*Spatial learning of novice engineering students through practice of interaction with robot-manipulators**

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***Abstract*—This paper presents a study in which learning interactions of novice engineering students with robot manipulators focus on training spatial skills. To support the interactions, we customized the robots' workspaces, designed virtual robotic cells, and developed robot manipulation tasks with oriented blocks. 20 high school students (HSS) majoring in mechanics and 248 Technion first-year students (TS) participated. The study indicated that following the training, the HSS improved their performance of spatial tests, and the TS gained awareness of spatial skills required to handle industrial robot systems.**

***Keywords*—industrial robotics laboratory; novice engineering students; robot-manipulator; spatial training**

I. Introduction

This template, modified in The ways to increase the efficiency of learning practices in Robotics and Computer Integrated Manufacturing (RCIM) laboratories are widely discussed [1]. When educating unprepared students, the recommended lab practice is that which combines training technical skills with learning the principles of robot operation and development of generic skills required in different workplaces [2]. Among the most important of these is the ability of spatial vision. Industrial robotics laboratories generally implement three types of learning scenarios [3]: setting up a robot system, programming different industrial robots, and performing advanced robot-handling tasks. The laboratories offer learning practice in hands-on, virtual, and remote environments.

To perform robot system setup, programming and operation assignments, the student needs immediate and detailed visual information from the robot workspace. In the hands-on environment the student is near the robot system and so all needed information is acquired directly through observation. In the remote control system visual feedback is transmitted from video cameras via a computer screen, and so is incomplete and delayed. In the virtual environment the student works with a graphic simulation of the robot system on the computer screen under limitations of the given software.

The advantages and constraints of the hands-on, virtual, and remote learning practices have been discussed and compared in the literature [4]. Less attention has been paid to the analysis of difficulties that students face while performing tasks in robotic environments, and to the impact of this practice on the development of fundamental engineering skills, including spatial skills [5].

The current paper reports on the results of our study conducted in the RCIM Laboratory of the Faculty of Industrial Engineering and Management (IEM) at the Technion–Israel Institute of Technology. Over four academic years (2011-2015) we ran in the laboratory robotics workshops for IEM first-year undergraduates and, separately, outreach robotics courses for 10th-grade students in an underprivileged vocational high school. Both sets of courses offered learning practice in programming and operation of robot manipulators, while the tasks focused on training spatial skills. Details of our study are presented in [6].

II. Spatial Learning in Robotic Environments

Engineering practice depends on visual information, and strong spatial perception, reasoning, and visualization skills are critical to success in engineering careers [6]. This is true for practice in design and operation of automated manufacturing systems (AMS). Engineers responsible for the design, operation, and supervision of AMS must have aptitude in dynamic perception and dynamic and flexible reasoning, as well as a capacity for autonomous work and for rapid yet accurate decision making. Strong spatial skills are crucial for all aspects of robot design and operation, whether hands-on or remote. Lathan and Tracey [7] showed that performance in teleoperating a robot through a maze using a single camera significantly correlated with performance in standard spatial reasoning tests. Menchaca-Brandan et al. [8] found spatial skills, particularly perspective taking and mental rotation, to be essential for operating robotic manipulation systems.

Spatial skills can be developed through experience and practice, and studies in spatial cognition suggest that digital technology environments can facilitate effective training in

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these skills [9]. Researchers recommend practice with both virtual and real robots. Modern virtual robotic environments, such as RoboCell [10], enable the learner to setup robotic cells and develop simulations of production processes. The virtual robotic cells can be made realistic and create some sense of immersion by displaying simulated machinery, furniture, and other objects. Although different approaches to training spatial skills in science and engineering education have been widely discussed, very little research has considered spatial learning through practice in robotic environments. While studies relating spatial skills to robotics exist, most of these consider spatial ability skills only as prerequisites and predictors of learning. In consequence, among 217 studies of spatial training reviewed by Uttal et al. [11], only two concerned robotics courses and our work [12] was one of them.

