Using LEGO Mindstorms as an Instructional Aid in Technical and Vocational Secondary Education: Experiences from an Empirical Case Study

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Abstract. This paper reports on an empirical study concerning the use of LEGO Mindstorms Robotics kit as an instructional tool in technical and vocational secondary education. In particular, a robot car was developed and programmed in order to be utilized in teaching classes in the field of Mechanical Engineering. The paper describes the rationale for that construction and the robot car itself and proposes a lesson plan exploiting this technology. The pilot study that was conducted aimed at measuring the effectiveness of this approach in terms of learning outcomes as well as students' satisfaction, enjoyment and perceived usefulness. The results of the study are encouraging towards the adoption of robotics in technical education although raising some issues that need to be further explored.

Keywords: LEGO Mindstorms; educational robotics; evaluation; technical education; mechanical engineering.

1 Introduction

Robotics, apart from being a subject by itself, can also be used as an instructional tool in a wide range of subjects: from Engineering (e.g. [1]) and Computer Programming [2], to Artificial Intelligence [3] and Psychology [4]. In the last twenty years or so, a lot of research energy has been put in investigating the role that robotics can play when integrated in the course work at all levels of education. The literature regarding research on that area indicates that robotics are used in education with several aims, such as teaching various scientific, design and mathematic principles through experimentation [5], developing students' ability to solve mathematical and logical problems [6], enhancing their critical thinking skills [7], motivating them to pursue careers in science and technology and increasing their technological literacy [8], engaging them [9] and promoting their collaboration spirit and skills [10]. Moreover, robotics may be effective for at-risk or under-served student populations ([9]; [5]; [11]).

The idea of using robotics in education is based on earlier research work of the MIT mathematician and Piaget's pupil, Seymour Papert, the creator of the LOGO programming language [12]. Papert believed that learning is more effective when

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students are experiencing and discovering things for themselves and that the computer is a perfect medium for discovery learning. LOGO was based upon these two ideas and was designed to let young students solve design problems using an on-screen small robot called the "Logo Turtle".

Papert's work with LOGO served as the basis for research partnerships between the MIT Media Lab and LEGO Corporation [13]. In 1998, the LEGO Company released a new product called the LEGO Mindstorms Robotic Invention System (RIS) kit that became an instant commercial success. In 2006 a major upgrade was released called LEGO Mindstorms NXT kit and won the 2006 Innovation Toy Award in the "Technology" category. The kit consists of 577 pieces including LEGO bricks, motors, gears, different sensors (touch, light, sound, ultrasonic), and an intelligent "NXT Brick" with an embedded microprocessor. Also, the set includes the Mindstorms NXT software. By programming the NXT brick -using a PC- one can create an autonomous robot made out of LEGO bricks. The Mindstorms NXT software is an icon-based programming language, loosely based on LOGO. It allows users to drag and drop in certain order graphical blocks of code representing commands such as left and right turns, reverse direction, motor speed, motor power, etc. and thus define the behaviour of the robotic construction.

This paper reports on our attempt to explore the potential of LEGO Mindstorms as an instructional tool in technical/vocational education. In particular, a robot car was developed and programmed in order to aid instruction in the field of Mechanical Engineering. The rationale of that development and the robot car itself are described in the subsequent section of the paper. The section that follows proposes a lesson plan utilizing this technology and describes a study that was conducted in a Greek Technical high school to evaluate this approach. Finally, in the last section of the paper some conclusions are drawn and discussed.

2 Development of an Educational Robot Car

2.1 Fulfilling the Need for Bridging Theory to Practice

The development of an "intelligent" robot car and its utilization in the classroom may support an interdisciplinary instructional approach in the field of Mechanical Engineering. A car is a complex system consisting of many subsystems whose role and functioning are usually described in a course that in Greek technical education is called "Automotive Systems". Students however, in order to understand these concepts, frequently need to trace back fundamental concepts that they have been taught in several other subject areas: physics, chemistry, biology, mechanics, mathematics, computer architecture and programming, electronics, etc. This need to look back and combine concepts from various subject areas introduces a high degree of difficulty in the courses taught in technical/vocational high schools, especially if we consider the cognitive gaps that many students may have from their previous school years. An approach aiming at directly addressing these gaps is impossible mainly due to time limitations. It is more realistic and appropriate to let students discover and address their gaps through trial and experimentation. Students are usually willing to try to assimilate concepts and procedures that they consider useful for their future profession and related to their vocational experiences so far, i.e. the mental models that they have built based on their observations on the operations of machines.

