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Experiential Learning through Designing Robots and Motion Behaviors: A Tiered Approach*

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This paper considers the Teaching Methods of Design and Manufacturing course, in which engineering students develop various robots and teach robotics to school pupils. The students are involved in the experiential learning process which integrates designing and producing working prototypes with studying engineering subjects and project guidance methods. The robots developed in the course and the experiments directed to their optimization through review–revise–prototyping cycles are considered. The features of rapid prototyping using construction kits and the value of practice in teaching robotics are analyzed.

Keywords: robotics; experiential learning; teacher education; design projects; competitions

INTRODUCTION

ROBOTS ARE A category of mechatronic engineering products, capable of acting autonomously implementing assigned behaviors in various physical environments. A robotics course at the introductory level of engineering education involves students in hands-on practice through which they can learn many engineering subjects and applications. These learning-by-doing activities can be characterized using the concept of constructionism [1]. Accordingly, learning processes happen most effectively when a learner is involved in the creation of external and sharable artifacts and uses them as 'objects to think with', in order to explore, embody, and share ideas related to the topic of inquiry. Many educators have emphasized the effectiveness of robotics courses based on the learning-by-doing approach [2, 3].

The robotics course can be especially effective if it meets two goals:

1. Practical-technical—designing and producing a working robot prototype capable of performing the given assignment through a project-team effort.
2. Instructional—providing systematic learning of science and engineering subjects by all the students in the robotics course.

An experiential learning approach which organizes learning-by-doing processes so that the learner can acquire both practical skills and theoretical knowledge was proposed by Kolb [4]. Leifer [5] showed that embedding the experiential learning process in designing a mechatronic system can combine the technical and instructional goals of the robotics course.

An important impetus to educational robotics development was given by a conceptual framework of digital manipulatives [6] which extended the traditional learning with manipulative materials. Accordingly, the computational and communications capabilities are embedded in the mechanical parts of a construction kit. The students use the kit to create various devices and program their movements. The paper [6] presented programmable bricks and crickets for use with Lego kits. It called for empirical studies of how and what students learn through their interaction with digital manipulatives.

Constructionism and digital manipulatives have been implemented in a great number of Lego robotics courses at all levels of education. Among them are the teacher education program developed at the Carnegie-Mellon University [7] and the courses [8, 9] in which engineering and teacher education students successfully assisted in teaching robotics to school pupils.

This paper presents an educational environment developed at the Department of Education in Technology and Science, in which Technion students and middle-school pupils form a learning community coping with common robotics challenges. In this environment Technion students develop various robots and instructional materials, and assist in teaching a robotics course to middle-school pupils. Our study applies the tiered approach [10], considering the two different groups of learners (university students and school pupils) through their collaboration in order to develop effective strategies of robotics education

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as part of teacher-training programs and middle-school curricula.

EDUCATIONAL FRAMEWORK

The Technion Department of Education in Technology and Science offers undergraduate and graduate teacher-training programs in engineering disciplines. Many students receive a degree in science-technology education in addition to their main degree from one of the Technion engineering faculties.

Science-technology education involves teachers of engineering disciplines at school and tertiary levels in guiding student projects. The project is effective if it answers the following criteria: (1) it engages students in real-world challenges and presents new technologies; (2) it includes designing, building and programming system prototypes; (3) it imparts knowledge in science and technology to students with different backgrounds; (4) it promotes reflective and divergent thinking and self-directed learning, and encourages collaboration.

The need to improve project-based instruction and include studies of the project method in pre-service teacher education is emphasized in the literature [11]. However, only minimal information is available on educational approaches and examples of courses which prepare university students to teach robotics and guide design projects in schools [8, 9]. Clear recommendations for development of such courses are currently required.

This paper considers our Teaching Methods in Design and Manufacturing course, in which students study engineering subjects and gain project guidance skills. The students perform laboratory and project assignments, develop instructional units (on subjects related to these assignments), and practice teaching them using the project method.

