International Journal of Engineering Education Vol. 36, No. 5, pp. 1691–1707, 2020
Printed in Great Britain

0949-149X/91 $3.00+0.00

Exploring Affordances of Robot Manipulators in an Introductory Engineering Course*

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In this paper, we report on our experience to develop a way for exposing industrial engineering (IE) students, already in their first year of studies, to the challenges of industrial robot operation. We implemented a workshop in which students performed spatial manipulation tasks, using a conventional robot Scorbot-ER5 and a modern Baxter. The goal of our study was to examine how the students learn through exploration of robot affordances and how the learning impacts their appreciation of the role of robotics in IE, interest in industrial robotics, and spatial awareness. We conducted two case studies: in the first, students operated Scorbot-ER5 in virtual and physical modes, and in the second, students operated both Scorbot-ER5 and Baxter, in the virtual mode. The study focused on students' performances, their difficulties, and responses about of the workshop contribution. Students' success in learning robot affordances was indicated by the improvement in task performance. The spatial difficulties that students faced in exploring affordances of the robots, and the ways by which they coped with the difficulties were identified and categorized. Most of the students self-evaluated that the workshop highly contributed to their spatial awareness and interest in industrial robotics and exposed them to the role of robotics in industrial engineering. These evaluations were significantly higher in the second study, in which students also operated the modern robot Baxter.

Keywords: industrial engineering; first-year students; robotic manipulation; robot affordances

1. Introduction

1.1 Background

The first-year of engineering studies is of decisive importance for students' self-identification as future engineers [1, 2]. Engineering schools support the development of this identification in their first-year students by offering appropriate introductory courses. Such courses introduce engineering from a broad perspective, present possible areas of specialization, attract students to engineering careers, and impart knowledge and skills needed for further studies [3, 4]. Vallim et al. [5] point to the value of introductory courses for providing students with an insight into the engineering profession, yet note that some courses are given in a declarative way with a minimum of practice. The authors propose to create productive learning environments that expose students to the world of technology, facilitate the learning of engineering fundamentals, and the development of professional skills in an integrated way. In such environments, students should "feel like engineers from the first day of class."

Castles et al. [6] developed such an environment for a first-year engineering course ENGE 1024 conducted at Virginia Tech Blacksburg. The course introduced fundamental engineering concepts and included hands-on practice in design, modeling, computer implementation, and application of different engineering systems. Another example is Rice University's "Introduction to Engineering Systems" course aimed to help first-year students to make a better-informed choice of technical majors - electrical engineering, mechanical engineering, and computer science [7]. The course demonstrated how these disciplines fit together into engineering systems. The course included robotics-lab experimentation in sensing, localization, mapping, motion planning, and state estimation. The results showed that the curriculum and the robot tasks were an effective way to recruit, retain, and train the students in STEM topics.

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* Accepted 12 April 2020.

The current digital transformation of industry, widely referred to as the fourth industrial revolution (Industry 4.0), necessitates an adequate reform of engineering education, which many call Education 4.0 [8]. The challenge is to prepare the new generation of engineers who will develop and implement new-type industrial systems referred to as cyber-physical systems (CPS). Monostori [9] defined CPS as "systems of collaborating computational entities which are in intensive connection with the surrounding physical world and its on-going processes, providing and using, at the same time, data-accessing and data-processing services available on the Internet." CPSs are designed to be safe for interaction with humans, and capable of self-organization and adaptation to the environment [10]. Planning, management, and operation of CPSs require industrial engineers to solve complex problems associated with the processing of large amounts of spatial data coming from physical and virtual devices of the systems [11]. To be able to solve such problems and optimize production processes, an industrial engineer is required to have a good perception of the CPS functionality and possibilities of manipulating objects in the workspace.

The challenge for engineering educators is to develop curriculums and instructional strategies to introduce students to the new concepts and technologies implemented in CPS [12]. Researchers point out that this challenge should affect the entire engineering curriculum from the first year of studies [13]. Involving first-year students in experiential tasks in realistic manufacturing environments and providing them with the experience of successful practice will help them shape their professional aspirations and develop their learning motivation [14–16]. Ilyas and Semiawan [17] noted the need to combine the acquisition of technical skills with the development of generic abilities "that engineers need now and will need in the future."

