

An Autonomous Educational Mobile Robot Mediator

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Abstract So far, most of the applications of robotic technology to education have mainly focused on supporting the teaching of subjects that are closely related to the Robotics field, such as robot programming, robot construction, or mechatronics. Moreover, most of the applications have used the robot as an end or a passive tool of the learning activity, where the robot has been constructed or programmed. In this paper, we present a novel application of robotic technologies to education, where we use the real world situatedness of a robot to teach non-robotic related subjects, such as math and physics. Furthermore, we also provide the robot with a suitable degree of autonomy to actively guide and mediate in the development of the educational activity. We present our approach as an educational framework based on a collaborative and constructivist learning environment, where the robot is able to act as an interaction mediator capable of managing the interactions occurring among the working students. We illustrate the use of this framework by a 4-step methodology that is used to implement two educational activities. These activities were tested at local schools with encouraging results. Accordingly, the main contributions of this work are: i) A novel use of a mobile robot to illustrate and teach relevant concepts and properties of the real world; ii) A novel use of robots as mediators that autonomously guide an educational activity using

a collaborative and constructivist learning approach; iii) The implementation and testing of these ideas in a real scenario, working with students at local schools.

Keywords Robots in education · Mobile robots · Autonomous robot · Robot-human interaction.

1 Introduction

With the emergence of new digital devices along with faster and more powerful computers, new scopes have opened in computer assisted educational activities. As an example, computer simulations have offered new educational environments, supplying a great variety of opportunities for modeling concepts and processes. At different educational levels, computer simulations have been successfully applied to support teaching a great variety of subjects, such as mechanics, biology, chemistry, and physics, among others, where they have proved to be efficient teaching tools [39, 42, 14, 38, 25].

In the area of Artificial Intelligence, intelligent tutoring systems or ITSs have received great attention, as another relevant way of using computer based technology as an effective educational tool. Originally introduced in [6] and [12], an ITS tracks the work of the student with the goal of identifying his main strengths and weaknesses. This knowledge is then used to suggest suitable additional work. Using this scheme, an ITS is able to adapt its behavior according to the student needs. See [29] for a in-depth review of ITSs.

With the advancement of robotic technology, the scope of simulations and ITSs has extended to the physical world, allowing new educational activities to take place in a real environment. Supported by sensors and actuators, robots are capable of exploring and interacting with the real world. Based on these capabilities, a

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series of educational activities have been developed to aid and foster learning of relevant topics. As an example, teachers have been able to increase the motivation and performance of their students by means of diverse robot building activities, such as robotic competitions and algorithm testing, to name just a few [28,31].

Among current educational activities that include robotic technologies, it is possible to distinguish two relevant common factors. First, most of the approaches aim to teach subjects closely related to the Robotics field [34,18,15]. Examples of these subjects are robot programming, robot construction, artificial intelligence, algorithm development, and mechatronics [45,46,3,15,1]. One of the notable exceptions to the previous cases, it is the early work of Papert [33], who began with the idea of using robots, and mainly simulations, to teach subjects such as planar geometry. Secondly, most of the approaches use the robot in the educational activity just as a passive tool. As an example, in the case of robot construction, the robot is the result of the assembling process of the students, while in the case of robot programming, the robot is just a physical machine that executes a set of instructions and algorithms provided by the students. In both cases, the robot has a passive role in the learning process of the students.

While the previous approaches have proved to be effective, research in this area has mostly left aside the possibility of using robotic technologies to teach non-robotics related subjects and to use an autonomous robot as an active mediator of the educational activity. These two key ideas are at the core of the Autonomous Educational Mobile Robot Mediator presented in this paper.

In terms of teaching non-robotic related subjects, the embodied nature of a robot provides a way to depart from the traditional abstract teaching scheme based on a blackboard to a teaching model in which the student can learn by directly observing the actions of a mobile robot. This opens a new teaching paradigm that, with the help of an embodied robot, can provide a more natural setting to teach subjects such as math and physics. For example, a mobile robot can use its rotational capabilities to illustrate angular relations, or it can use its acceleration and velocity capabilities to illustrate relevant kinematic principles.

In terms of the role of the robot in the educational activity, an autonomous robot provides a way to actively guide the development of the activity. In particular, the robot can act as an interaction mediator. Interaction mediators, mainly used in collaborative and constructivist learning environments [16], focus not only on the content, but also on the management of the virtual and physical interactions established among groups of

students. As an interaction mediator, an autonomous robot can define roles and supervise the appropriate and fluent development of the educational activity. Moreover, regarding motivation, an environment based on an active robot mediator may help students to develop affective bonds with the robot [35], helping to develop a stronger situational interest in the educational activity [13,11], a form of externally controlled motivation.

Based on the previous two ideas, this paper presents a novel application of robotic technology to primary and secondary school-level education. The application consists of an autonomous mobile robot that helps students in the creation of abstract models of relevant concepts and properties of the real world by physically illustrating them. Furthermore, by acting as a situated mediator of the educational activity, and using a collaborative and constructivist learning approach, the robot is able to guide the activity, playing a key role to increase the motivation and social bonds among the students. As far as we know, this is the first time that robotic technologies are been used in such educational setting, opening a new paradigm to apply robots in education.

Accordingly, the main contributions of this work are: i) A novel use of a mobile robot to illustrate and teach relevant concepts and properties of the real world; ii) A novel use of robots as mediators that autonomously guide an educational activity using a collaborative and constructivist learning approach; iii) The implementation and testing of these ideas in a real scenario working with students at local schools.

This paper is organized as follows. Section 2 presents a review of previous works related to the use of robotic technologies in education and the use of autonomous robots as activity mediators. We also review some previous projects regarding the use of collaborative environments in education. Section 3 describes the details of our approach, including two concrete examples that illustrate the use of our educational framework. Section 4 analyzes the results of testing our approach in local schools. Finally, Section 5 presents the main conclusions of this work.

2 Bibliographic review

There is an extensive list of educational initiatives that use robotic technologies as pedagogical tools. As we noted before, most of these initiatives are oriented to teach subjects directly related to the Robotics field. In [37] and [41], the authors describe educational activities mainly focused on robot construction using toolkits, such as commercial Lego bricks. Similarly, the work in [31] uses a robot kit that allows students to assemble

their own robots. As the main purpose of these activities is to motivate students with technology, particularly the Robotics field, the robots are usually provided with appealing locomotion capabilities able to execute engaging behaviors but under constrained situations.

Robot competition is another area where there have been lots of activities at all educational levels [28]. In particular, large scale robot competitions, such as First¹ or RobotCup², have become highly popular, being the focus of attention of an extensive list of educational activities, such as complete courses or summer camp programs.

In the case of robot programming, the work in [19] describes a course oriented to program robots to achieve high-level tasks in a structured world, leaving aside hardware and low-level issues. In the same way, in [40], we present our own experience teaching a mobile robotic class that includes the implementation of low-level robot behaviors performed in a real world environment, as well as the implementation of high-level behaviors performed in a structured world.

As we pointed out, in all the previous cases the robot plays a passive role, being the end or a tool of the educational activity. Furthermore, to keep the complexity and cost of the robots to a manageable level for a medium size class, the robots are constrained to execute specific tasks in structured environments. In our approach, we also constrain the robot to execute a specific educational activity in a structured environment, however, this work is distinguished from the previous mentioned works by focusing on teaching non-robotic related subjects and using the robot as an active mediator.

