanding – forces and torque, differential gear, robot motion, motor shaft loading and motor control.
- Electronics Understanding – light and touch sensors feedback, motor current, current loop and impedance.
- Other Generic Physics Theories Understanding

Mindstorms curriculum should be structured into a cooperative learning environment where small groups of students working together to maximize their own and each others' learning. Robotics project assigned to the students could be consisted of multiple task and components, where students are given the chance for collaboration among themselves to produce work that interface and integrate well as a whole project, mimicking true industrial teamwork spirit. To ensure the success of the group project, students hold each other personally and individually accountable for assigned share of the work, and appropriately use the interpersonal and small-group skills needed for cooperative efforts to be successful [4,9]. Also, as Mindstorms is highly unstructured, students are encouraged to be creative in implementing solutions to complex problems that can be easily related to the real life equivalent of robotics usage or even daily automation and machinery applications.

3. Surveys results

In order to acquire a better understanding of how the students and teachers see the possibility of introducing robotics curriculum to modern educational process, we carried out a small survey based on two sets of online questionnaires. Our second intention was to evaluate the current level of students' understanding and interest for robotics, and their willingness for a more interactive way of learning. A few supplemental questions helped to determine a correlation between robotics interests and general interests of students and teachers. Several other questions addressed the current implementation of ICT in schools.

Respondents were in several continents, which allowed for a comparison of the cultural differences. In the target age group, there were students of 10-18 years and school teachers. Subjects were solicited through announcements in Usenet discussion forums, Internet mailing lists and visits to classes in selected schools. The complete evaluation of the feedback using the two online forms with about 40 questions is available at (http://www.ifi.ntnu.no/~petrovic/lego/survey_en.html).

The early results indicated that most students favor more laboratory work for physics or science classes, since laboratory work is helping them to understand the subjects better. Most students thought that the use of LEGO construction sets in education is helpful and interesting, and could be used in mathematics, physics and computer classes. About half of them were still using LEGO construction sets at home. Some of the respondents were familiar with several concepts of robotics, but less than 50% were able to solve a simple gear arithmetic exercise. All teacher-respondents saw advantages in using the LEGO sets. They complained most often about the lack of financial resources and sometimes felt that the schools or the teachers were not ready yet.

4. Conceptual Model for implementing Mindstorms Program in school

i) Guidelines for Management: Operation, Key-players and Cost

To understand the operation of a robotics program in school, the management first needs to understand the robotics curricular plan itself. The Mindstorms base set includes over 700 LEGO pieces, the RCX, infrared transmitter, light and touch sensors, motors, gears, and a detailed building guide. The building guide provides children with guidance to build working robots in under an hour, as well as inspiration for more complex robotic inventions. The heart of this robotics system is the RCX, an autonomous LEGO microcomputer that can be programmed using a PC. The RCX serves as the brain of Mindstorms inventions. It uses sensors to take input from its environment, process data, and signals output motors to turn on and off. Users first build their robot using the RCX and LEGO pieces. They then create a program for their invention using programming language on a computer. Next, they download their program to the RCX using a supplied infrared transmitter. Their creation can now interact with the environment, fully autonomous from the computer.

Implementing the robotics program presented in this paper is simple and direct. The main key-players for the implementation are:

a) Educators to guide the students.
b) Technology-enabler to provide consulting and training to the educators.

c) Supplier to supply the building set.

The role held by educators involved in this program is discussed in later part of this paper. Technology-enabler could be a commercial provider, a local university, or a voluntary group with the relevant technical knowledge.

An estimated procurement cost for a class-size of 20 students is shown in Table 1 (assuming that 2 students share a set of Mindstorms).

Item	Cost
LEGO MINDSTORM SET (10 sets) @ $220 per set	$2200
Printed matter (guidebooks, etc)	$500
Personal Computers (10) @ $900 each	$9000
Reserves for LEGO expansion sets and parts	$500
TOTAL	**$12200**

Table 1. Cost estimation for a class-size of 20 students.