The course is given in the departmental laboratory of technology. It consists of three modular parts. The first part includes lectures and laboratories. The lectures consider pedagogical aspects of experiential learning and subjects related to systems and control design. The laboratory activities include the following: (1) assembling sensor systems and implementing feedback control processes; (2) computer-aided design and producing machine parts; and (3) programming robot manipulations. The students enhance their product design skills through performing hands-on tasks and experiments with virtual environments [12]. Synchronous and asynchronous E-learning methods [13] are used for developing instructional units and in-class presentations. The second part of the course focuses on robotics projects. The third part of the course is practice in teaching robotics to middle-school pupils in our laboratory of technology.

Robotics has become an especially effective medium for engineering education [14]. It involves students in self-directed learning, interdisciplinary design, teamwork, professional communication, technical invention, and research. We believe that robotics as part of a teacher-training program can help engineering students to develop the professional and pedagogical skills necessary for their careers.

INSTRUCTIONAL ROBOTS AND EXPERIMENTS

Many prototypes of computer-controlled mechanisms in the course are built using the Robix kit [15]. This robot construction set implements the concept of digital manipulatives. Essentially, it contains all the components required for desktop robot construction. Its mechanicals include servomotors, aluminum links, parallel-jaw wrist-and-gripper assembly, construction bases, and other parts. The learner uses these to build various mechanical devices driven by the servos. An electronics interface (EI) is connected to the host computer through the parallel port. It has servo outputs, on-off outputs for device control, and sensor inputs (analog-to-digital and switch-closure). The EI is used to control and power servos, together with sensors and other devices introduced by the learner. The software supports a script language for generating point-to-point motion sequences, each move with matched velocity trapezoids and motion parameters per-servo. The user can define the positions (points) in 'teach pendant' or 'coordinate' modes. Scripts run by operator from console and also programmatically from C/C++, Visual Basic, or Java.

Below we consider a number of robots developed in the course, the reasons for their development, the design stages, and learning experiments.

Ellipsograph

Mechanisms for drawing algebraic curves are intensively studied in machinery design [16]. Visualizations of algebraic curves through graphic simulation of mechanical drawing are used in mathematics education [17]. In order to implement the experiential learning approach in this context, we run a number of projects in which Technion students develop computer-controlled mechanisms for automatically drawing mathematical curves. One of them was a mechanism for drawing ellipses.

The first prototype utilized the slider-crank mechanism (see Fig. 1A). Experiments showed that it drew only part of the ellipse because of the limits imposed by the Robix servomotors. This drawback was eliminated in the second prototype by adding a Lego gearing transmission to the mechanism (Fig. 1B).

The experiments conducted by the student with the second prototype included the following: selecting an optimal drawing instrument, the influence of the slider-crank parameters on the curve