Regarding robots as activity mediators, some of the most relevant robotic initiatives have focused on museum robots that guide their human counterparts through the museum, explaining to them the relevant aspects of the different expositions and halls. This is the case of robots such as Rhino [5], Minerva [43], Sage [30], and Joe Historybot [32]. As an example, Rhino was the first museum tour-guide robot, installed in mid-1997 at a museum in Germany. Rhino was responsible for greeting visitors and guiding them through a fixed set of museum attractions. As another example, Sage, later renamed as Chips, was a robot that operated in the Dinosaur Hall at Carnegie Museum of Natural History, USA, providing tours and presenting audiovisual information regarding bone collections. All the previous robots proved to be helpful to guide and teach museum visitors [9].

Social robots, such as Pearl [36] and Valerie [10], are also examples of a new generation of robots able to interact with people and to play the role of mediators to specific knowledge sources. Pearl is intended to assist elderly individuals with mild cognitive and physical impairments, as well as support nurses in their daily activities. Valerie currently operates as a robot receptionist for Newell-Simon Hall at Carnegie Mellon University, helping people by providing information about university members, campus directions, or retrieving data from the web. Although these robots perform specific tasks, they are designed to operate in highly general environments.

In order to operate in highly unconstrained environments, museum tour guides and social robots are provided with powerful and expensive sensors, actuators, and processing units. In contrast, as we describe in the next section, our educational robot mediator is designed to be a low cost robotic platform, equipped with limited hardware resources that provide enough robustness to successfully deal with the complexity of a structured and specific educational activity.

In terms of collaborative educational environments, computer-based technologies have been successfully used to foster learning, motivation, and social bonds among students [17,8,16]. In this type of educational environments, students build knowledge by actively interacting and assuming asymmetric roles. In particular, [47] demonstrated that in these collaborative settings a technological system able to interact independently with each student can effectively control their interactions, supervise the educational activity, regulate tasks, rules, and roles among the students, and mediate in the students acquisition of new knowledge. This is exactly the type of mediation that we envision for our robot in the educational activities presented in this work. Therefore, our robot is able to interact not only with the students as a group, but also with each student independently. As we describe in Section 3, this dual flexibility in the interaction with the students is a key feature of our approach.

3 Our approach: The Autonomous Educational Mobile Robot Mediator (AEMRM)

As we pointed out before, the main novelties of our approach are twofold. On one hand, we exploit the mobility of our robot to illustrate relevant concepts of school subjects, such as physics and geometry, with the goal of helping students in the process of creating abstract models of reality. On the other hand, we exploit the autonomy and situatedness of our robot to mediate in the development of the educational activities, with the

¹ <http://www.usfirst.org/>

² <http://www.robotcup.org/>

goal of improving the motivation and social interactions among the students. This is performed using a collaborative and constructivist learning environment. Next, we describe the generic aspects of the educational framework that we develop to apply our ideas. Then, we present a methodology to implement educational activities using this framework. Afterwards, we illustrate the use of this methodology by describing the implementation of two practical cases.

3.1 General educational framework

Figure 1 shows the general setting of our educational framework. As shown, we extend the local capabilities of our mobile robot by providing it with remote wireless interfaces. These remote interfaces correspond to handheld devices distributed to each of the students. Using these devices, the robot can either, individually interact with each student by sending an exclusive message to the corresponding handheld device, or it can communicate with the group as a whole, by sending a shared message to all the students.

The general educational framework presented in Figure 1 provides the robot with 3 relevant features to support our goals. First, the use of handheld devices, as the main communication channel between the robot and each student, makes possible an effective mediation of the robot in the educational activity. In effect, by using a suitable graphical interface on the touch screen display of each handheld device, the robot is able to control the progress of the educational activity. Although, there exist more flexible communication modalities for human-robot interaction, such as verbal communication through a speech recognizer and synthesizer, or gestural communication through a vision based gesture recognizer; these technologies are still not robust enough to be deployed in the intended application, particularly if the goal is to use a low cost robotics platform. In this sense, the use of remote handheld devices provides the robot with a highly structured communication channel that facilitates its work as mediator of the educational activity. Furthermore, given their reduced size and wireless communication, the handheld devices do not interfere with the students mobility and face-to-face communication.

Second, besides the individual and shared communication through the handheld devices, the robot can also communicate visually with the students as a group by simply performing actions in the real world. In effect, since the robot and the students reside in the same physical space, any physical action that the robot performs is by default an interaction with the group of students. This visual communication is the key element

used by the robot to physically illustrate relevant concepts of school subjects.

Third, by distributing different tasks among the students, the robot can grant unique roles to each of them. In this way, the robot can assign a specific software tool to each student or it can allow each student to contribute with only part of the solution to a proposed problem. By using such strategies, the robot can require every student to collaborate and agree with the collectively assembled solution before continuing with the activity, thus compelling the group of students to reach a consensus. This form of consensus is the key element that helps our framework to support a collaborative and constructivist learning environment.

In the next section, we present a methodology that can be used to implement educational activities under the proposed educational framework.

3.2 Methodology for robot mediation

To further specify the role of the robot as a mediator of the educational activities, we propose the following 4-step methodology, as shown in Figure 2.

1) *Initialization*: in the first step, the robot assigns roles and supply relevant data to each of the students (Figure 2a). This is achieved by sending suitable messages to the handheld device of each student. The roles and data being distributed depend on the concepts being taught under the current educational activity.

2) *New Problem*: the next step is the formulation of the new problem. To achieve this, the robot perceives its surrounding and performs a set of actions that physically complete the information required to fully specifies the new problem (Figure 2b).

3) *Deliberation*: after the new problem is presented, the robot compels the students to deliberate, argue, and to collaboratively construct a common answer, thus, forcing explanations, discussions, and negotiations among them (Figure 2c). In the eventual case that the group does not achieve consensus, the robot repeats the set of actions of the previous step, providing additional information that can be helpful in the deliberation process of the students.

4) *Solution*: finally, when the group has achieved a consensus, the robot evaluates the proposed answer. If the answer is correct, the robot displays it in each remote interface; otherwise, the robot physically executes the correct answer, displaying on each handheld device suitable feedback to guide the learning process of the students (Figure 2d).

To exemplify the usage of the proposed educational framework and the methodology for robot mediation

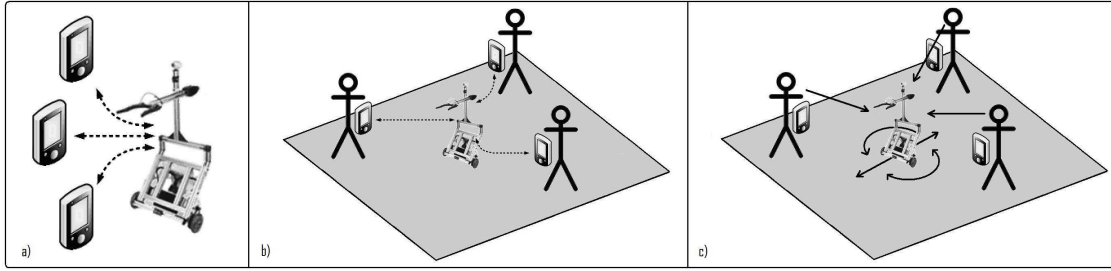


Fig. 1 General setting of the proposed educational framework. a) The robot is augmented with remote interfaces. b) The robot can communicate independently with each student by handheld devices. c) The robot can communicate visually with the group of students.