However the cost can be further reduced to suit the budget of the school by certain ways like increasing the amount of students sharing a set of Mindstorms or seek financial sponsorship from external source e.g. private institutions, engineering and educational based company.

Other ways capable of generating funds that involve students are:

a) Organizing inter-institution contests, which test the creativity and skills of the students participating in the program. At the same time generating funding from sponsorship.

b) Impose a small fee on each and every participating student.

ii) Guidelines for Educators: Curriculum, Skills and Philosophy

The new family of programmable LEGO products from LEGO Mindstorms and LEGO Dacta (the educational unit of LEGO Group) provide a rich set of learning materials that can encompass a wide variety of curricular activities and thinking skills. With such a wide variety of activities, students from kindergarten through college are all able to learn something from an experience with these technological tools. All students are able to dream-up an invention that is personally meaningful to them regardless of their background or gender. Teachers and researchers have used programmable bricks and their related hardware and software tools with curriculum units that include classroom systems engineering projects such as a recycling center or a town [2], designing robotic animals [7], kinetic sculptures [8], robotic competitions, scientific experimentation, and many more. Many activities fall outside the range of what people normally consider "robotics", which should broaden the appeal of the LEGO system to more teachers of different disciplines ranging from art to science to technology and engineering.

There are numerous thinking and social skills that are developed by designing, building, and programming with these LEGO robotics systems in a classroom setting. By using motors and sensors, students are building intuitions about such concepts as feedback and control. By programming the behavior of a robot, the student has to get inside of the mind of the RCX, and think about thinking! In other words, the student has to become an epistemologist. By constructing the mechanics of a robot, students build intuitions for concepts such as structural stability, gear ratios, and mechanical advantage. Working in groups offers an opportunity to build communication skills between partners of a project. A large-scale systems engineering project involving the entire classroom can build a sense of community among the students, and touch upon diverse academic areas from researching, writing, and presenting, to science, math, architecture, and technology [3].

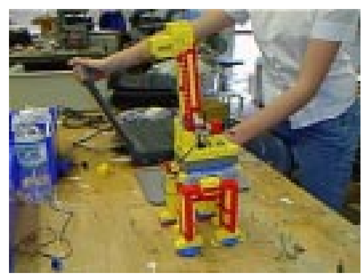

Figure 1. A LEGO giraffe being programmed by three seventh grade girls in Weston, MA. The giraffe can walk and also bend its neck.

A theoretical basis for a design-based curriculum goes back to the early progressive movement in education and such work continues into today. John Dewey, famous philosopher and educational theorist, believed that a child's natural impulses and personal interests to create, construct, and invent should provide the motivation for learning, investigating, and thinking [10]. He laid down the foundation of a philosophy of experience. His simple yet far-reaching idea that learning happens best when beginning with direct experience is the basis for much of the "hands-on" curriculum that we see today [1]. Constructing and creating are within the experiences of every young child, and thus is connected to their lives in a meaningful way. The LEGO system provides the perfect environment for creating the opportunities for meaningful learning. In recent years

Seymour Papert and others at the MIT Media Lab have coined the phrase "constructionism" to talk about a related philosophy of learning. Taking the idea from constructivism that knowledge in constructed inside one's head (and not transmitted into the head like a pipeline), constructionism adds that such knowledge construction inside the head is facilitated by constructions outside of the head, be it computer programs or physical models [7]. In this type of education, the learning takes place in the problem-solving, "debugging", and engineering designing and testing [7].

