Educational Robotics as Mindtools

Tassos A. Mikropoulos, Ioanna Bellou
amikrop@uoi.gr, ibellou@sch.gr

The Educational Approaches to Virtual Reality Technologies Lab,
The University of Ioannina, Ioannina, GR 45110, Greece

Abstract. Although there are many studies on the constructionist use of educational robotics, they have certain limitations. Some of them refer to robotics education, rather than educational robotics. Others follow a constructionist approach, but give emphasis only to design skills, creativity and collaboration. Some studies use robotics as an educational tool in engineering education, science and programming learning implying mindtools, but they do not give evidence of mindtool characteristics. This work proposes educational robotics as mindtools based on constructivism and especially constructionism. The positive learning results from two case studies on physics and programming teaching indicate that educational robotics can be used as mindtools supporting knowledge construction through the design of meaningful authentic projects, learning by doing in both the virtual and real world, facing cognitive conflicts and learning by reflection and collaboration.

Keywords: educational robotics, mindtools, physics, programming

Introduction

The pedagogical exploitation of Information and Communication Technologies (ICT) is the most important aspect as far as ICT introduction in education is concerned. This is not dependent on the technological approach used, but rather on the theoretical perspective followed. ICT are considered to be the most powerful tools for support in the learning process. Their main contribution comes from their technological characteristics, the ways they record, represent, manage and transfer information. These characteristics concern the management of high volumes of data and information in a short time, information presentation through dynamic interactive and multiple representations, as well as the communication and motives they provide. The essential contribution of ICT to the learning process comes indirectly, through their pedagogical exploitation and certain features that arise from their technological characteristics. The contribution mainly involves tasks for the active participation of students and teachers, action and counteraction through interactive activities, as well as processes that support the creation of mental models (Mikropoulos & Bellou, 2006). These are in accordance with the constructivist theoretical model developed by Piaget proposing that learning is an active process of knowledge construction based on experiences gained from the real world, as well as with the social dimension to knowledge construction proposed by Vigotsky.

Constructivism deals with how learners construct knowledge. This depends on what learners already know, the experiences they have, and the way they organize their experiences into knowledge structures (Jonassen, 2000). The main principles of constructivism are rich user – centred interaction, use of authentic problem situations, collaborative learning and learning experience of and with the knowledge construction process. Based on these, Boyle has compiled the following seven principles for constructivist ICT – based learning environments (1997):

- provide experience of the knowledge construction process
- encourage the use of multiple modes of representation
- provide experience and appreciation of multiple perspectives
- embed learning in realistic and relevant contexts
- encourage ownership and voice in the learning process
- embed learning in social experience
- encourage self – awareness of the knowledge construction process.

The above seven principles imply that learners do not learn from technology, but they learn with technology. This happens when ICT support knowledge construction, exploration, learning by doing, learning by conversing, learning by reflection (Jonassen, 2000). Papert gives his perspective to constructivism, by describing knowledge construction in a more concrete way (1993). This is now a well-established educational approach, namely constructionism. Papert claimed that knowledge construction is more effective when learners are engaged in designing meaningful projects and constructing artefacts, and that technology provides tools for this design and construction (1993). The four main principles of the constructionist approach can be compiled as (Bers et al., 2002; Resnick & Silverman, 2005):

- learning by designing meaningful projects, creating things and sharing them in community
- using manipulative objects to help concrete thinking about abstract phenomena
- identifying powerful ideas, tools to think with from different realms of knowledge
- learning by reflection.

Papert "pays particular attention to the role of constructions in the world as a support for those in the head" (Bers et al., 2002).

ICT offer tools to engage students in developing meaningful projects through real world constructions. Papert gave the first examples with the logo programming language and turtle geometry with the turtle either on the floor or on the computer screen. Nowadays, this approach is evolved to the visual, drag-and-drop programming languages such as scratch from MIT, BYOB and snap from Berkeley University. These kinds of educational programming environments provide easy ways for the interaction with the real world, as well as for the development of intuitive human – machine interfaces. Microcomputer Based Laboratories (MBL) are also systems that provide manipulative objects – sensors and actuators – and help students to create things, think about phenomena, identify powerful ideas, design meaningful projects and learn by reflection and collaboration. MBL have had great success in teaching and learning science and especially physics at all educational levels (Thornton, 1999). Educational robotics is considered to be an approach to educational technology that fits constructivism and especially its constructionist approach. The existence of the robotics artefact, a physical machine, acts as a concrete object that gives the tool to the users to work with and construct their mental models more easily and effectively. We believe that educational robots bring into effect the constructionist theses as a result of both their hardware and software characteristics. Resnick and Silverman propose that robots are the technologies that engage children in constructing things, encourage and support them to explore the ideas underlying their constructions (2005). They also propose robots such as the LEGO's programmable bricks for the design of microworlds for exploring the idea of feedback. Feedback is an important parameter in the learning process, and is easily achieved and understood using physical artefacts like robots. The integration of a robot – based educational project by the students includes four steps (Dagdilelis et al., 2005):

- constructing a robot (mainly) using students' imagination
- developing a program using the visual programming environment
- downloading the program on the robot
- program execution.