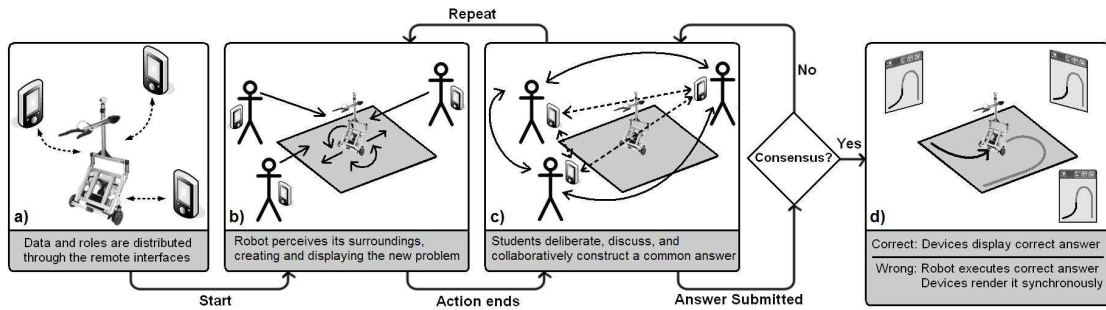


Fig. 2 Methodology to implement educational activities using the AEMRM. a) *Initialization*: robot distributes roles and relevant data through the handheld devices. b) *New Problem*: robot perceives its surrounding and performs a set of actions that fully specify the new proposed problem. c) *Deliberation*: robot compels the students to deliberate and to construct an answer in a collaborative manner, requiring every group member to agree with it. d) *Solution*: after consensus has been achieved, the robot evaluates the proposed solution providing suitable feedback to the students.

presented above, the following sections describe the implementation of two real cases used to teach concepts related to geometry and physics.

3.3 See-You-There learning activity

See-You-There is an activity aimed to teach and reinforce, in a problem solving approach, geometric concepts, such as lengths, relative positions, angles, and vectors [27]. In this activity, the group of students must help the robot to solve a path planning task to arrive to a predefined goal location. The activity is oriented to second-grade school children who work in groups of three students to complete the activity.

Figure 3a shows a schematic view of the playground area of the activity. This area is delimited by three artificial visual landmarks that are freely allocated by each of the students. The goal of the students is to select and order a sequence of motions proposed by the robot, such that the robot successfully moves from an initial to a goal location. If the students answer correctly, the robot successfully navigate to the predefined goal, as shown in Figure 3b; otherwise, the robot end up in a different, erroneous location, as shown in Figure 3c.

In pedagogical terms, the goal of the See-You-There learning activity is to teach basic geometrical concepts in a more natural way, facilitating the process of creating mental abstractions of the real world. In particular, the activity aims to help in the development of the “measurement sense” or “mental ruler”, defined as the ability to estimate lengths and draw lines of a given size [7]. This is a highly important concept that usually current teaching techniques are not addressing in a proper way. As an example, it was determined that in USA more than 50% of students of seventh grade cannot measure the length of a segment when this is not aligned with the beginning of the ruler [7].

3.3.1 Robot architecture

In terms of robot architecture, one of our main goals is to achieve robust autonomous navigation using a simple and low cost robotic platform. We achieve this goal by constraining the environment of the educational activity to be a small playground, assumed free of obstacles, and surrounded by a set of bright color artificial landmarks. For our application this turns to be a highly reasonable scenario, mainly, because we em-

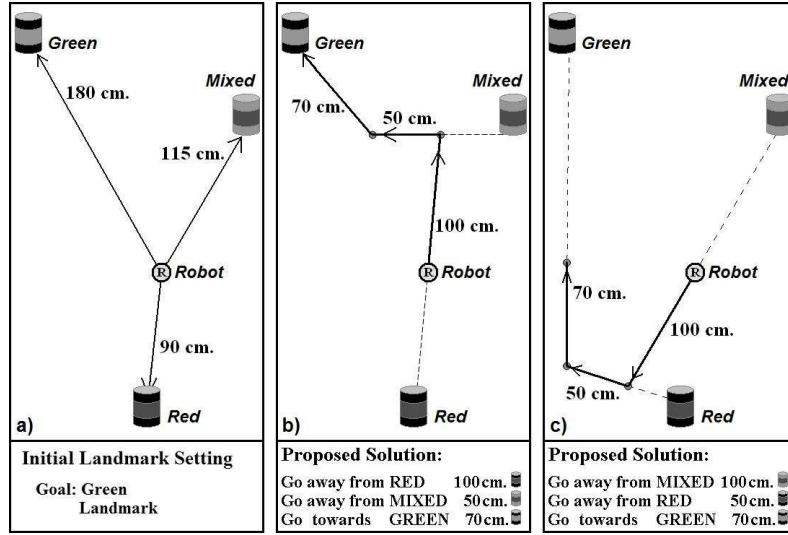


Fig. 3 a) Initially the robot detects the landmarks and generates a problem according to the current configuration. In this case the goal is to arrive to the green landmark. b) Path followed by the robot when the correct answer is selected by the students. c) Path followed by the robot when an erroneous answer is selected.

bed the landmark positioning phase as a playful part of the activity. By using these simplifications, we achieve autonomous navigation by using low cost sensors and simple perception algorithms.

Figure 4 shows a picture of the robot used in the See-You-There learning activity and a diagram of its hardware architecture. As the basic mobile platform, we base the robot on the Palm Pilot Robot Kit³. We chose this platform due to its holonomic motion capability. This feature facilitates the robot motion planning scheme and also produces an attractive impression on the students. Mounted on the robot, the processing device consists of a 206 MHz PocketPC equipped with wireless communication. This processing unit provides real time processing of sensors and actuators, being also the main brain of the robot functionalities as a mediator of the educational activity.

In terms of sensing, the robot is able to measure distance using an off-the-shelf Polaroid sonar. Vision algorithms are accomplished using a CMUcam, with a resolution of 80 x 143 pixels. As this camera transmits data using serial communication at 115.200 bauds, real time color video is not possible. Nevertheless, this camera has on-board color processing capabilities that allow us to define color ranges to sequentially retrieve binary images only of the relevant colors of the visual landmarks, at a rate of 17 frames per second with a final resolution of 80 x 44 pixels. In this way, we developed a set of single-color vision algorithms that, when combined, can efficiently detect and differentiate the set of landmarks. For further details regarding the vision al-

gorithms and control architecture designed to support the See-You-There learning activity see [27].

3.3.2 Robot mediation

1) *Initialization*: in its role as a mediator of the See-You-There learning activity, the first task of the robot is to assign roles and relevant data. In this case, the robot assigns to each student the task of freely allocating one of the visual landmarks in the playground area. This is performed by sending a message to the corresponding handheld device of each student.

2) *New Problem*: after the students have positioned the landmarks, the robot spins in place using its visual and range perception to detect the position of each landmark. Using this information, the robot generates a new problem, consisting of a sequence of three straight motions that, if executed in the right order, will move the robot right next to one of the landmarks, as in the case of Figure 3b. Figure 5a shows the screenshot used to present the new problem to the students. The problem is presented as a target goal location and four suggested motions, three correct ones plus a distracter. Each suggested motion has three parameters: the distance to travel, a referential landmark, and the direction of the motion (towards or away from the referential landmark). In this way, the task of the students is to select the appropriate motions, order them correctly, and assign to each motion a corresponding reference landmark. It is important to note that by using an holonomic motion base, the robot can go everywhere in the playground using just straight motions.