The vital role of spatial reasoning abilities in engineering and the need to develop them in engineering education are widely recognized [18, 19]. Educators recommend "starting instruction on spatial strategies used by practicing engineers in introductory engineering courses and building on these skills throughout the curriculum" [18]. Many studies explored spatial learning in introductory courses of engineering graphics and technical drawing [18–20], evaluating the outcomes using paper-and-pencil spatial tests. However, little research has been conducted on the development of spatial reasoning through training in robot planning and operation in introductory robotics courses [21]. Our research on spatial training through practice with robot manipulators was among the first in this area [22].

1.2 Purpose Statement

Our study has been conducted in the robotics laboratory (RobLab) of the Technion Faculty of Industrial Engineering and Management. We have developed and taught a robotics workshop since 2014, every semester, as part of the Introduction to Industrial Engineering and Management (IEM) course. In the first stage (2014–2017), the students programmed and operated conventional robot manipulators while the study explored and compared outcomes of spatial learning in physical, virtual, and remote environments [22, 23]. At the end of this period, the RobLab was upgraded and equipped with advanced robots, among them a collaborative industrial robot Baxter [24]. The transformation of the RobLab motivated us to update the workshop. In the renewed version of the workshop, in addition to the exercise with the conventional robot, we included a specially developed exercise in programming and operating the Baxter. The exercises focused on performing pick-and-place manipulations with blocks and oriented cubes. The practice with the two robots enabled to enhance student training in operating robot manipulators. Consequently, the goal we posed for this study was to examine how the students learn through exploration of robot affordances and evaluate how the learning impacts their appreciation of the role of robotics in IE, interest in industrial robotics, and spatial awareness.

1.3 Paper Organization

The next sections of the paper are organized as follows. In Section 2 we consider the spatial skills needed for operating industrial robots. We focus on how the operator perceives robot affordances for manipulating objects. Then, we analyze the affordances of conventional and modern robots, Scorbot-ER5 and Baxter, to execute the specific task of rotating oriented cubes. Section 3 presents the robotics workshop conducted in two modes: in one of them, first-year IEM students performed the noted robotic task with Scorbot-ER5 only; in the other, the students did it with both robots. Section 4 describes the evaluation method: research setting, sampling, data collection, and analysis. In Section 5, we present the evaluation results related to learning robot affordances, the contribution of the workshop, and its implications. The conclusions in Section 6 complete the paper.

2. Affordances for Robotic Manipulation

2.1 Perception of Robot Affordances

With the rapidly growing complexity of robot systems, the functions of human operators in industrial settings are becoming increasingly intellectual. An operator who monitors and supervises industrial robots has to acquire and apply the skills of dynamic perception, flexible reasoning, self-dependent judging, and decision making [25]. As practice in the loop of robotic systems can foster the development of such generic abilities, we found this practice appropriate to engage novice engineering students. Unlike the training of technical personnel for working with specific robots, teaching novice engineering students aims to facilitate the understanding of robot operation and develop generic skills required in different workplaces [16].

Operating a robot system in an industrial environment is highly dependent on the operator's ability of situation awareness. In general, situation awareness in monitoring and supervising a system is defined as the ability to perceive the system's elements in the environment, to comprehend their meaning, and to anticipate changes in their status [26, p. 13]. Perception and comprehension of the environment in situation awareness are selective and concentrate on features that are relevant for operating the system.

Although, generally speaking, the environment is perceived by humans through a combination of senses, robot operation is mainly based on visual input. Therefore, from now on, we will focus on the spatial aspect of situation awareness, and to refer to it, we will use the term spatial awareness (SpA). Bolton & Bass [27] defined spatial awareness as the ability to perceive and organize spatial information of objects and understand their relative positions and movements in the workspace. Like situation awareness, SpA includes a spatial perception of the robot and objects, comprehension of their relative positions in the workspace, and the projection of their displacement with time when performing a robot task.

To predict the dynamics of the robot system, the operator needs to have a good understanding of its functional capabilities in the workspace. These capabilities are defined in robotics using the concept of affordances, which serves to model the operation of industrial systems [28].

In a broader context, the concept of affordance can be defined as the functional property of an object or an environment that makes possible some action to an agent equipped to act, whether this agent is a human or a robot [29]. For example, a block in the robot workspace has its affordances to be grasped and manipulated by the robot arm [30]. Since the recent adoption of the concept of affordance in robotics, it draws significant and increasing attention of researchers, who found it highly applicable to autonomous robot control and behavior-based robotics [31, 32]. The related literature considers perception and learning of affordances and their use in decision making, almost exclusively, as a relationship between the robot and the environment, focusing on the ability of autonomous robots to detect functional opportunities to utilize tools or manipulate objects [33]. However, when considering robot operation, there is a need to explore the relationship between the human operator and the robot. From the operator's perspective, the mechanical arm has the affordances to be operated or programmed to pick a block and place it in some other location. In this context, the affordances of the robot are actualized through the operator's capability to utilize them. So, for manipulating a block, the "graspability" of the block depends on the functional characteristics of the robot arm. "Manipulability" of the robot arm is manifested through robot operation, which depends on the skills of the operator.