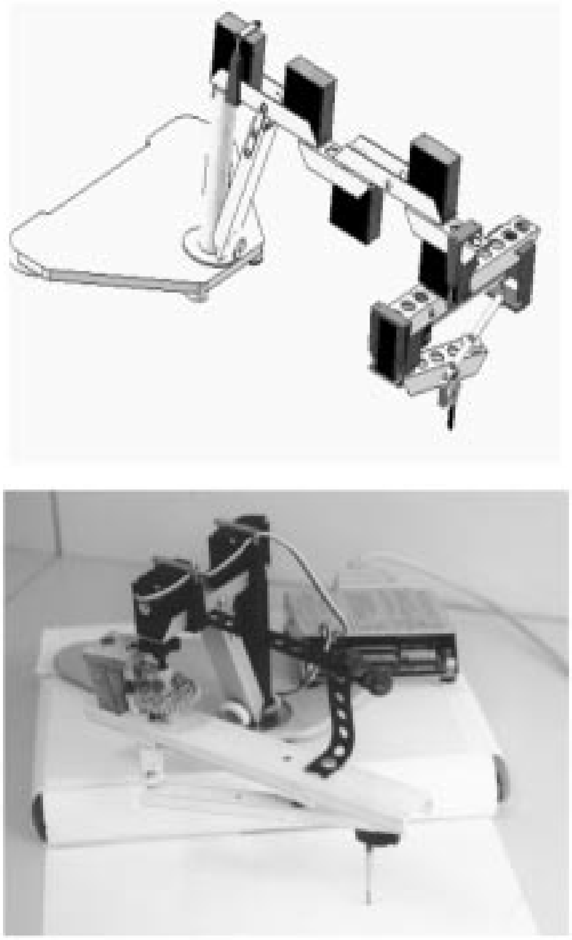

Fig. 1. Ellipsograph mechanism: (A) the first prototype; (B) the second prototype.

shape, and the drawing accuracy. The students in this project deepened their knowledge in linkages and gear trains, and programmed the mechanism for drawing an accurate ellipse.

A catapult and ballistic motion

Projectile motion is a basic topic of mechanics. The ballistic experiment in mechanics courses usually applies an elastic thrower or is performed in a simulation mode. In our course the students developed a tool which provided a real ballistic experiment and the opportunity to control its parameters. The project assignment was to develop a robot system capable of throwing ping-pong balls into a target (a cup). The first prototype was a three degrees-of-freedom (DOF) computer-controlled mechanism assembled using the Robix kit and programmed in its script language. The second prototype was developed (see Fig. 2) in order to extend experiential practice with the robot system. It included a 4 DOF mechanism, infrared sensor and light source, and was programmed in C. Through rotary scanning, the system determined a current location of the cup and threw the ping-pong ball into the target.

The following experiments were made with the system: motor calibration for determining angle velocities in the mechanism's joints, the effect of different factors on the throw accuracy, and the use of an optical lens to improve light sensing. In this project the student acquired practice in mechanical design, sensor-based control, and C programming.

Bio-inspired projects

Animal-like robots are attracting an increasing interest in engineering, biology and AI as a way of examining the general principles of locomotion. A series of projects performed in the course were related to the development of computer-controlled mechanisms which model different types of locomotion behaviors. The projects developed models imitating a snake crawling (Fig. 3A), a spider's movements (Fig. 3B), and human-like walking (Figs 3C and 3D).

These projects were carried out by the students through the following stages:

- Movement creation—understanding the biological principles of the given type of locomotion.
- Kinematic scheme synthesis—examining alternatives and creating a robot scheme.
- Mechanism analysis—determining the robot structure, dimensions and parameters.
- Building a prototype and its optimization.
- Programming robot movements and locomotion experiments.

The experiments with these models were directed to their optimization through review–revise–prototyping cycles. The following factors were examined: gravity center position, friction and inertia effects, a mechanism's stability, balance and coordination. The students in these projects focused on the optimization of mechanical structures and programming locomotion behaviors.

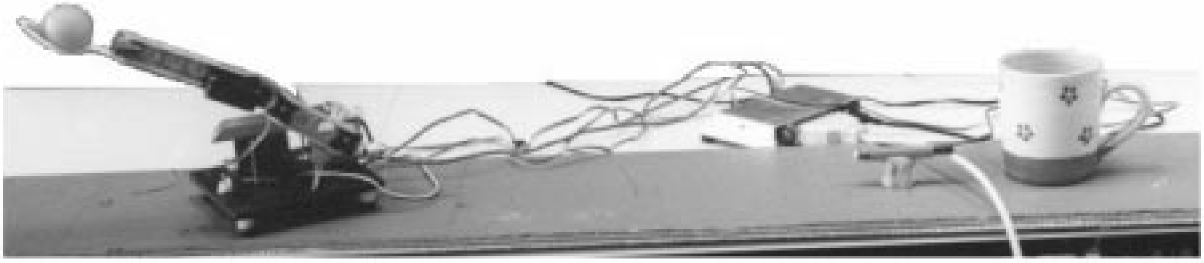

Fig. 2. The catapult experiment.