³ <http://www.cs.cmu.edu/pprk>

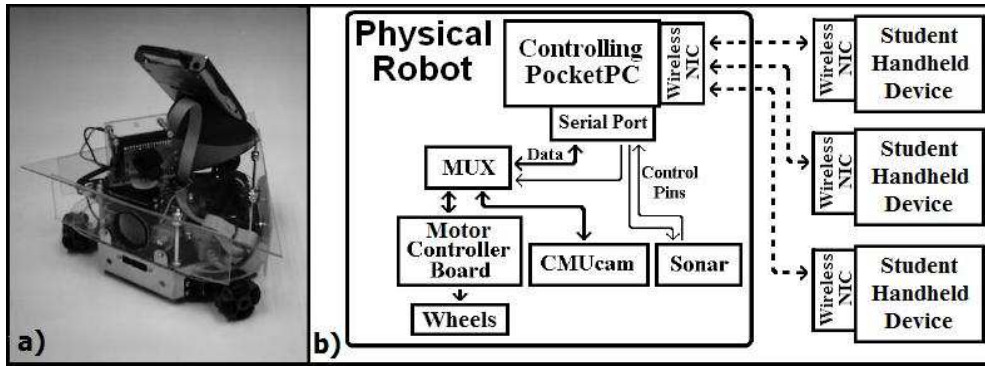


Fig. 4 a) Picture of the physical robot used in the See-You-There activity, displaying the camera, sonar, and on-board PocketPC. b) Hardware architecture of the robot.

3) *Deliberation*: to foster collaboration and constructivism among the students, each student is allowed to choose only one of the four possible motions suggested by the robot. Hence, each student alone cannot construct a solution, yet the group as a whole can, by means of each student constructing a part of the solution. Figure 5b shows a screenshot of a case where a student has already selected one of the suggested motions and he/she has allocated this motion as the second one in the sequence.

4) *Solution*: finally, once every student has selected a motion, the robot asks the group to confirm the constructed answer, as shown in Figure 5c. If there is agreement, the robot physically executes the selected answer; otherwise, the students have to discuss the proposed solution and eventually select new motions. The discussion process repeats until the group reaches a consensus.

3.4 Graph-Plotter learning activity

Graph-Plotter is an activity aimed to help students in the development of skills for the construction and interpretation of 2D graphs while also reinforcing diverse kinematics concepts. In this activity the problem posed to a group of students is to graph, in a blank set of coordinate axes, different linear motions performed by a mobile robot. The activity is oriented to secondary-school teenagers who must work in groups of three to complete the goals of the activity.

A schematic view of the playground area of the activity is shown in Figure 6. The robot moves following a straight path, varying its speed and acceleration. Students are requested to plot either position versus time or velocity versus time graphs. In their handheld devices, the students are supplied with different software tools that enable them to measure time, perform math calculations, take notes, and plot the graph in

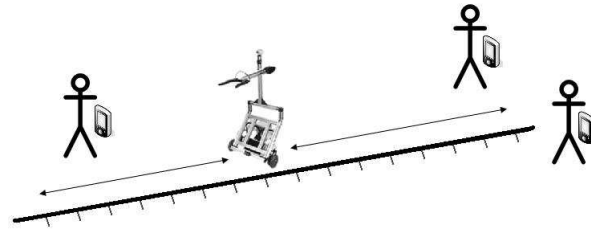


Fig. 6 Graph-Plotter activity scenario. The robot moves through a straight path while a group of students observes and measures relevant data to build a 2D kinematics graph according to the requirements of the posed problem.

the virtual set of coordinate axes. Additionally, a physical measuring tape is provided to measure relevant distances. Depending on group demand, the robot may repeat the performed motion so that the students are able to gather all the required data to construct their plots.

As in the case of the See-You-There learning activity, the pedagogical goal of the Graph-Plotter activity is to teach school subjects in a more natural way, in this case, graph representations and kinematics. Regarding graph representations, research shows that despite the amount of experience working with graphs, students of all ages have difficulties comprehending them [24,20]. Regarding kinematics, studies have shown that students often emerge from traditional physics courses with serious misconceptions about kinematics [2,22,23,44]. Even students who show good understanding of kinematic concepts often experience a series of difficulties when making connections between graphs and both, physical concepts and the real world [24,21]. These difficulties and connections are the main problems that the Graph-Plotter learning activity seeks to overcome.

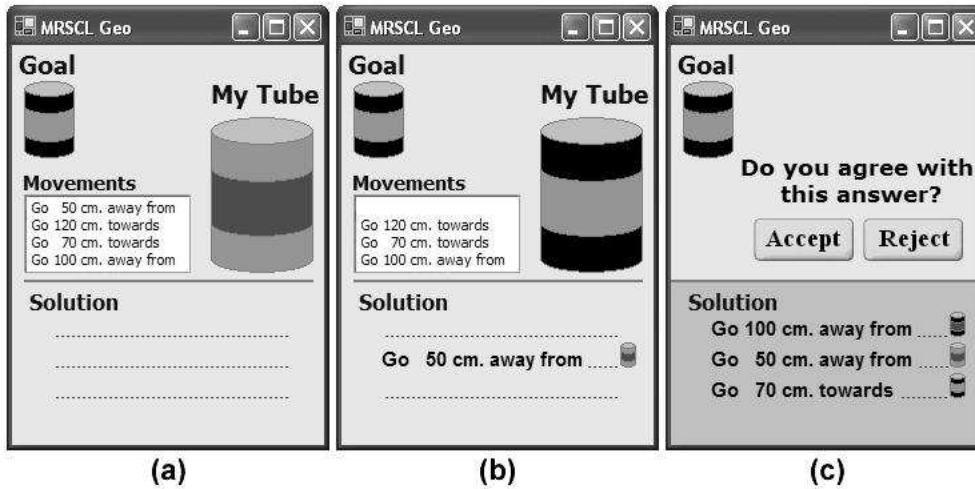


Fig. 5 a) A new problem along with the assigned landmark are shown in the handheld device of each student. b) A student has selected one of the available motions and this motion disappears from the available list, c) After all the students have selected a motion, the robot asks the group to confirm the constructed answer.

3.4.1 Robot architecture

The key requirements for the Graph-Plotter learning activity are motion accuracy and clock-synchronization between the robot and the remote handheld devices. Regarding motion accuracy, as the students are required to precisely graph the motions of the robot, these must be executed with minimum acceleration, speed, distance, or time errors. Hence, fast and rigorous wheel motor control is needed to successfully develop the activity. Regarding clock-synchronization, inaccurate time synchronization between the handheld devices and the robot would translate into erroneous or delayed student measurements. Hence, an accurate clock-synchronization algorithm is needed to overcome the variable latency-time and communication delays inherent to wireless network connections. We explain next how we face these problems.

Figure 7 shows a picture of the robot used in the Graph-Plotter learning activity and a diagram of its hardware architecture. As the basic mobile platform, we use an ER1 robot⁴. We chose this platform, mainly, because of its affordable price and accurate motions. The ER1s are differential drive robots, equipped with two driven wheels powered by stepper motors controlled by microsteps. High precision in the generation of the microsteps provides an accurate control of the kinematics of the wheels, especially regarding their angular position, velocity, and acceleration. The microsteps are generated by a dedicated hardware controller, achieving displacement errors of less than one centimeter per

meter traveled. This accuracy level satisfies our practical purpose.