These four "technological" steps follow the four principles of constructionism as reported above. They are also in accordance with the peer interactions identified by Staszowski and Bers (2005), namely:

- design
- building
- building concepts
- programming
- programming concepts.

During the whole process that is construction of the robotic systems, writing, downloading and executing the appropriate program, students think about the problem under study, design their own meaningful projects, create things and manipulate objects, reflect, and collaborate. The most important factor is that students use their powerful ideas, their own way of understanding, they represent their knowledge. The above arguments are supported by many empirical data reporting the positive contribution of educational robotics to the acquisition of technical skills and learning outcomes in various disciplines and educational levels (Erwin, Cyr, & Rogers, 2000; Bers et al., 2002; Alimisis, Karatrantou, & Tachos, 2005; Isela & Mota, 2007). Educational robotics incorporate the constructivist and especially constructionist principles, but we think that their contribution becomes more effective when they are regarded as cognitive tools or "mindtools" as proposed by Jonassen (2000). This is proposed by Chambers and Carbonaro who state that "mindtools, in the form of robotics, represent a constructionist approach to using technology – where such activity is intended to engage the learners in representing knowledge, manipulating virtual and concrete objects, and reflecting on what they have designed and built. Using robotics as mindtools involves the learner in simultaneously building both a functional physical object and the problem-solving knowledge it takes to accomplish the task" (2003).

The goal of the present work is to connect educational robotics as tools for constructionist learning with mindtools, by presenting certain mindtools' characteristics and giving two examples of using robots in physics and programming learning.

Educational robotics as mindtools

Mindtools are defined by Jonassen as computer – based learning environments that learners develop or modify in order to engage and facilitate critical thinking and higher order learning (2000). Mindtools act as cognitive amplifiers, intellectual partners, and reorganization tools. It is obvious that mindtools do not follow a technocentric approach; their use is not aimed at technical skills development or computer literacy. Mindtools act in a framework of meaningful learning, fostering reflective thinking, scaffolding thinking.

As constructive tools, mindtools follow the holistic, horizontal approach of ICT in the didactic process. ICT through mindtools are exploited in every discipline, supporting students to represent their knowledge, to build their own mental models. This can be done through various technological approaches and software applications. These can be dynamic modelling tools, knowledge construction tools, semantic organization tools, interpretation tools, communication tools, as well as computer – real world interfaces. Although Jonassen does not explicitly proposes educational robotics among the technological approaches to mindtools, we claim that robots in education are powerful mindtools since they follow mindtools' principles through their characteristics of fostering students to think about a problem, design their meaningful projects, create things and manipulate objects, reflect, and collaborate. Moreover, robots go a step beyond, by taking the student out of the limits of the computer screen into the real world. This makes it easier for the students to overcome certain difficulties when working with the computer. Educational robotics contributes to the understanding of the notional machine (that describes the role of the machine to programming) and its relation to the physical machine. Working with robots, students also shorten or even eliminate the distance between the "objects of the world" and the "computational objects" such as variables. The way a robot – based project integrates as reported by many authors (e.g., Dagdilelis et al., 2005) including the robot construction, program development and execution, implies mindtools, although they are not mentioned by any author, except the general statement by Chambers and Carbonaro (2003). A robot – based project involves intentional work and meaningful learning, constructive and authentic tasks, collaboration, and reflective thinking, which are the main attributes of mindtools. By compiling the common characteristics and goals of educational robotics and mindtools, we propose the following reasons for using educational robotics as mindtools. They both support:

- knowledge construction through the design of meaningful projects and students' representations using authentic paradigms
- learning by doing in the virtual and real world providing a safe problem space
- cognitive conflict through the comparison between causes and results
- learning by reflection by helping students to represent their knowledge
- learning by conversing through collaboration, discussion, argumentation.