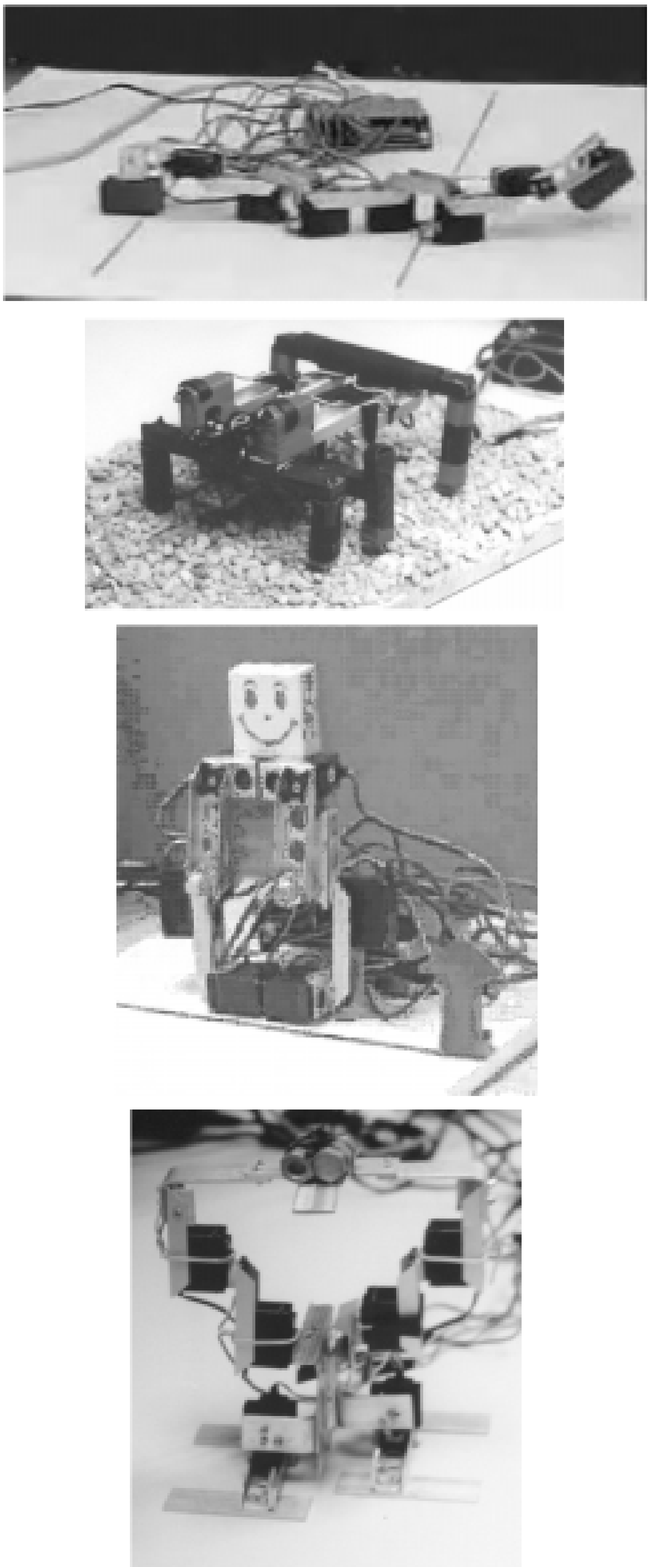

Fig. 3. Bio-inspired projects: (A) a snake crawling; (B) a spider's movements; (C) human-like walking (stiff feet); and (D) walking with flexible feet.