Mounted on the robot, the overall system-controlling device is a 1.4 GHz laptop computer supplied with wireless communication and a High-Resolution Hardware Counter (HRHC). This HRHC has a resolution of one microsecond. Using this counter and similar HRHCs provided in each of the handheld devices, we implement a time synchronization scheme between the controlling laptop and each handheld device. Under this scheme, we use the laptop clock as the activity master-clock. At the moment of transmitting this master-clock to each of the handheld devices, we also consider the latency time of the wireless link. We measure this latency by independently estimating the mean message-sending delay between the laptop and each handheld device. In this way, we are able to achieve a synchronization error of less than 100 milliseconds, which is suitable for our application.

3.4.2 Robot mediation

1) *Initialization*: at the beginning of the activity, and in order to regulate the solving process, the robot distributes two roles among the students. While one student is assigned to be the grapher (Figure 8a), the rest of the students are assigned to be data collectors (Figure 8b-d). The grapher is responsible of plotting the answer, while the data collectors are responsible of supplying him with the needed data. Each data collector can switch among the different tools, which are a blank pad (Figure 8b), a calculator (Figure 8c), and an interactive chronometer (Figure 8d).

⁴ <http://www.evolution.com/>

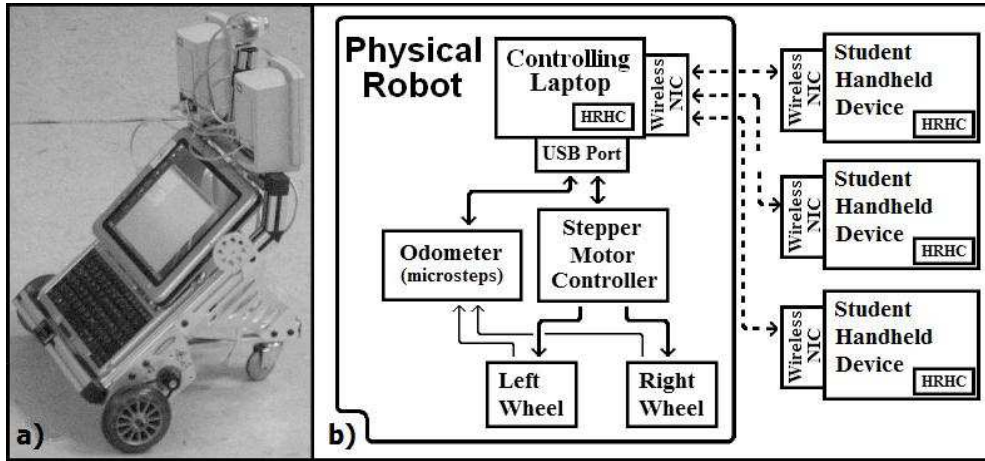


Fig. 7 a) Picture of the physical robot used in the Graph-Plotter learning activity. b) Hardware architecture of the robot.

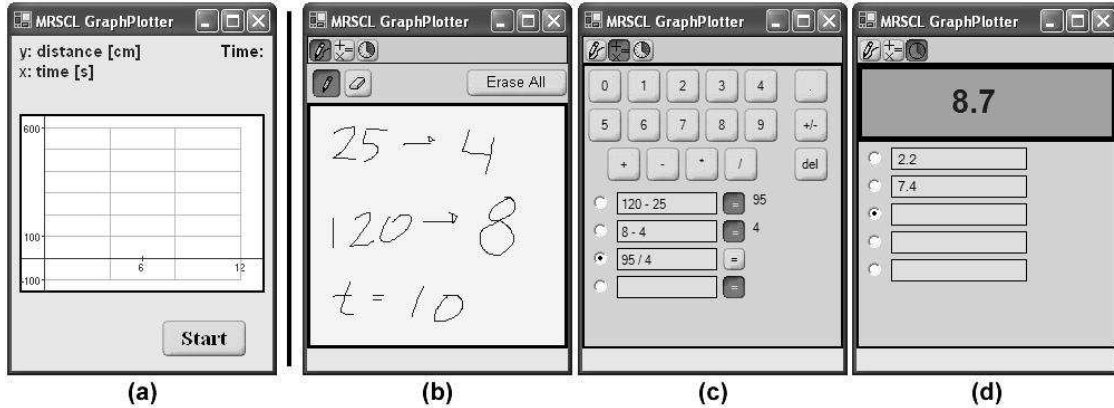


Fig. 8 Screenshots of Graph-Plotter roles: a) Grapher has coordinate axes in which to graph the motion of the robot. Data collectors, on the other hand, can switch among different software tools: b) A blank pad, c) A calculator, and d) A chronometer.

2) *New Problem*: the new problem consists of presenting a new robot motion to the students. Accordingly, after the roles have been assigned, the robot begins its motion while synchronously starting the chronometers of the grapher and the data collectors. While the robot moves, the grapher is entitled to plot the robot motion in his coordinate axes, where the passing of time is shown visually as a widening shade (Figures 9a-b). After the robot motion ends, the grapher is entitled to edit his graph (Figure 9c), to submit it, or to ask for a motion repetition. In this last case, the robot returns to its starting position, the chronometers reset, and the motion is repeated (Figure 9d).

3) *Deliberation*: after the grapher submits his proposal answer, each data collector must consent with it (Figure 10a). In case that a data collector rejects the proposed graph, the robot prompts for agreement, displaying a “Come to an agreement” message in each handheld device (Figure 10b). Afterwards, the system returns to the previous editing stage (Figure 9c).

4) *Solution*: when a graph proposal has finally been accepted by the whole group, the robot evaluates the graph determining whether it is correct or wrong. This is done by analyzing its similarity with respect to the exact graph of the true motion. If the robot determines that the proposed graph is correct, each remote interface shows the group answer superimposed to the exact solution (Figure 10c) giving the students the opportunity to analyze their accuracy and precision. In case that the robot determines that the answer is wrong, it repeats its motion once again, but this time the correct graph is plotted synchronously in every device, superimposed over the plot constructed by the group (Figure 10d). In this way, the students can not only visualize their mistakes, but they can also observe, in real-time, how the motion is represented on the graph. This facilitates the understanding of the relationship between reality and the graphical abstract representation.

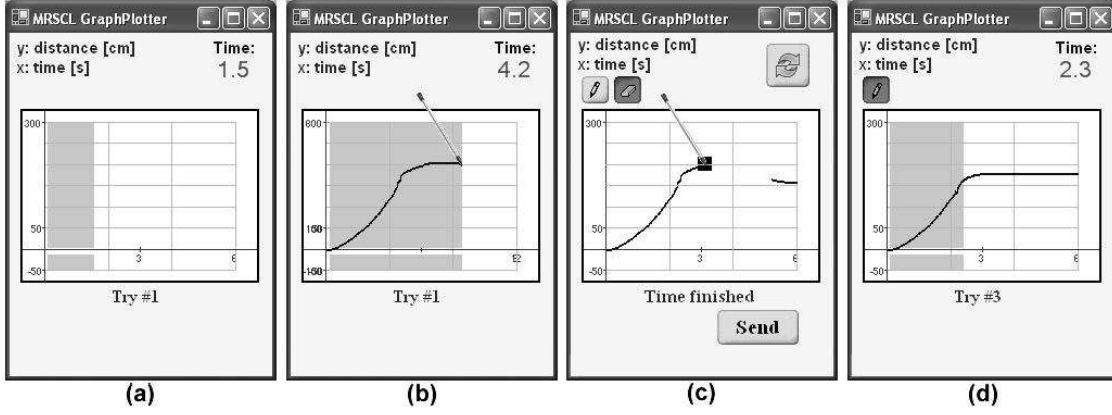


Fig. 9 Screenshots of Graph-Plotter answer construction: a) Blank coordinate axes. Elapsed time is represented by a widening shade, b) Grapher can plot during the motion of the robot, c) After the robot ends its motion, the Grapher can edit the plot, d) Grapher can ask for repetition of robot motion, starting a new elapsed time.