As mentioned in the previous section, there is a great deal of empirical data showing the positive results of educational robotics. The brief review that follows refers only to work published since 2000, when mindtools and the pedagogical use of ICT have been widely applied.

Erwin, Cyr and Rogers report on teaching engineering with LEGO bricks to students from 5 to 50 years old (2000). The authors' point of view is technocentric since they use robotics as a tool for technical skills development. Besides, they report that "as students design and build their projects, they are motivated to learn the math and science they need to optimize their project". The students' main aim is to build and control a bumper car or a smart house rather than to construct knowledge on science concepts that are studied in an interdisciplinary and secondary framework.

Denis and Hubert report on a collaborative and problem based learning educational robotics environment (2001). Pupils work in small groups and their tasks are the building and programing of a robot. They work in a constructive collaborative framework with positive results as far as the collaboration is concerned. In this article, robotics seems to act as a mindtool, only by supporting learning by conversing. Collaboration is also found to be a way of creative thinking among engineering and design students (Goff & Vernon, 2001). Similar conclusions on the contribution of collaboration have also been reported by Wang with mechanical engineering students (2001). The author reports that LEGOs provide an excellent medium for teaching design, creativity and programming compared to C and LABVIEW languages. Positive results are also reported concerning design skills and creativity in meaningful projects by engineering students (Ringwood, Monaghan & Maloco, 2005).

Bers and her colleagues propose robotics as the tool to introduce technology into the early childhood classroom, following constructionism (2002). They propose educational robotics as "objects to think with" and design meaningful projects, in accordance with the philosophy of mindtools. They also present positive empirical data from their study on teaching pre-service teachers to engage pupils in learning new concepts and ways of thinking. The authors show that the constructionist model is well suited since they report identification of powerful ideas and project design by the teachers. Despite this, their article has a more or less technocentric approach since it is on robotics education trying to develop technological fluency to the teachers, referring to robotics as a discipline. Robotics education is a step before educational robotics, our approach to the constructionist model with robots as a tool for the holistic approach and as a mindtool, supporting other disciplines.

Hacker in her thesis reports on the constructivist approach in educational robotics proposing it as tool for learning science and engineering (2003). The author's empirical study follows the constructivist model, gives positive learning outcomes coming from the collaboration between elementary school children and their teachers, and reports on comprehensive understanding of science and engineering principles. Although Hacker refers to concepts such as energy transformation, friction, tension, etc., it seems that these come from the children's work on robotics engineering rather on robotics use as mindtools for these specific disciplines.

Barker, Nuget, and Grandgenett (2008) report positive learning outcomes on programming concepts such as loops and multitasking in 11-15 years children, under a science, technology, engineering and mathematics (STEM) context based on robotics, without referring any pedagogical approach. The potential of educational robotics in science literacy under a proper pedagogical approach, as well as the existence of little research in the field, are underlined by Sullivan in 2008. Sullivan claims that robotics is a field that is closely related to science literacy. Robotics learning shares the same thinking skills as science learning that is computation, estimation, manipulation, and observation, and engages students to programming. Concerning programming concepts, the author reports that robotics contribute to input, output processes, variables, procedural flow, conditions, iteration, and parallel processing. As far as it regards the appropriate pedagogy, Sullivan does not refer to constructivism or constructionism, but she implies them, by stating relevant principles such as rich environments, immediate feedback, and open-ended, student directed inquiry. The same team reports positive learning outcomes on programming concepts for 11-12 years old children (Nuget et al., 2009).

We think that a direct reference to mindtools, although there is no reference to the term, is given by Alimisis, Karatrantou and Tachos (2005). They report positive learning outcomes on understanding concepts and phenomena of mechanics, such as rotation speed and frequency, by technical high school students. The approach of Dagdilelis, Satratzemi and Kagani (2005) is similar to that, by reporting positive learning outcomes on basic programming principles. The authors use LEGO robots to teach the output, input, wait for commands, modifiers and the repetition structure to high school students. They conclude that "the understanding and correct use of the basic programming concepts appears to be made easier with the use of robotic systems. As is to be expected, certain concepts and programming processes are obvious in a system which has real entities". It is clear that without mentioning the term, the authors use educational robotics as mindtools in a constructionist framework. Isela and Mota (2007) report similar results with engineering freshmen students, aiming at the improvement of comprehension of structured algorithms using meaningful projects with Robolab. Robotics as mindtools, under the term of cognitive tools are reported by Papanikolaou and Frangou (2009). Robots are implied as mindtools in science learning by Datteri, Zecca, Laudisa, and Castiglioni (2012) who report positive results on primary school children being engaged in collaborative processes, reflecting on their acts, using and developing metacognitive strategies. In this case already made robots are used as mindtools by the children, who modify, program and explain their behaviours, developing critical thinking and higher order learning. Cavas and colleagues report on the increase of scientific creativity and skills of 12-13 years old children, by the use of robots (2012). The authors refer to constructionism and conclude that even in 2012 "the pedagogy of teaching robotics is still in its infancy and the research regarding robotics learning in science and technology is limited". The same is the sense of a recent systematic review on the educational potentials of robotics in schools (Barreto & Benitti, 2012). Among the 70 articles reviewed, few are those concerning science and programming learning (e.g., Barker, et al., 2008; Nuget, et al., 2009; Sullivan, 2009). The review shows the potential of robotics as a learning tool, especially in teaching disciplines not closely related to robotics.