5. Teaching-Learning Materials

To program the intelligence into the Mindstorms robotics set, students would require to use computer software to design their program to be run on the robotics set. The default standard computer software that comes with the Mindstorms retail version is RCX Code. RCX Code is a simple visual programming environment that caters for basic capabilities of Mindstorms. It enables user to visually plug programming module into each other to form a program. The educational version of Mindstorms set comes with the software ROBOLAB. There are many other high-end advance Mindstorms programming environments developed by individual enthusiasts. Most of these programming software are distributed on the Internet. Below are a few examples of these software packages:

- NQC – A text-based Mindstorms programming tool based on the popular programming language C.
- Bot-Kit – An interactive object oriented environment for the RCX using Smalltalk programming language.
- TalkRCX – A programming interpreter for programming Mindstorms in Linux environment
- Mind Control – A Visual Basic program that interprets user command text.

Educators could choose to develop their own Mindstorms software for their curricular needs since the manufacturer made available a software development kit (SDK) that makes this possible.
(http://www.legomindstorms.com/sdk)

There are a few curricular materials available at the moment, from the official manufacturer channel and third party channel. Among these are:

- Lego Dacta provides guidance material for Mindstorms e.g. teacher's notes and worksheets. (http://www.lego.com/dacta)
- LDAPS, a non-profit educational project of CEEO, provides lesson plans on the WWW (http://ldaps.ivv.nasa.gov/Curriculum)
- Viztel Interactive Ltd, an Asian based company provides educator's specifics tailored multimedia CD-ROM syllabus for purpose of teaching robotics at school level (http://www.viztel.com/robotics).

6. Curricular Model and Feedback from a Norwegian pilot program

The main idea of "learning by playing and experiencing", which stands behind all the LEGO construction sets, was the idea we adopted for our curricular experiments at the Norwegian University of Science and Technology (NTNU). In general, one is not limited to this vision and can perfectly make use of the LEGO robotics technology for small demonstrations in physics, mathematics or science classes. That would be gamesome and very useful too, when compared to a traditional class, but still a bit away from the main purpose of LEGO construction sets. Our objective was to establish a class of high school students aged 12+, who would learn the basic principles and concepts of robotics. Recent innovative approaches to teaching ICT in schools are usually built around sequences of projects often solved by teams of learners. The concept and knowledge are thus hidden in many entertaining activities with high motivational value. Students are inclined to learn more from practical encounters. They relate new knowledge with the encounters. That's why this knowledge is retained more strongly. For an example, see [5], which inspired us also for the structure of the curriculum.

We were allowed to use the Trondheim Robotics Laboratory at IDI NTNU, which is equipped with several computers and LEGO Mindstorms sets. We selected a group of pupils from the local middle school (Lade, Trondheim) with the aim to provide an example of a robotics program, which could be implemented directly in schools. No doubt, current classroom curriculum is already very heavy and there is little space left for another subject, even in students' spare time. Accordingly, we relied on well-prepared intensive lessons lasting only 10 weeks, 1.5 hours per lesson every week. Although the course was only halfway through at the time we wrote this article, it indicated success in reaching the goals and identified some difficulties, which might be typically encountered. The titles of our robotics lessons are as the following:

1. Hop into the world of robots
2. The whole consists of pieces
3. Lend the beast your brain
4. The art of design
5. Nothing is perfect at the first trial
6. Robots speak each to other
7. Herds of cooperating fellows
8. Several players in one arena
9. Build your racing car
10. Which one is the best?

During the first lesson, we wanted the learners to experience the full scope of the system capabilities. A pre-constructed vehicle-robot with a front bumper was given to each group. A few simple program codes for collision avoidance were prepared and printed out on paper. Thus the course started with a demonstration, and all groups learned how to start the Mindstorms system, and create, save and load a program. They understood the principle of designing the robot's brain on the PC, and the working system was a great reinforcement and motivation for the following classes. The robots can be prepared by older or more experienced learners, so the teacher does not spend too much time on them.

The second lesson started with another modify-challenge, using the robots from the first meeting. Students were able to modify robot programs and show that they understand their meaning. Later, they assembled a complete robot according to a given detailed instruction from the original LEGO documentation (another source can be used instead, the number of available material on the Internet is growing quickly). In this lesson, students got involved in the intricacies of robot assembly.

Figure 2. Simple robot with a front bumper used at the first lesson.