The traditional approach in technical education suggests that students should be attending a hands-on lab lesson only after they have been taught the corresponding theory. On the contrary, the constructivist approach and especially discovery learning theory [14] argues that students are more likely to understand and remember concepts they had discovered in the course of their own exploration. The LEGO Mindstorms constructions can be extremely helpful in that direction. For example, though a student may not know the theory that predicts a cantilever's bending moment, s/he may find out -while trying to build a machine- that a long axle will bend more than a short axle of the same cross section when a force of the same magnitude is exerted on their ends. In that way, we can assume that robotics construction kits like LEGO Mindstorms may help students not only to deeply understand concepts they already know but also to discover concepts that they have not been taught yet.

Furthermore, working with robotic constructions offers students an authentic problem solving experience since the procedures they should follow emulate those needed in real-life situations. Providing such experiences to students is probably a way of preventing what Brown et al. in [15] called inert knowledge (i.e. skills that students have learned but do not know how to transfer later to problems that require them) which results from learning skills in isolation from each other and from real-life application.

2.2 The Robot Car

The car that was constructed is illustrated in Fig. 1 (left). It is a front wheel drive car with a classic chassis type, powered by an electronically controlled electric motor (Lego NXT), and a 3-speed gear box. The car can drive straight forward or reverse. In order for the car to interact with its environment, three sensors are connected to the NXT brick: a sound sensor, an ultrasonic sensor and a touch sensor. The sound sensor is used for remotely controlling the car with a clap sequence: one clap starts or stops the car and two claps drive the car backwards. The ultrasonic sensor (front part) is

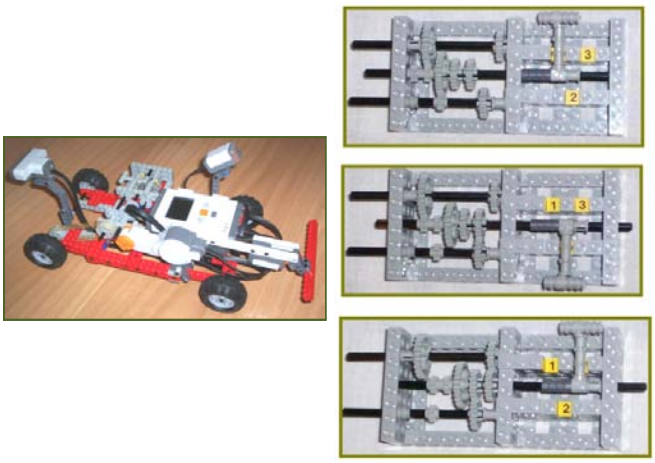

Fig. 1. Left: The robot car. Right: Top view of the gear box with 1st, 2nd, 3rd gear selected.

used for reversing the motion when an obstacle is detected within a given distance (e.g. 30cm). The touch sensor (rear part) is used for reversing the motion when the rear bumper hits an obstacle.

The gear box is a variation of the mechanical sliding gears type. First, second, and third gear give a gearing down ratio of 9:1, 3:1 and 1:1 respectively. The primary axle is connected directly to the rotor of the electric motor. The secondary axle is connected to the car's front axle via a triple elastic belt with a transmission ratio of 1:1. Electric motor's power can be adjusted from 0% to 100% in 5% increments. Fig. 1 (right) illustrates three top views of the gear box with 1st, 2nd and 3rd gear selected. The transmission ratios are formed with 8, 16, and 24 teeth gears.

The car functions only if the proper executable file is loaded into the NXT brick's memory. The workflow algorithm (program) is written in the provided graphical user interface of the NXT software by selecting the proper icons where each icon represents a specific action for the robot (i.e. motor movement, sensor reading, etc). Then the executable is automatically generated from the NXT software and transmitted to the brick via USB cable or wireless Bluetooth connection. The program consists of the main routine and many subroutines (MyBlocks and WebBlocks). The main routine and one of the subroutines (right NXT button control for power increase) are shown in Figures 2 and 3 respectively.