The conclusions from our bibliographical research on educational robotics can be summarized as follows:

- The majority of the studies refer to engineering education aiming at robotics education rather than at educational robotics (robotics as an educational tool).
- The majority of the studies follow a constructivist – constructionist approach giving emphasis to design skills, creativity and collaboration, but not to the contribution to concepts and principles of certain disciplines.
- Only a few studies use robotics as an educational tool in science and programming learning implying mindtools, but without referring to this term.

Educational robotics as mindtools in physics and programming

Following our proposal for educational robotics as mindtools, we present two case studies on physics and programming learning, thus showing the potential of educational robotics as mindtools in the classroom.

Case 1: The physics project

The understanding of basic physics concepts such as displacement, time, and velocity are important to elementary school pupils, since these contribute to other magnitudes and phenomena. Following the constructionist theoretical model and mindtools, we choose educational robotics as a tool to engage pupils in designing meaningful projects through real world constructions. Our aim is to use educational robotics as the medium for the understanding of the phenomenon of simple motion and the concept of velocity through "constructions in the world as a support for those in the head".

The sample of the study was a class of 10 – 12 year old pupils. In this work we present the work done by two groups of pupils. The first group (G1) consisted of three boys 10 years old, and the second (G2) of three girls 12 years old. The pupils had a little experience in computer use. G1 had a little experience in logo programming, and G2 had a little experience in physics. The problem posed to the pupils was to study a simple motion by using the LEGO and Robolab system. All the pupils worked with robots in five one-hour sessions. In the first sesion, the pupils had a theoretical and practical course on educational robotics. During the second meeting, the pupils easily built a robotic vehicle and programmed it to move in a "steady way", by programming the vehicle to move with a "stable power". The pupils managed to build and move their vehicles easily because of their experience with traditional LEGO bricks, electric and electronic toys. The pupils used a "stable power" since they decided that this was the easier and simpler motion. During the other three sessions the pupils integrated their project.

The pupils decided that they had to make the vehicle run in a straight line and move at various distances observing the time the vehicle ran. Collaborating and reflecting, they reached the conclusion that it was better to watch the distance the vehicle drove in a certain period of time. This was a great success because the pupils discovered the relationship between distance and time, the parameters for simple motion. G1 made the robot run for different periods of time and reached the conclusion that the longer the time period, the longer the distance is. G2 reached the same conclusion, but having experience in mathematics and physics, made the robot run each different period of time more than one repetitions. They thought that it was better to calculate the mean distance for each period of time, "to be sure" for their results. Recording and studying the data, the pupils concluded that distance and time are two reciprocal magnitudes, and constructed the concept of velocity. The pupils gave the definition of velocity as "the division of distance by time". Although the pupils of G1 understood the concept of velocity, they did not manage to express its definition in a better way.

The above case study shows that educational robotics is a powerful tool that can be used as a mindtool for science teaching and learning. The following characteristics of mindtools are exploited by the pupils:

- they constructed knowledge through the design of meaningful projects and their powerful ideas using an authentic paradigm developed by themselves
- they learned by doing in both the virtual (by programming) and real world (by constructing the vehicle and studying its motion)
- they faced cognitive conflicts through the comparison between causes and results during programming the vehicle's motion
- they learned by reflection and the representation of their knowledge, discussing their observations
- they learned by conversing through collaboration, discussion, and argumentation.

Case 2: The programming project

Students face many difficulties in programming, especially in control and repeat structures. The main reason is the fact that students are mainly taught programming skills and not problem solving methodology. Although there are proposals for teaching and learning programming, there is no evidence for control and repeat structures.