III. THE ROBOTICS AND CIM LABORATORY

The RCIM Laboratory in the Technion's IEM Faculty conventionally supports courses and research activities for industrial engineering majors by enabling hands-on experimentation in the design, control and operation of automated manufacturing systems. The laboratory facilities include nine semi-industrial robots. In terms of software, the lab is equipped with the RoboCell.

A. Customizing the Robot Workspaces

For each robot we constructed and installed special superstructures that cover the devices used in advanced courses (buffers, jigs, conveyer belts, etc.) and enable performance of the manipulation tasks. Fig.1 shows a modified robot setup. We supplied plastic plates (pushers) that the robot uses to align objects in the assembly area. For SCARA robots that do not have gripper pitch we constructed a LEGO rotator that can rotate objects (blocks) around horizontal axes, thus enabling rotation manipulations using these robots.

B. Extending the RoboCell virtual environment

RoboCell is a software environment developed by Intelitek to setup virtual workcells and program robot handling processes. Robot manipulations in workcells created with

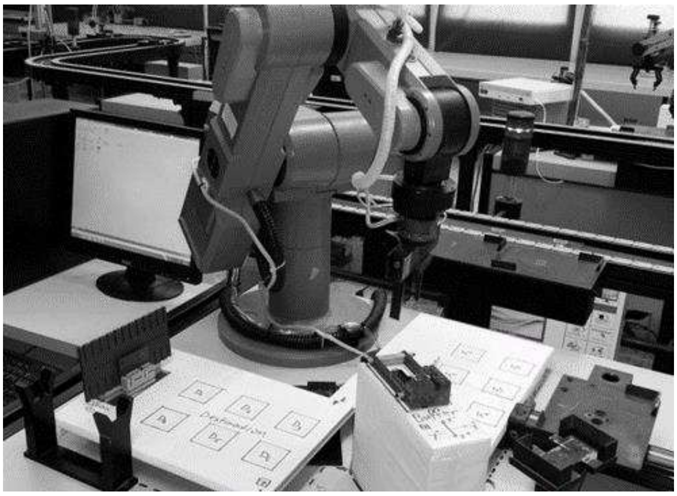

Fig. 1. Robot setup adapted for performing manipulations.

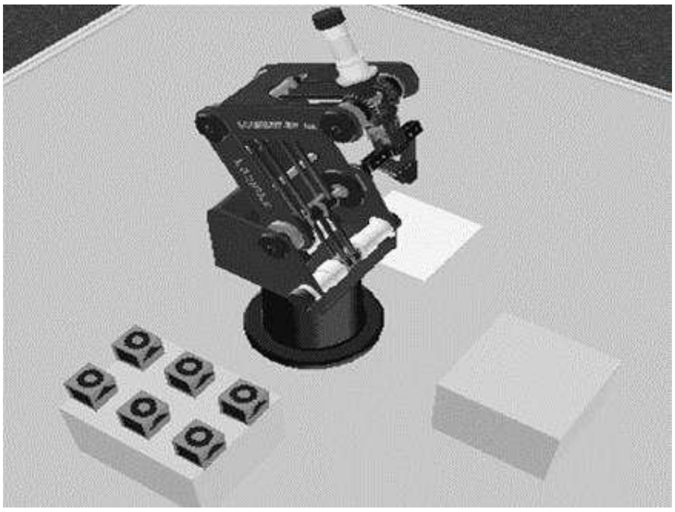

Fig. 2. Manipulating cubes with symbols on their faces.

RoboCell can be performed with parts having the shape of cylinders, cubes, and blocks. To enhance spatial learning, for our request Intelitek updated the RoboCell so as to enable defining and manipulating cubes with different symbols on their faces (Fig. 2). This enabled us to offer tasks in which the students rotate and orient the cubes by the robot.