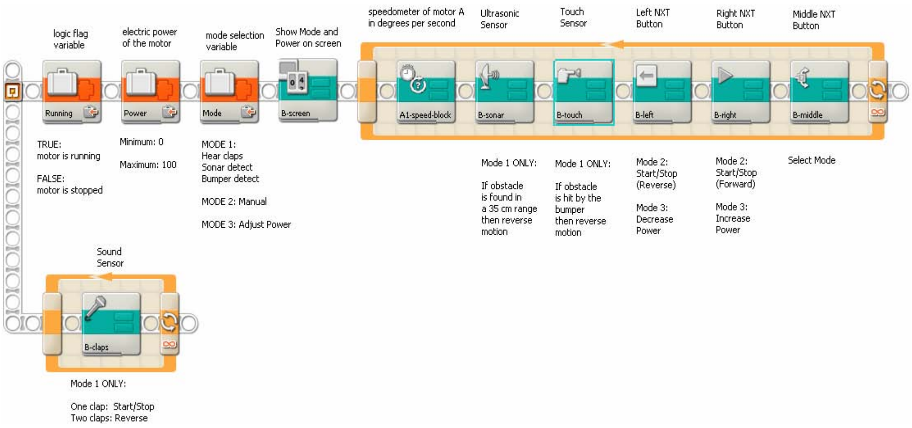

Fig. 2. The main program

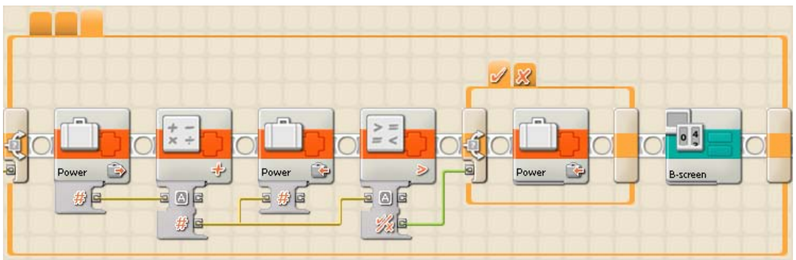

Fig. 3. MyBlock: B-right subroutine

3 The Robot Car in the Classroom

3.1 Lesson Plan

After the development of the robot car, a lesson plan was designed in order to be used in the pilot study that would follow. The objectives of the proposed lesson are the following: (i) students should understand the concepts of speed, torque and power of a rotating axle, (ii) they should be able to describe the direct or inverse proportion ratio of speed and torque of two axles coupled with gears, (iii) they should become familiar with the programming environment of a microcontroller, (iv) they should realize the necessity of a flowchart in order to create a correct control algorithm.

Teaching with the robot car includes a number of phases/activities. In the first phase, the instructor presents the LEGO Mindstorms kit: the bricks, the gears, the NXT brick, the sensors, the motors, etc. and makes clear to students that the software is necessary for the operation of the car since its motors and sensors are controlled by the NXT brick and they are not operating autonomously. Following that, the instructor describes briefly the car's capabilities: electronic control of the electric power, mechanical control of the torque via the gear box, sound controlled via clap sequences, front and rear obstacle avoidance mechanism.

In the next phase, students are separated in groups and they are asked to study and write down the transmission ratios of 1st, 2nd, and 3rd gear of the gear box. In case that a group does not know how to proceed, the instructor offers help explaining them that they have to count the number of teeth of every gear. To facilitate their work, the instructor may give them a real copy of the car's gear box so that they can turn both primary and secondary axle by hand and observe the resulting transmission ratios.

In the third activity the car's wheels are running without touching the ground and students are asked to empirically notice the torque output change according to the selected transmission ratio and try to find an empirical formula that connects these two quantities. Students can feel the magnitude of the secondary axle torque by applying on it an opposite braking torque with their fingers. Additionally the output torque for every gear can be observed by the ability or not of the car to run on a gradually increasing ground slope.

After the students will have discovered by themselves the formulae that link the ratio of gear circumferences with the ratio of axle speeds and torque, the instructor may present them these concepts in their theoretical form.

During the last activity, students in pairs are encouraged to experiment with programming the robot car, either by altering the initial algorithm that controls the car's operation, or by making from scratch their own small programs to control the vehicle. Each pair of students modifies the program or creates a new one and the rest of the class is watching their actions.

Finally, students are asked to fill in a test in order to assess their knowledge and understanding in the corresponding concepts. Obviously, a traditional paper-and-pencil test is not the most appropriate way to measure the overall learning gains obtained from working with LEGO Mindstorms. However, the limited time that was available for completing the whole pilot lesson precluded any other -more appropriate- kind of assessment.

3.2 The Study

The above mentioned two-hours lesson plan was implemented at a Technical and Vocational School in Greece (4th T.E.E. of Sivitanidios School) in a class of the Mechanical Sector, attending the second year of the three years course of study for "Car Machinery and Systems" field of specialization. The class that participated in the study consisted of 14 students aging between 16 and 18. The concepts that are involved in the lesson plan had already been taught to those students in previous years of their studies in the context of the lessons entitled «Machine Design» and «Automotive Systems I». The reason for choosing this class instead of a class that had not been taught those concepts yet was twofold: there was a serious time limitation (the study could not exceed two hours) that would not allow the teaching of completely new concepts and also, it would be interesting to see whether the robotics approach could manage to correct students' possible misconceptions and address their cognitive gaps.