Cooperative robotic arms

Coordination and communication of robots is a central subject of modern robotics which will be introduced in the introductory robotics in the near future. In this context, one of the projects in our course dealt with designing and building two autonomous robotic arms which carry out a common manipulation task through their

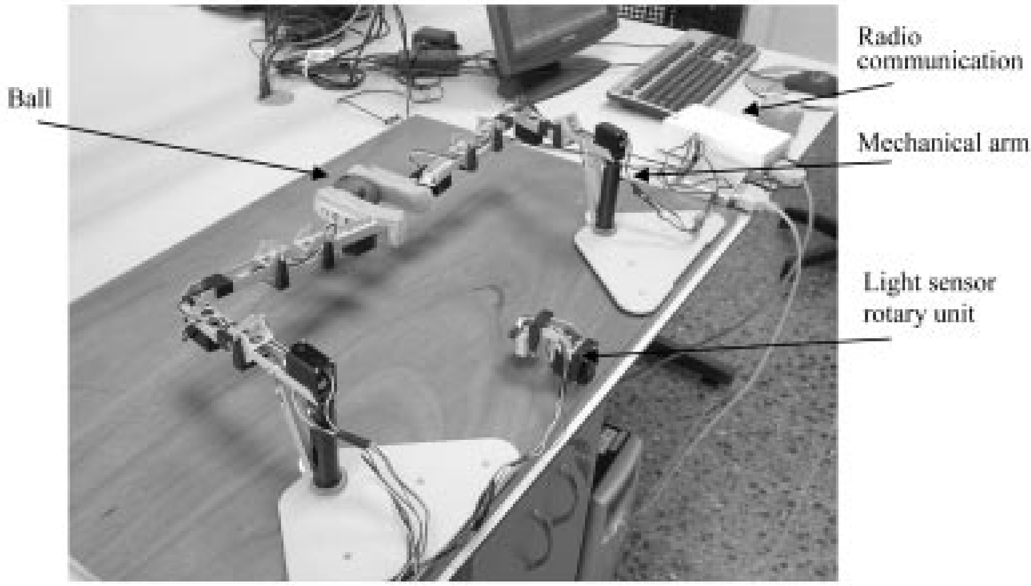

Fig. 4. The two-arm robotic system.

cooperation. The project assignment was to develop a two-arm robotic system which detected the location of an object (a ball) and grasped it through coordinated action of the arms. The system prototype is presented in Fig. 4. It includes two manipulators, built using two Robix kits. The 3 DOF manipulators are connected to different computers. Each of the computers is equipped with a radio communication module working under the RS 232 communication protocol. The light sensor rotary unit is connected to one of the computers and used for the ball detection.

The stages of the system development were:

- Selecting an object detection method.
- Developing remote communication.
- Designing and building mechanical arms.
- Developing a system and applied software in C.

Experiments performed by the students throughout the project include the following: testing communication parameters (time, reliability, and distances), arm prototyping, light sensor functioning factors, and arm positioning accuracy.

The three-year experience of integrating robot projects into the Technion teacher-training course indicated their significant impact on students' learning motivation in both the engineering and the education domains. The projects formed an environment which we use for teaching robotics to school students and for educational research.

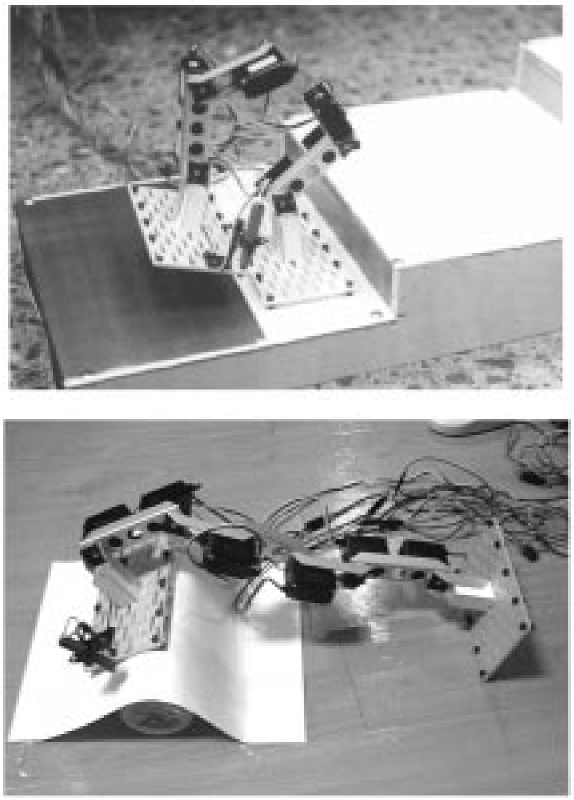

Fig. 5. (A) Rotation around itself and balancing; (B) clambering over obstacles by crawling.