During the third lesson, we focused more on the programming part and created several versions of robot controllers. Some of them required physical modification of the robot. At this time, students were asked to think about their own model.

The fourth lesson started with the whole class brainstorming on robotics models. Then the class was divided into groups. Each of them selected their models and made a plan for assembling the robot, and possible tasks, which the robot could perform. Most students finished a first version of the robot.

Next, students finished, tested, tuned-up, programmed and improved their models. Most of them were anxious to understand the gear control and requested explanation on behalf of the class.

Another lesson was dedicated to inter-robot communication capabilities, where students saw an example of avoiding physical conflicts of robots based on individual robot priority. At the end, we sat down for a brainstorming on an inter-group project, where the communication capabilities would be used. Students decided to invent a herd of robots, which will determined the "amount of food" at a location and negotiated with other robots on effective use of the resources. This kept us occupied for two more lessons and the rest of the course was devoted to building racing cars following a line for the final contest.

The mathematics teachers from the school were delighted by the Mindstorms technology and wished to have the sets used by more students, and volunteered to help organize the lessons.

The main difficulties met were mainly those of a technical nature. Special care had to be taken that the batteries were in good condition and that the IR communication was working (this problem was amplified by using multi-purpose computers instead of dedicated computers, as hardware conflict might surface). We sorted the LEGO pieces from all sets into a separate storage that made the robot construction faster and easier, although students had to move around more.

Albeit the pilot robotics program was small in size, the local feedback was satisfactory and hopefully provided some inspirations to everyone involved.

7. Inter-school and school-organization collaborations

Tufts University Center for Engineering Educational Outreach (http://www.ceeo.tufts.edu/)

The Center for Engineering Educational Outreach (CEEO) at Tufts University (located near Boston) provides numerous opportunities for teachers, student-teachers, and students to learn about engineering. One of the largest programs, LDAPS (LEGO Data Acquisition and Prototyping System), is aimed at creating new software tools, curriculum units, and workshops for students and teachers. The latest software from the CEEO is ROBOLAB. Known as the *Mindstorms for Schools™*, ROBOLAB is a programming environment that uses a graphical flowchart style of programming that utilizes more features of the LEGO RCX than the Mindstorms retail set. The highlight of the teacher workshops is the culmination project. Teachers are introduced to the concept of systems engineering - where groups of "experts" in structural engineering and programming collaborate together to plan, construct, program, and present a complex engineering system.

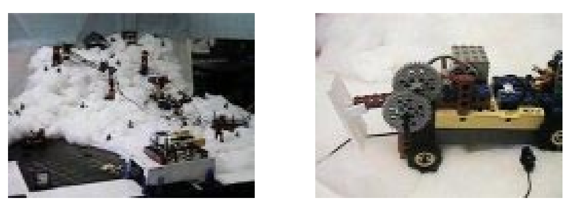

Figure 3. The LEGO Ski Resort - the systems engineering project at the first two-week workshop to use the RCX and ROBOLAB. The resort, left and close-up of snow plow, right.

U.S. FIRST (http://www.usfirst.org)

U.S. FIRST (For Inspiration and Recognition of Science and Technology) is an organization aimed at bringing popularity to intellectual pursuits among the children of today. In the same spirit of the popular baseball "little league," U.S. FIRST has begun a program called FIRST LEGO League, using the LEGO RCX. FIRST LEGO League is a middle school version of the popular high school FIRST Robotics Competition.

This past fall a pilot program of FIRST LEGO League was conducted at which much insight was gained into the kind of learning that can take place in such an activity. Among the schools involved in the pilot program was Weston Middle School, a community in the suburbs of Boston where author Ben Erwin is the technology teacher. The first point of interest is that the program, run as an after-school activity, appealed more to boys than to girls. Out of 40 initial attendees, there were 3 girls. Most likely due to societal expectations and marketing pressures (the LEGO aisle in toy stores is blue and gray) rather than aptitude, measures need to be taken to insure participation of young women in such programs. The types of activities that have been shown to appeal more to girls might include events where robots must be cooperative rather than competitive, where the event is tied to a real-world situation, and where the design of the robot can include aesthetic as well as functional design (FIRST LEGO League meeting, personal communications).