Before the beginning of the lesson, the instructor initiated an informal discussion with the students on the concepts involved in the lesson to follow, in order to diagnose their current knowledge and misconceptions. Students' responses in the discussion revealed that their knowledge on the subject was average and some of them were rather confused.

Then, the lesson began following the aforementioned phases. During the last part of the lesson at which students attempted to modify the existing program controlling the robot car or build a new one, the instructor was closely observing students' discussions, activities and reactions and kept notes on all that. These notes were one more source of information to be used in the evaluation of this approach.

Table 1. Assessment quiz

Questions, possible answers (the right one appears here in bold face) and percentage of correct responses to each question (appears in brackets)	
1. By knowing the transmission ratio between two gears we can find	
A. The speed ratio of the axles	
B. The torque ratio of the axles	
C. Both A and B ***[100%]***	
2. In a working pair of gears their speed ratio is a direct proportion of their circumference ratio.	
A. True	**B. False** ***[0%]***
3. In a working pair of gears their torque ratio is a direct proportion of their circumference ratio.	
A. True ***[50%]***	B. False
4. Shifting down during driving can help	
A. Reduce car speed	
B. Increase car speed	
C. Both A and B depending on the way the accelerator pedal is used ***[100%]***	
5. Some cars cannot reach top speed with the longest (5th) gear selected. This is:	
A. True. Near top speed, 5th gear may prove very weak to provide the needed torque for acceleration towards top speed. ***[57%]***	
B. Just a myth. The longest gear always moves the car faster or it wouldn't exist since it adds more cost and complexity to the gear box.	
6. Changing the memory contents of an Electronic Control Unit (ECU) can	
A. Either improve or worsen the car's performance ***[93%]***	
B. Only benefit the car	
7. Car's sensors (e.g. exhaust gases temperature sensor) collect information which is processed by the ECU depending on the program that is loaded in its memory.	
A. True ***[93%]***	B. False

Table 2. Questionnaire regarding the LEGO Mindstorms experience

Questions and possible answers
1. What is your previous experience with LEGO: A. LEGO DUPLO B. LEGO Bionicles, City, StarWars etc. C. LEGO Racers D. LEGO Technics E. LEGO Robotics
2. What are the teaching tools that you have used in the past in order to understand the theory of today's lesson? A. Real engines B. Educational engine models C. Other (please describe)_______________ D. None
3. How would you rate LEGO in comparison with the other tools used? A. Much more effective. B. About the same effective. C. Less effective. Besides, it is just a game.
4. Would you like to gain experience in building LEGO machines and robots? A. Yes, although it will not be helpful in my profession B. Yes, it will also be helpful in my profession C. No. Job and school are so much time consuming that I would prefer to learn something more directly useful.
5. My current professional status is: ____

After the completion of the lesson students were requested to answer along with the assessment quiz, a questionnaire regarding their experience with the robot car. The assessment quiz and the questionnaire are presented in Tables 1 and 2 respectively.

3.3 Results of the Study

Students' answers to the assessment quiz (see Table 1), especially if compared to their responses in the discussion preceding the lesson, show that in general, the robotics approach was useful in helping them understand the principles that underlie the transmission of rotational motion with gears. In particular, all of the students answered correctly questions 1 and 4, all but one also answered correctly questions 6 and 7 and 57% answered correctly the quite difficult 5th question.

However, all of the class gave the wrong answer to question 2 and half of them also to question 3. Since these two questions are related to each other, we believe that students who answered erroneously to both these questions (50% of the class) have understood better the corresponding concept, than those who answered correctly the 3rd question, because the first group of students has probably understood that torque and speed of an axle are inversely proportionate quantities. The reason for giving wrong answers to these two questions is possibly the "mathematical" language that was used for their statement. If this is indeed the case, then it can be assumed that these students were not able to answer the questions correctly due to the deeper cognitive gaps that they have. This finding was not surprising considering the group of students that participated in the study: students that attend Technical and Vocational Schools in Greece are mainly students with strong technical skills but rather weak in traditional math and science classes. These students who are not usually willing to work in a more formal way, could be extremely benefited by approaches like the one described here which are based on the "learning by doing" paradigm [16] and look more like a game than like a learning aid.