This work proposes educational robotics and visual programming for solving such difficulties. It aims to investigate the results of seven 15 year old students on eight problems both in pen and paper and Lego / Robolab. The problems were on the IF … THEN … ELSE, WHILE … DO, REPEAT … UNTIL, and FOR … DO structures.

The students had 15 meetings of two hours each. They had a little programming experience and no experience in robotics. After the two first meetings, all the students were familiarized with the LEGO / Robolab system and managed to build their robot, a moving vehicle. All the problems were real world problems. An example of a pen and paper problem is the following: "A student wants to transfer six bags from his/her house to a friend's house, and return to his/her house. The student can hold only two bags at a time, one in each hand". A LEGO / Robolab problem with the same structure is: "Rotate the robotic vehicle with power two clockwise or counterclockwise for two seconds. Then, rotate it with the same power for another two seconds. Repeat the whole procedure three times". Table 1 shows the solution given by a student (S6) in pen and paper. Figure 1 shows the solution of the same student in Robolab.

Table 1. A pen and paper solution to the problem with the 6 bags (S6)

```
PROGRAM bag
bags Å 6
REPEAT
get 2 bags and transfer them to your friend's house, leave them and then come back
UNTIL bags = 0
END
```

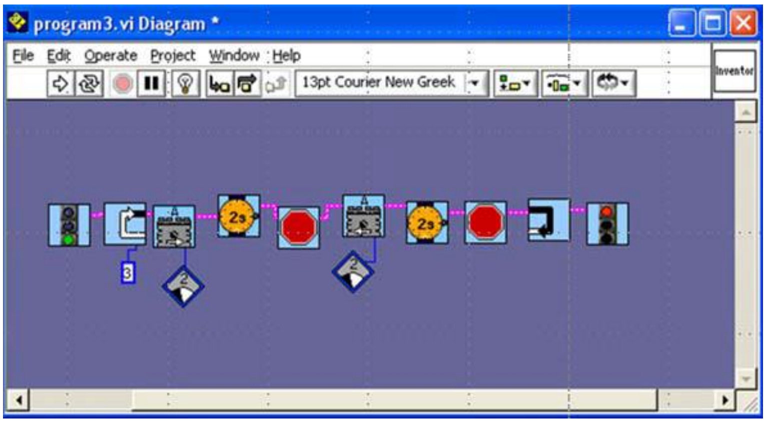

Figure 1. The solution to the problem with the 6 bags (S6) in Robolab

The student (S6) in his answer to the pen and paper problem uses the REPEAT … UNTIL, and not the FOR … DO structure. Both solutions are correct. The solution in Robolab uses the terminus structure. The results of this case study show that all seven students gave the correct solutions to the eight problems using the Robolab, while five of them gave correct solutions to pen and paper problems. It is noteworthy that all the students used the same, correct and intended programming structures in Robolab. This was not the same with the pen and paper activities, even for the five students that gave the correct solution using different programming structures. It seems that both the physical machine and visual programming contribute to the understanding of programming structures. Moreover, programming in Robolab increases and sustains students' motives for programming.

This case study shows that educational robotics is a powerful tool that can be used as a mindtool for programming teaching and learning. The following characteristics of mindtools were exploited by the students:

- they constructed knowledge through the use of their powerful ideas working with meaningful and authentic projects

- they learned by doing in both the virtual (by programming) and real world (by studying the robotic vehicle's motion)
- they faced cognitive conflicts through the comparison between causes and results during programming to solve their problems
- they learned by reflection and the representation of their knowledge, discussing their observations
- they learned by conversing through collaboration, discussion, and argumentation.

Conclusions

This work proposes educational robotics as a mindtool based on the constructivist – constructionist theoretical model. Although there are many studies on the constructionist approach of educational robotics, they have certain limitations. Some of them refer to robotics education and not to educational robotics. Some others follow a constructionist approach, but give emphasis to design skills, creativity and collaboration. Some other studies use robotics as an educational tool in science and programming learning implying mindtools, but they do not give evidence of the characteristics of mindtools (Barker et al., 2008; Nuget et al., 2009).

We believe that the positive learning results from our two case studies on physics and programming indicate that educational robotics can be used as mindtools. An important factor is that pupils and students used their declarative knowledge; they used the physical machine as a medium to develop structural knowledge and overcome their inert declarative knowledge; they used structural knowledge to develop procedural knowledge and thus to solve their problems. Moreover, it seems that the holistic use of educational robotics does work, and children can acquire the necessary technical skills during their project integration.

Memorandum

This article is a memorandum to our inspirer and friend David H. Jonassen.

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