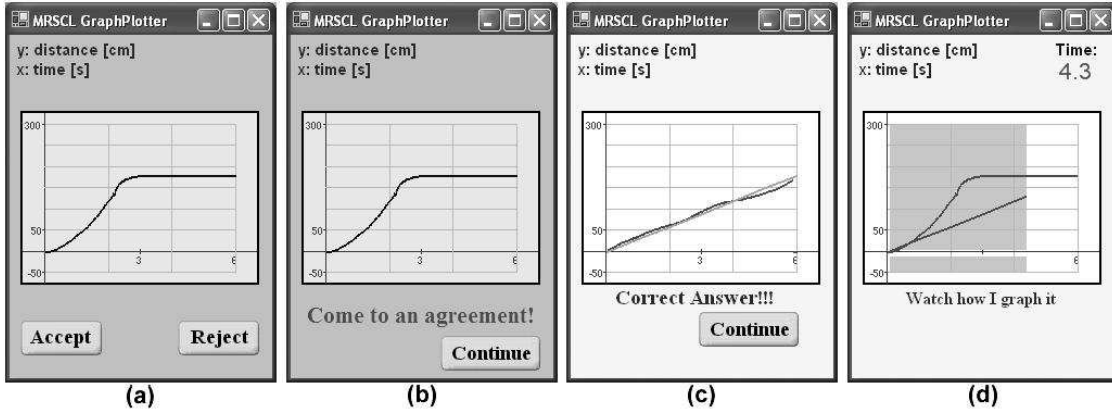


Fig. 10 Screenshots of Graph-Plotter answer evaluation: a) Proposed graph needs to be accepted/rejected by the other group members, b) If any member rejects the proposal, the system prompts for an agreement confirmation. c) Proposed answer is correct and is shown over the exact answer. d) Proposed answer is wrong and the system plots in real-time the true motion of the robot.

4 Results

In this section, we present the main results of testing the See-You-There and Graph-Plotter learning activities at local schools. We start the section by providing details about the testing scenarios and experimental conditions. Afterwards, we describe our major findings, focusing on 4 main aspects of our proposed educational framework: a) Robot Autonomy, b) Learning of target concepts, c) Collaboration and motivation among the students, and d) Social interactions among the students.

4.1 Testing scenario and experimental conditions

Figure 11 shows two of the testing scenarios. They correspond to regular classrooms at local schools. To analyze the educational impact of the proposed framework,

the participating students were divided into two groups, an experimental one which used the AEMRM, and a control group that did not.

In the case of See-You-There learning activity, the control group worked with a paper based version of the activity performed by the experimental group, as shown in Figure 12a-b. Figure 12-a shows an example of the answer sheet used by the students. Each answer sheet indicates a landmark (small circle) assigned to the student. As in the experimental case, the students also worked in groups of three to solve each problem (Figure 12-b). The solution to each problem consisted in selecting and sorting a set of three robot motions, where each student must indicate a motion relative to its assigned landmark.

In Graph-Plotter learning activity, the control group worked with a computer based simulation of the activity performed by the experimental group. This simulation consisted of a virtual robot presented on a com-

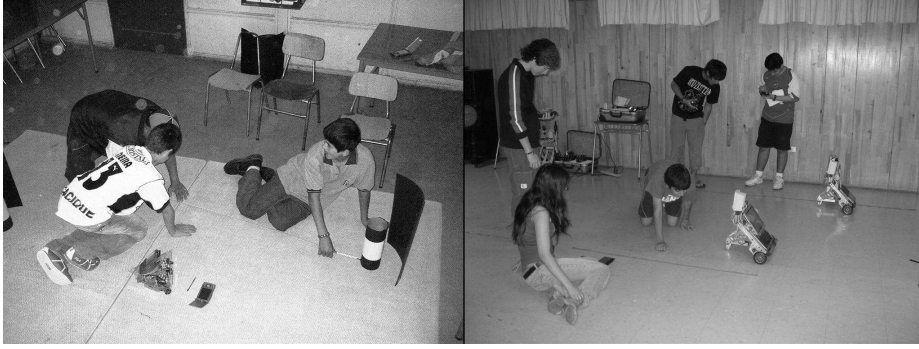


Fig. 11 Students using AEMRMs: a) See-You-There activity, b) Graph-Plotter activity.

puter screen, as shown in Figure 12-c. Besides the virtual representation of the robot, the activity remained the same. Each student had a handheld device wirelessly connected to the computer running the simulation (Figure 12-d). All the main features of the original Graph Plotter activity (motion repetition, face-to-face collaboration, consensus, etc.) were also present in the simulation. Furthermore, as in the experimental case, the simulation also provided a virtual scaled measuring-tape underneath the animation. The set of daily exercises was common for both groups. In this sense, the main difference between the activity performed by the experimental and the control groups was the presence of an embedded robot able to illustrate the relevant concepts in the real world instead of a computer screen.

The See-You-There learning activity was tested with twelve 7th-grade students at a local public school, assigning another six students to be part of the control group. The students worked with the activity during 6 sessions of 30 minutes each. The Graph-Plotter learning activity was tested at two local schools, one public and one private, being used by a total of 26 10th-grade students. In this case, the students in the public school worked with the activity during 6 sessions of 30 minutes each, while the students in the private school worked during 4 sections of 60 minutes each. Table 1 shows further details about the testing conditions of both activities.

It is important to note that in the case of the See-You-There learning activity, there was just 1 robot available, therefore the different groups worked sequentially. In the case of Graph-Plotter, there were 5 robots available, then all the experimental groups worked in parallel in the same room.

4.2 Robot autonomy

In this section, we analyze the performance of the AEMRMs in terms of their autonomy to conduct the educa-

tional activities. We organize the analysis in terms of the three traditional modules of a robotic system: action, perception, and reasoning.

In terms of action, the robotic platforms used in both educational activities were highly robust. In the case of See-You-There activity, as expected, the holonomic motion of the robot made a very attractive impression on the students. Furthermore, the straight motions of the robot presented an accuracy suitable to conduct the activity. The main limitation of the robot was given by the lifespan of its batteries. In particular, when the batteries of the robot were slightly discharged, the power consumption of the motors caused a voltage drop when the AEMRM was in motion. This in turn affected the quality of the video images acquired by the robot, introducing important errors in its perception modules, particularly, the landmark detection algorithms. In practice, we solved this problem by changing the set of batteries at the middle of each session. In the case of the Graph-Plotter activity, both the accuracy of the robot motion and the time synchronization scheme were highly robust during all the experimental sessions. Also, the battery charge of the robot lasted for a complete educational session without causing problems, therefore each robot was able to guide the complete activity without interruptions.