Stair-climbing biped robot

Raibert [18, pp. 1–3] outlined the following advantages of studying biped robots: (1) legs provide better mobility in rough terrain than do wheels or tracks requiring a continuous path of support; and (2) studying legged robots helps to understand human and animal locomotion.

The biped robot presented in this section has been developed in our lab in the framework of the Technion International Youth Summer Research Program SciTech and the subsequent International Robot Olympiad (IRO) in Korea (www.iroc.org). Our 6 DOF robot implements two kinds of locomotion: climbing steps by somersault rotation around itself and balancing (see Fig. 5A), and hill scrambling by crawling (Fig. 5B).

The project was motivated by the IRO stair-climbing robot assignment. In building the project team we implemented the tiered approach [9], whereby different groups of learners collaborate in a common assignment. In our case, the team included two high-school pupils (participants of the SciTech), three Technion teacher education students and a supervisor (Verner). In the project the students practiced teaching robotics subjects through the experiential learning approach; one of them (Korchnoy) mentored the pupils and conducted the educational follow-up.

In the 'Creative Category' competition of the IRO, the pupils participated in four contests: (1) a written test, (2) a robot concept design, (3) building, programming and running a robot within the scope of the assigned theme and time limits, and (4) oral presentation of the project. They succeeded in winning first place in the competition. This success indicated that the proposed team organization effectively helped to introduce robotics subjects, didactical issues, and educational research methods.

EXPERIENTIAL LEARNING APPROACH

Through experiential practice in the course the students study a variety of robotics subjects, including the following: mechanisms, motors, kinematics and dynamics, control processes, sensors, programming, and applications. In addition, the students learn educational concepts and methods: experiential learning, design theory, technological literacy, team guidance, authentic assessment, technical skill development. The students also apply their knowledge to practical teaching of robotics subjects.

The course involves students in the experiential learning process, which can be described using the Kolbian circle model [4]. According to this model, the learning process is a circle which consists of four steps: (1) carrying out a particular action; (2) perceiving the effects of the action through observation and reflection; (3) understanding the general principles of each particular instance through abstract conceptualization; and (4) application through action in a new circumstance within the range of generalization.

In our course the students develop an understanding of robotics and educational concepts through their involvement in two different but connected learning circles. The first is the design circle, in which the student develops a working robot prototype. The second is the educational circle, in which the student develops, implements, and evaluates a unit for experiential learning using the prototype. The two circles are connected so that the student designs the robot as an educational tool and teaches the concepts which can be effectively studied using it. In the educational circle, the students recognize the robotics concepts, which can be effectively studied using the robot, and get real feedback, which helps them to revise their prototypes.

For most of the students, designing a robot is the first experience of rapid prototyping. Rapid prototyping is a methodology for designing and building accessible instructional tools for understanding systems or processes through experiential learning. This methodology 'presupposes a design environment which makes it practical to synthesize and modify instructional artifacts quickly' [19, p. 38]. It tends to utilize unified and cost-efficient components and modular technology. The potential educational advantages of rapid prototyping in our course are:

- It encourages active student participation in the design process.
- Due to its modularity and flexibility, the prototype can be easily modified, enabling experiential learning of different concepts.
- By reducing the time needed to modify the prototypes, the students obtain opportunities to develop their creative skills through examining more alternative design solutions.

The robots and lesson units developed by the engineering students are used in the introductory robotics course (IRC) which we give to middle-school pupils at the departmental laboratory of technology. In the IRC the pupils learn basic robotics concepts and perform experiments with the robots. The instructional robots form a learning environment which exposes the pupils to different applications of robotics in science education.

The level of understanding robotics concepts was assessed for engineering students through evaluating their project portfolios and instructional units, and for school pupils by means of comprehension tests.