IV. THE OUTREACH COURSE

This robotics course was designed at the request of a vocational high school to help 10th graders majoring in mechanical engineering who were having spatial difficulties mastering technical drawing. The 16-hour course consisted of eight two-hour sessions. The curriculum was divided into three parts, where each part focused on a certain aspect of robot programming and operation, and on training one of the main categories of spatial ability: spatial perception, mental rotation, and visualization.

The first three sessions focused on robot pick-and-place operations and spatial perception tasks. In the first session the students learned about the structure of the robotic arm and its motion in the workspace. In the second and third sessions they studied the robot control language ACL, learned to define robot positions by coordinates, and practiced programming simple pick-and-place manipulations with cubic parts. The next three sessions dealt with rotation of objects by the robot. In the fourth session the students learned about rotations around coordinate axes and how to perform them using the robotic arm. In the fifth and sixth sessions, they learned to use the RoboCell software and to operate a robot in the virtual environment. They completed this module by assembling a six-cube picture puzzle from identical cubes with geometrical symbols drawn on their sides (Fig. 2). The seventh and eighth sessions were devoted to performing three assembly tasks with real robots. The first task was to assemble a six-cube picture puzzle through teleoperating the robotic arm based on visual feedback from two digital cameras. In the second task the students were required to assemble a puzzle from six identical cubes with geometric figures drawn on their sides. The puzzle was presented using three orthographic projections (front, top, and side views) and a sketch. The students were asked to use the sketch to depict a three-dimensional view of the puzzle by drawing appropriate geometric symbols on the sides. They then had to assemble the puzzle using the robot.

V. Robotics Workshop

The 6-hour workshop was delivered to first-year students as part of the Introduction to Industrial Engineering and Management course. The workshop included a 2-hour lecture and two 2-hour robotics lab classes. The lecture "Principles of Robot System Operation" introduced the students to the concepts of CIM, robot programming, and robot operation. The lecture also presented the lab assignments. The first laboratory class was devoted to practice in the RoboCell virtual environment. The students were assigned to program a 5 degrees-of-freedom robot to assemble a structure from different blocks. In the second laboratory class the students operated real robots. The task required to operate the robot so as to pick up an oriented cube, move it from the storage area to the buffer, rotate it to the final orientation, and place it in the destination position at the assembly area. The students planned and operated robot movements using predefined positions of the mechanical arm and subroutines implementing basic pick-and-place operations (written in the Advanced Control Language).

VI. Evaluation of Learning Outcomes

The evaluation study involved twenty high school students participated in the course and 248 university students participated in the workshop. We evaluated whether the HS students improved their performance in spatial tasks following the laboratory practice in operating robot manipulators. The objective of the university workshop was to expose first-year students to industrial robotics and foster awareness about spatial challenges in programming and operating robots. Therefore, in this case our evaluation addressed the development of spatial awareness.

Evaluation of the outcomes of the university workshop was in line with its objective: to expose first-year students to industrial robotics and foster their interest and awareness about spatial challenges in programming and operating robots. Awareness is defined as individual's consciousness of something to the degree that it can influence her/his behavior [13]. Raising interest in industrial engineering and fostering awareness of its professional requirements, particularly spatial awareness, is one of the core missions in educating novice IEM students. Therefore, in the evaluation our interest was whether the practice in operating robot manipulators improve the students' awareness of spatial skills in industrial robotics.

A. Gain in Performance of Spatial Tasks

At the beginning of the outreach course we evaluated students' spatial skills using three paper-and-pencil spatial tests: the spatial perception test [14, p. 18], the mental rotation test [14, p. 290], and the visualization test [14, p. 149]. The same three tests were repeated at the end of the course. In addition, we ran an interim spatial perception test at the end of the first part of the course and a mental rotation test at the end of the second part. The purpose of the interim tests was to provide feedback for lesson planning and to encourage students' interest in the course. The results of the spatial tests show that the students in the course improved significantly both in relation to their initial scores, and in comparison to their classmates who did not take the course (the control group). Specifically, scores for the experimental group rose by 19.6% in the spatial perception test, by 104.5% in the mental rotation test, and by 30.1% in the visualization test compared with their pre-test scores. With respect to the comparison with the control group, the students in the experimental group achieved higher average grades in the 2013 matriculation exam in technical drawing (88.0) compared with their classmates from the control group (83.3). The pre-course tests showed no significant differences in spatial performance between the experimental and control groups.