In terms of perception, the AEMRM used in the See-You-There activity presented serious problems at the beginning of the testing period. These problems occurred as the testing location provided by the school had walls and floor painted in colors similar to those of the landmarks. As a consequence the landmark detection algorithm worked poorly. In practice, the problems were solved by placing a white carpet over the playground floor and situating a black cardboard behind the landmarks (Figure 11a). An alternative solution is to provide the robot with a more diverse set of landmarks. In the case of Graph-Plotter, the perception

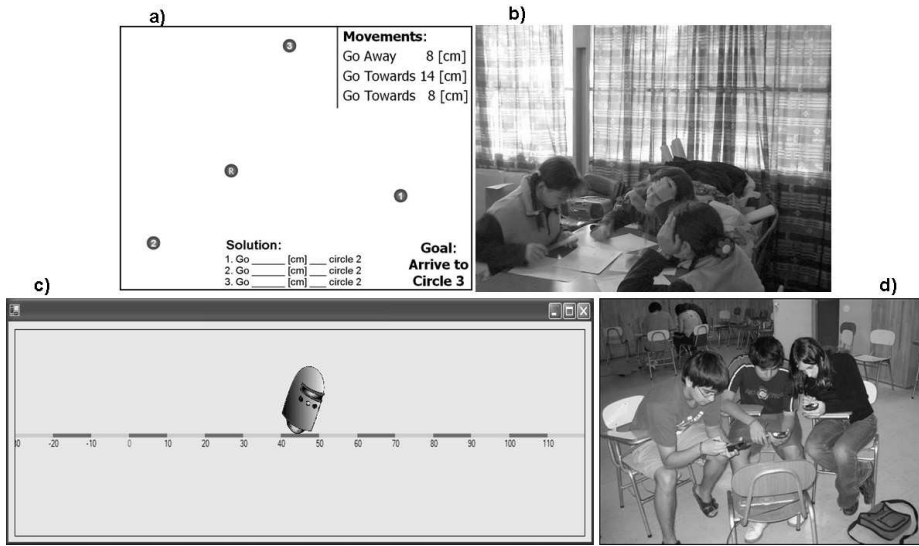


Fig. 12 Activities performed by the control groups. See-You-There: a) Answer sheet used by the students, b) Students working in the activity. Graph-Plotter: c) Simulation used by the students, d) Students working in the activity.

Table 1 Descriptive information about the experimental conditions of the AEMRM activities.

| Activity | Type of school | Grade | Participating students | Experimental group size | Control group size | Num. Sessions | Session length [min] | Overall length [min] |
|---------------|----------------|-------|------------------------|-------------------------|--------------------|---------------|----------------------|----------------------|
| See-You-There | Public | 7th | 18 | 12 | 6 | 6 | 30 | 180 |
| Graph-Plotter | Public | 10th | 29 | 14 | 15 | 6 | 30 | 180 |
| Graph-Plotter | Private | 10th | 23 | 12 | 11 | 4 | 60 | 240 |

modules, mainly based on the micro-steps counters and HRHCs did not present any practical problem.

In terms of reasoning, in both learning activities the AEMRMs were able to execute their planning strategies without inconveniences. Two supervisors were present during each experimental session, however, the AEMRMs did not need major assistance being able to autonomously guide the complete sessions. In this way, the main role of the supervisors was to clarify conceptual doubts of the students, such as the difference between position and velocity graphs or relations between variables, among others. On average, during each session just one of the AEMRMs required assistance, and only once throughout the session. This assistance was mainly required because of problems with the wireless network, such as the disconnection of a handheld device. Given that the AEMRM software was provided with recovery mechanisms, after the assistance, the AEMRMs were capable of retaking the activity at the point the failure occurred, neither losing any data nor needing to restart the educational activity.

4.3 Learning of target concepts

Regarding academic issues, by means of a pretest-posttest scheme, we were able to determine how the proposed activities foster learning. The tests used for each activity aimed to determine the knowledge and understanding of the students regarding the subject matter taught by the activity. As we detailed before, See-You-There focused on teaching distances and angles, while Graph-Plotter focused on teaching kinematics and graph construction and interpretation.

In the case of See-You-There, the instrument used to measure the proficiency of the students was designed by our group according to the target concepts of the activity. An example question of this test can be seen in Figure 13-a. As can be seen, this question is very similar to the paper-based exercises, with the difference that no particular landmark (small circle) is assigned to the student, since each student must provide a complete answer. In the case of Graph-Plotter, the proficiency of the students was measured by the Test of Understanding Graphs in Kinematics (TUG-K) [4], a test whose reliability and internal consistency have been determined by means of the “KR-20” coefficient, the point-biserial

coefficient, and the Ferguson's delta, among others [4]. An example question of this test is shown in Figure 13-b.

To determine and compare the impact of the experimental and control treatments, we used an ANCOVA analysis. The required normality assumption was supported by the results obtained from the Kolmogorov-Smirnov test. The treatment F-test value was found to be 6.169 (p-value = 0.022) at a significance level of 95% (Table 2), indicating that there exist significant differences between the posttest scores of the experimental and control groups. The estimated marginal means of these analysis allow us to analyze which of these groups attained a greater score increase (Table 3). It can be seen that, based on a pretest score of 8.04, the experimental group improved its score in 4.354 (54.2%) correct answers while the control group accomplished an increase of 2.166 (26.9%) correct answers. Thus, the effect of the experimental treatment outperformed the control one, doubling the effect of this last.

Regarding gender, the analysis showed that there were no significant differences between the learning accomplished by boys and girls throughout the experiments. Regarding previous knowledge, pretest scores were found to be not correlated with the improvement accomplished after the treatment [26]. Thus, the AEMRM was similarly effective among the participating students, independent of their gender or previous subject understanding.

4.4 Collaboration and motivation among the students

Collaboration and motivation were analyzed based on qualitative in-site observations and quantitative results obtained from a post activity survey. Comparing the experimental and control groups, a greater amount of collaborative interactions were observed in the students of the experimental groups. Moreover, in these groups it was common to see all members involved in discussions and explanations, situations not often seen in the control groups where discussions were less frequent and usually between just two group members; the third member usually had a completely passive role. Regarding motivation, during the last session, students of the experimental groups usually expressed their wish to continue working with this kind of activities. On the contrary, students of the control groups usually showed and verbally expressed their boredom after two activity sessions.

The previous observations were consistent with the results of the post activity surveys, shown in Table 4 and Figure 14. As it can be seen, 42% of the experimental group students found the activities to be "very

Table 4 Post-activity survey: Motivation and Collaboration mean results. Scale ranges from -2 to 2.

| Group | Collaboration | Motivation |
|--------------|---------------|------------|
| Experimental | 1.27 | 1.45 |
| Control | 1.04 | 1.22 |

Table 5 Variation of the number of students assigned to each social-appreciation category before and after the activities.

| | Control | Experimental |
|-----------------------------|---------|--------------|
| I like him/her very much | 7 | 11 |
| I like him/her | 22 | 36 |
| I am indifferent of him/her | 7 | 10 |
| I dislike him/her | 3 | -2 |
| I dislike him/her very much | 0 | -1 |

motivating" versus a 26% of the students of the control groups. Regarding collaboration, every student of the experimental group believed to have collaborated either "more than usual" (55%) or "very much" (45%) (Figure 14).