As for the students' responses to the questionnaire, these were recorded as follows:

- To almost all students this technology was completely unknown. Half of them were familiar with LEGO Technics or Racers and only one with LEGO Robotics. 5 students out of 14 had no idea what any kind of LEGO is. This finding implies that in order for these technologies to be welcomed in the classroom, students should get hands-on training and given plenty of time to practice on them before using them in the context of a specific lesson.
- Concerning the tools that were used so far in their teaching, not surprisingly, most of the students stated that these were either real engines or educational engine models. Indeed, this finding confirms the general picture that the approach of educational robotics has not reached yet the mainstream of education, albeit it has gained a lot of attention and most of the studies on them have yielded positive results. Possibly, the reason for this delay is the fact that teachers have not been trained -at least not in a wide scale- in the use of these technologies.
- Compared to the above mentioned instructional aids, LEGO was judged by 40% of the students as more effective. 30% of the students believed that LEGO is less effective and the rest 30% could not tell the difference. Taking into account that the group of students participating in the study were experiencing this technology for the first time and they have not even had enough time to explore its full potential, the fact that 70% of them perceived the robot car as being equally or more effective than the traditional instructional tools is considered definitely a very encouraging finding towards the use of LEGO Mindstorms as a teaching/learning aid.
- All but one of the students expressed their desire to learn more about developing LEGO machines and robots and an impressive 30% of them felt that such knowledge would be needed in their future workplace. This is also a very positive finding, not only because this technology seems to have gained students' interest but also because their experience helped them realize that in order to be competitive in their profession they should be well informed and trained in the use of the emerging technologies.

As it has been already mentioned, while students were modifying the existing program or building one of their own, the instructor was observing them and kept notes on every point he considered interesting. Overall, according to those observations, students seemed to be satisfied with their experience with LEGO Mindstorms. In particular, the LEGO construction encouraged students to be actively involved and hence awakened their interest in the lesson. Moreover, students seemed to enjoy watching the car interacting with the environment through its sensors (obstacle avoidance and sound control) and they were impressed by the capability of using the menu to adjust according to their will the power of the car as well as its mode of function. Furthermore, they were impressed by the ability of the car to climb on a very steep slope with 1st gear due to its massive torque as well as by the quite high top speed reached with the 3rd gear.

4 Concluding Discussion

This paper reported on the first of a series of studies we plan to conduct regarding the use of LEGO Mindstorms as an instructional aid in technical and vocational secondary education. For the purposes of the study, a robot car was developed and used in a two-hour lesson with a class of the Mechanical Sector in a Greek technical school. The prime motivation for the study was to gather some initial evidence about students' attitudes and feelings towards the use of robotics technology in the classroom. In addition, the study attempted to measure the effectiveness of this approach in terms of short-term learning outcomes. Indeed, the results of the study were positive and thus provide the impulse for further and in-depth research in the field.

In particular, students' scores to the assessment quiz were rather high, showing that in general, the robotics approach was useful in helping them understand the underlying concepts, correct possible misconceptions they previously had and address their cognitive gaps. Hence, the objectives of the designed lesson seem to have been met. However, the fact that the majority of students failed in two of the questions which were stated more formally, on one hand confirms the need for practical, hands-on learning experiences for those students, but on the other hand raises questions that need further investigation: how can these students see more positively math and science in their theoretical form? And can educational robotics -through their motivational quality- help in that direction too? In the study described here, students were exposed to this technology for a very short period of time thus not allowing to draw any conclusion about what would happen in the long run.

Another finding of the study -rather common knowledge- was that currently this kind of technology is not being used in school classrooms. The research on the field is ongoing and the results so far are in their majority positive but what we believe is missing is large-scale and long-term experiments to prove the effectiveness of that approach. If such experiments manage to confirm that educational robotics is indeed effective, the next step will be to design a framework for their integration in the school curricula and properly train the teachers that will be using them.

Students participating in the study were satisfied with the robot car, enjoyed working with it, expressed their desire to learn more on this technology and the majority of them judged it as being equally or more effective than the tools that were normally used for their instruction. These findings are definitely positive, but the short duration of the experiment poses some considerations: Would the students' feelings and attitudes be the same if they were been using that technology over longer time? Becoming more familiar with that would replace the initial enthusiasm with boredom or with greater acceptance? Answering these questions is a matter of further research that we plan to conduct in the near future.

As a matter of fact, it is within our future plans to examine the long-term effects of using robotic constructions in technical education. In this examination we will investigate how the increase of students' motivation may be connected to long-term effects in their performance and also whether students' attitude will remain positive if they are using this technology on a regular basis. Furthermore, we intend to run more experiments following this approach involving students from other Technical education's sectors and fields of specialization as well, and from various age groups. In that way, we will have the opportunity to evaluate the effect of robotics along the two dimensions of the domain taught and the age of students.

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