OBSERVATIONS AND REFLECTIONS

Kolb's model [4] emphasizes the essential role of student's reflective observation in experiential learning as a way of perceiving the effects of the experiment and thereby increasing their understanding. Shoen [20] distinguished between reflection-in-action, which is embedded in practice, and reflection-on-action, which is undertaken after a project is completed.

This section considers students' reflections on their practice in our course as an important source of educational data. We summarize some of these reflections, which refer to the course activities and contributions. The students' reflections were collected through ten recorded personal interviews after completion of the course projects and were studied by means of the protocol analysis. Twenty-three project portfolios of the Technion students and one of the high-school students were analyzed.

All the interviewees pointed out that the projects assigned presented problems and new environments. They required studying new subjects through self-directed learning and practical activities. As already mentioned, 'Creativity was an integral part of the project'. The project offered a 'tangible assignment', which included the building stage, which verified the design solution, and the prototype application stage. Many of the reflections related to repeated experiments undertaken by the students in order to find the appropriate solutions for implementing in the projects.

The student who performed the ellipsograph project pointed out that his experiments referred to defining the mathematical model, arranging the gearing unit, and selecting a drawing instrument. The student who participated in the walking robot project emphasized the importance of planning project time and work and the need to learn the principles of human locomotion. The same was reflected by one of the students who dealt with the coffee-maker robot and had to learn new subjects in chemistry.

With regards to the contribution of the course, all the students expressed great interest in the projects and noted that their interest increased as they progressed. The value of dealing with real situations and prototypes was emphasized. A student's typical comment was that practice in building, assembling and breaking parts was the best way to learn machines and understanding design. One of the students said: 'If people do not see my real prototype, not all of them can perceive what I did.'

The students' reflections about their progress in the course are in agreement with our assessment, based on their project portfolios and instructional units.

Many interviewees pointed out that the project introduced them for the first time to problems which required taking account of many different factors at one time: 'I did not know that this is so complicated in nature.' With regard to teaching robotics to school pupils, the students noted that teaching robotics projects at school can significantly improve the learning achievements and motivation of pupils. The Technion students found that their robots aroused great interest in middle-school pupils, and their assistance helped the pupils in the introductory robotics studies.

DISCUSSION AND CONCLUSION

Modern engineering education requires teachers' involvement in guiding student projects which include designing and building computer-controlled technological systems. It follows that the integration of engineering and pedagogical aspects is essential for teacher training. Our Technion Teaching Methods in Design and Manufacturing course presents a possible approach to this integration.

The new features of our course compared to other robotics courses for teacher education [7–9] are as follows:

- Students and pupils collaborate as learners.
- The students design working robot prototypes, develop instructional units for experiential learning using the prototypes, and teach them to middle-school pupils. The pupils learn through experiments with the prototypes using the instructional units, and interact with the students.
- The departmental laboratory of technology is a shared learning environment.
- The laboratory effectively supports the design and learning activities of both groups, is convenient to students, and attracts pupils.
- The robotics curriculum integrates projects and courses, learning and teaching, theory and practice.
- Robotics in our curriculum provides an integrated learning environment for different subjects, methods, and activities.

Our three-year experience shows that the course achieves its goal of involving students in self-directed learning, interdisciplinary design, teamwork, communication, technical invention, and research. The projects offered by the course involve engineering students in designing and building robot systems which function in various physical environments. The students use their robot prototypes as instructional tools for teaching different subjects.

We found that rapid prototyping based on the use of robot construction kits is effective for creating accessible robotic systems and understanding engineering and educational concepts through experiential learning. It provides the students with experiences of machine control, involves good practice of applying mathematical methods, and promotes development of spatial imagery, creativity, and technical and practical skills.

Students' reflections on their experiences in the course indicated its significant contribution. In the professional domain, the course introduced the students to designing tangible instructional tools for engineering education. In the pedagogical domain, it introduced them to instructional design concepts and experiential learning guidance.

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