B. Increase in Spatial Awareness

At the end of each workshop we administered a questionnaire. Eighty of the 93 participants in the 2014-2015 workshop responded. 92% those who responded had never studied robotics and had no experience with robots. A few students had studied robotics as an optional subject at school. More than 90% reported that the workshop exposed them to industrial robotics, and 17% evaluated this contribution as strong. 65% reported that the workshop effectively presented problems in operating and programming industrial robots; 23% considered this contribution to be high. The workshop aroused students' interest in studying robotics (55%), with about a quarter of the respondents reporting strong interest.

Moderate Pearson correlations were found between the workshop contribution scores for the presentation of spatial problems and for the exposure to industrial robotics $r = 0.53$ ($p < 0.0001$) as well as between the contribution scores and the interest to study industrial engineering $r = 0.51$ ($p < 0.0001$).

The questionnaire solicited students' reflections on their spatial learning practice in the virtual and physical robotic environments. The students' evaluations of the practice were highly positive. The repeated reflections:

> *It is hard to imagine robot operation without seeing how it is performed. I think we need to practice it because not everyone has good spatial skills.*
>
> *It is a good practice in planning manipulations in the workspace and enhances spatial vision.*

Students note the advantages of the spatial practice in the virtual environment:

> *The virtual lab lets you perform operations with the robot without fear that something will break or go wrong.*
>
> *The virtual lab made it easier to understand considerations in planning robot operations: calculating angles, heights and positions.*

Evaluations of the spatial practice with real robots were even higher:

The physical lab was much more interesting, since it was a new work environment. The challenge was to think how to accomplish the task in the most effective way.

The difficulties noted by the students related to the following spatial tasks: determination of the height of the robot gripper above the working surface, use of coordinates of the robot arm and their calculation, and collisions the arm with objects in the workspace, while performing manipulations. From students' reflections:

It was difficult to estimate distances between objects in the virtual environment.
Cube rotation tasks were complex and required spatial thinking

In response to our request to compare the contributions of the virtual and physical labs the students did not strongly favor one over the other. Rather, their responses suggest that both platforms serve important functions:

In the virtual lab it is easier to understand the thinking behind operating the robot, calculating angles, heights and locations.

The physical lab better demonstrates the robot workspace and gives an idea of the production process.

VII. Conclusion

In this paper we presented our experience in adapting the Technion Robotics and Computer Integrated Manufacturing Laboratory for introductory engineering courses. We engaged first year IEM students in robotics activities and opened the laboratory to high school students majoring in mechanical engineering.

Building on the educational opportunities afforded by placing students in the loop of robotic system, we focus their practice in the RCIM lab on understanding the principles of robot operation, fostering spatial skills and awareness of their importance in industrial robotics. This practice is crucial for novice engineering students who are choosing the future profession. The key features of our approach are:

- Customizing the robot workspaces to enable performance of spatial operation tasks.
- Combining practice in direct, virtual and remote robot operation.
- Extending the robotic environment to enable the manipulation of oriented blocks.
- Directing robot operation tasks to train spatial skills.

We implemented and evaluated the developed approach in our RCIM lab for engineering novices of two categories: high school students majoring in mechanical engineering and first-year IEM students. As found, the high school students in the course improved significantly in perception, mental rotation, and visualization tests. In the case of IEM students, the workshop provided the first-hand experience in operation of real and virtual robots, helped to understand the spatial problems dealt with by industrial engineers and recognize the skills needed to cope with them.

Based on the results of our study, obtained under specific conditions, we argue for further exploration of the proposed approach and call for using robotic environments for training spatial skills that are highly demanded in engineering education and practice.

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