4.5 Social interactions among the students

Finally, social interactions were measured using sociograms in which each student scored his/her social appreciation of each of his/her classmates. When comparing the results of the sociograms, completed before and after the activities, it could be seen that the enhancement of the social bonds of the experimental students surpassed that of the control students.

Table 5 shows the variation of the number of students assigned to each social-appreciation category before and after the activities. While in the control groups the number of students positively classified (top two categories) increased in 29 students (87.8%), the same increase in the experimental groups was of 47 students (235%). Moreover, in the experimental groups the number of students evaluated negatively (bottom two categories) diminished in 3 students (out of 4), while in the control groups this number increased from 0 to 3 students.

5 Conclusions

The Autonomous Educational Robot Mediator has shown to be a powerful educational tool capable of becoming an active actor in the development of educational activities. After testing the AEMRMs in three different schools, they successfully proved to be capable of autonomously guide educational activities, foster the cre-

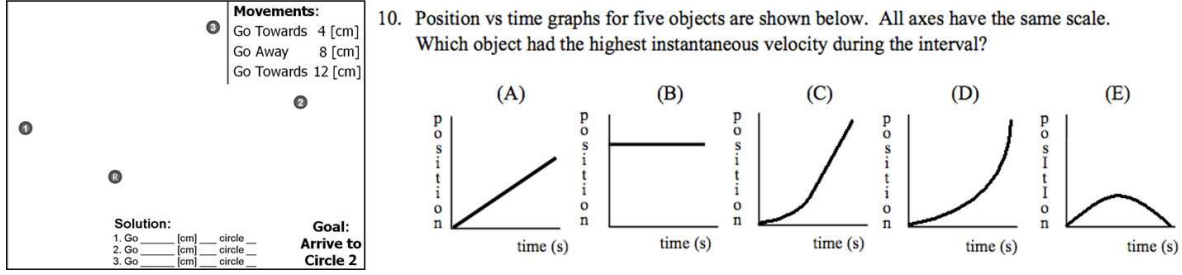


Fig. 13 a) See-You-There pre-post test exercise example. b) Graph-Plotter pre-post test question example.

Table 2 Results from ANCOVA: Dependent variable = (Posttest score); Factor = (Treatment group); Covariates =(Pretest score, Assistance).

| Type III | | | | | |
|-----------------|----------------------|----|-------------|--------|------|
| Source | Sum of Squares | df | Mean Square | F | Sig. |
| Corrected Model | 352.526 ^a | 3 | 117.509 | 32.503 | .000 |
| Intercept | 13.501 | 1 | 13.501 | 3.734 | .068 |
| Assistance | 25.330 | 1 | 25.330 | 7.006 | .016 |
| Pretest | 340.215 | 1 | 340.215 | 94.103 | .000 |
| Group | 22.400 | 1 | 22.400 | 6.196 | .022 |
| Error | 68.692 | 19 | 3.615 | | |
| Total | 3383.000 | 23 | | | |
| Corrected Total | 421.217 | 22 | | | |

^a *R Squared = 0.837 (Adjusted R Squared = 0.811)*

Table 3 Estimated marginal means of ANCOVA.

| Group | Mean | Diff. | Std. Error | 95% Confidence Interval | |
|------------|---------------------|--------------------|------------|-------------------------|-------------|
| | | | | Lower Bound | Upper Bound |
| Robot | 12.394 ^b | 4.354 ^b | .578 | 11.185 | 13.604 |
| Simulation | 10.206 ^b | 2.166 ^b | .606 | 8.937 | 11.475 |

^b *Evaluated at covariates appeared in the model: Pretest score = 8.04, Assistance = 3.83.*

ation of abstract representations of relevant concepts of the real world, and effectively mediate in the development of the proposed activities.

In relation to its teaching potential, it has been shown than the proposed educational framework can help students to understand different physical and mathematical concepts, such as geometry and kinematics. Students who worked with the AEMRMs experienced a substantial increase in their understanding of relevant target concepts. When compared with students who worked with similar but non robotic-based activities, the AEMRM users significantly outperformed them, attaining an increase in their test scores of nearly twice the increase observed in the non-AEMRM users.

Regarding mediation, since the students handed the activity solution through the AEMRM remote interfaces, the robot was able to mediate the interactions among the students by establishing interaction rules and guaranteeing their fulfillment. With these interaction rules, the robot could also prevent students from

developing free-riding behaviors, compelling them to work as a team. An example of this interaction rules was the consensus requirement implemented in both activities, which forced the students to explain the answer to any non-convinced group member. In the same way, other rules may be implemented, such as the order in which the different students must answer, or the possibility for other group members to edit or correct a teammate answer.

Regarding collaboration, teamwork among students was mainly achieved based on the wireless remote interfaces, since it was using these devices that the robot was capable of distributing roles among the students, and of providing different software tools and hints about the proposed problems. In this way, the robot was not only able to guide the team of students to pursue a common goal, but it was also able to provide unique capabilities to each student, fostering collaboration and inhibiting free-riding behaviors. This establishes a need for collaboration and interaction among the students

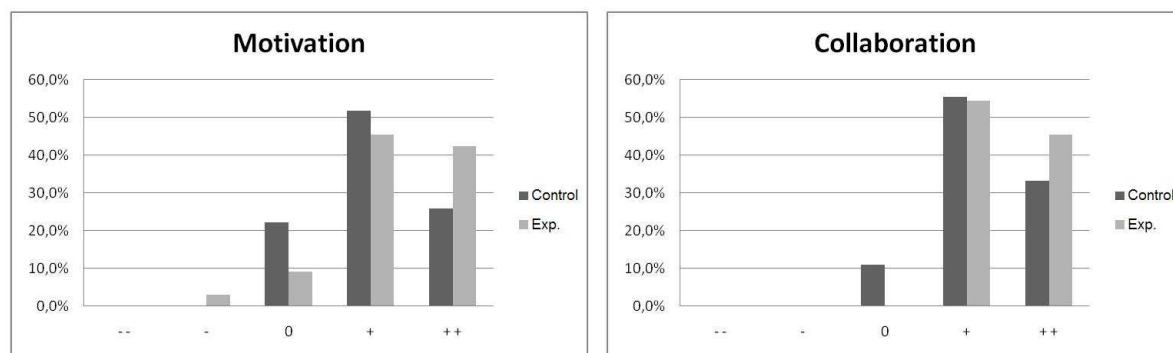


Fig. 14 Post-activity survey: Histograms of the results of motivation and collaboration questions.

that emerges in a natural way. Examples of this were the landmark assignation in the See-You-There activity, or the tools and roles distribution in the Graph-Plotter activity.

It is important to note that in relation with technology usability, students of the three schools needed no more than half a session to become proficient users of the technology. This is highly remarkable given that most of the students had never used a handheld device or interacted with a robot before. Also, the pieces of hardware did not interfere with the face-to-face communication among the students, a key factor for achieving good results in collaborative work groups.

Finally, we believe that part of the success of the proposed educational framework resides in the fact that, even though it has to operate in real time in the real-world, the activities implemented possess a high-level of structure that helps the robot to correctly guide the activities and the students through them. As the Robotics field advances and more powerful and more adaptive robotic technologies emerge, we will be able to increase the degree of autonomy of the AEMRMs. In particular, we plan to include more sophisticated planning strategies on the AEMRMs, that include mechanisms to help the robots to decide the best way to proceed with the educational activities, based on an estimation of the learning achievements and motivation of the students.

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