Another observation centered around the kinds of learning that were taking place during the project. The first question come into mind was why this activity so intriguing? Why are kids so willing to participate in this kind of learning? The easy answer is "it is fun," or "its learning in disguise," but it can be explained more precisely by saying that it is so intriguing because there is no right answer!

Too often in schools these days there is one right answer to a question. When students have the notion that there is one right answer, it can often scare them into not even trying to think about it. If they give their version of the answer, it might be wrong, and they will immediately be labeled as stupid. During the FIRST LEGO League, on the other hand, the atmosphere was one of open experimentation. The "one answer" type of learning is also very unlike reality, where there are always numerous solutions to a problem. These students were learning about the real engineering process of coming up with their own unique solution to a problem.

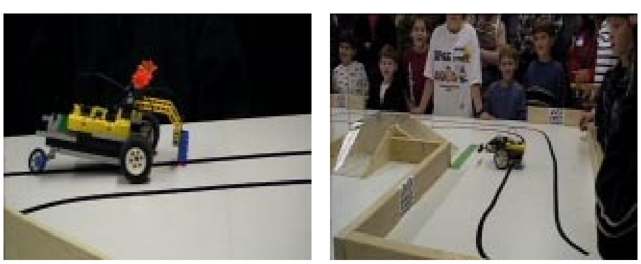

Figure 4. Images from the competition among the teams of Weston Middle School students. Left: A Robot follows the black electrical tape reliably around the course. Right: Parents and siblings watch as the bumper-robot navigates the course by bumping into the wooden walls.

8. Conclusions

Teaching technology in school is a concept to be endorsed indisputably. Robotics, being an important technological field of today and tomorrow, brings out the best of many knowledge, skills and ideas.

A conceptual curricular model of robotics program in school is developed and implemented through a Norweigian pilot program. The proposed creative learning strategy with LEGO programmable robotics products is well received and solicited significant results.

Questionnaire and various events observation indicated that most students could better appreciate practical creative activities than the traditional classroom methods.

9. References

[1] Dewey J., Experience and Education. 1938. Kappa Delta Pi.

[2] Erwin B., Rogers, C., Cyr, M., Osborne, J. Middle School Engineering with LEGO and LabVIEW. Proceedings of National Instruments Week August 1998, Austin, TX, Education Category.

[3] Erwin B.. K-12 Education and Systems Engineering: A New Perspective. Proceedings of the American Society of Engineering Education National Conference, July 1998, Seattle, WA, session 1280.

[4] Johnson D.W., Johnson R.T., Smith K.A., "*Active Learning: Cooperation in the college classroom*", Interaction Book Company, Edina, 1991.

[5] Blaho A., Kalas, I., Learning by Developing. Logotron 1998. ISBN 0582 340489, pp. 331

[6] Martin F., Kids Learning Engineering Science Using LEGO and the Programmable Brick. AERA 1996 Annual Meeting, April 8-12, New York, NY.

[7] Papert S., A Critique of Technocentrism in Thinking About the School of the Future. Espitemology and Learning Group Memo No. 2. MIT Media Lab: Cambridge, MA.

[8] Resnick M., (1993). Behavior Constuction Kits. Communications of the ACM, 36(7), pp. 64-71.

[9] Smith K. A., "Cooperative Learning: Effective Teamwork For Engineering Classrooms", Proc. 1995 IEEE Frontiers in Education Conf., Atlanta, 1995, pp. 2b5.

[10] Tanner, Laurel N., Dewey's Laboratory School: Lessons for Today. 1997. Teachers College Press.

[11] Waks S., "Curriculum Design From an Art Towards a Science", Tempus Publ., Oxford, 1995.