Only a few researchers have studied how humans perceive robot affordances. Cognitive psychologists [34] claimed that they didn't find in the literature studies on learning robot affordances. They conducted an experiment in which university students, studying an introductory psychology course, were trained to assess step climbing affordances utilized by wheeled robots. The students watched video clips in which the robots with different wheel diameters attempted to climb stairs with steps of various sizes. Following the concept that humans can develop the ability to perceive affordances through practice [35], the researchers explored if the students' judgments improve with the experience. Based on this experiment, the authors claimed that the ability to perceive robot affordances can be acquired through experience and call for further research to validate this claim.

To our knowledge, our study is the first to investigate student learning of robot affordance in the context of industrial robotics. We conducted a multi-case study in which first-year students of the Faculty of Industrial Engineering participated in our robotics workshop and experientially learned the concepts of spatial awareness, and robot affordance. The absolute majority of the students were completely new to robotics and automated manufacturing. Our challenge was to engage them in experiential learning of robot affordances and spatial awareness. The workshop we conducted to the students followed the recommendations given in [26, pp. 235–238]:

- Combining the learning of the principles of robot motion and control with exercises in robot operation.
- Providing opportunities for training fundamental spatial skills needed for robot operation.

- Facilitating novice operators in the development of mental models and schemas for carrying out prototypical spatial tasks.
- Identifying the types of spatial difficulties faced by the students and providing them the means to cope with the difficulties.

2.2 Rotation of Oriented Cubes

The pick-and-place manipulation of an object by a robotic arm is a fundamental task in robotics, which requires careful consideration of the relationship between the robot, the object, and the environment, during the object's grasping, moving, and placing. As discussed in chapter 2, the practice in planning and operating robot manipulations makes use of robot affordances and spatial awareness. To develop a practice accessible for first-year students, we simplified their learning assignment by setting the following constraints:

- The manipulative objects are oriented cubes
- The robot's end of arm tool (EOAT) is a two-fingered parallel gripper.
- The cubes are picked off and placed on a horizontal tabletop.
- The Cartesian coordinate system XYZ is predefined relative to the robot and with the XY plane parallel to the tabletop.
- The oriented cubes are positioned on the tabletop in predefined locations so that their faces are parallel to the coordinate planes.

An oriented cube is a cube with signs or pictures on their faces. In each position in the workspace, the cube can be in one of 24 different orientations (four orientations for each of its six faces). A two-finger gripper, whose fingers remain parallel throughout opening/closing, is a useful tool for many robot manipulation tasks due to its simple mechanism and control [36]. It is particularly suitable for manipulating cubes.

From our experience [22], the proposed arrangement provides the students with useful training in planning manipulations. The practice does not lead to information overload that may hinder their spatial awareness. The central task is to pick up the cube from its initial position, rotate it to the desired orientation, and place it in its destination position. To perform this task, the student must analyze the affordances of the oriented cube to be rotated by the robot arm.

An oriented cube has 23 orientation-change affordances that the robot can utilize by grasping the cube, picking it up, rotating it, and placing it down in one of the new orientations. Under the imposed constraints, as the cube should be picked off and placed on the table by a two-fingered gripper, not all grasp and rotation affordances are available. For example, the robot cannot pick the cube from below and cannot place it, after rotation, on faces that are used to hold the cube. It can be shown that even with these constraints, all 23 orientation-change affordances can be utilized by carrying out one appropriate pick-and-place manipulation. However, because of the specific kinematic constraints, the robot can lose its ability to carry out some of the rotation tasks in one pick-and-place manipulation.

So, to plan the desired rotation, the student must first figure out whether the robot can execute the action in one or several pick-and-place manipulations, and then design the manipulation(s). These spatial tasks are quite challenging for novice students. Following the recommendations presented in Section 2.1, we supported the students carrying out the tasks by introducing the Robot Manipulation Language (RML) interface.

The language describes pick-and-place manipulations in which the cube is picked up from a given position, rotated by the robot, and placed in the same position, but in a new orientation. Each pick-and-place manipulation is described by a specific RML spatial code, which consists of four characters in the format "**S**α**F**$\boldsymbol{\beta}$" as defined below:

S – the direction of the gripper axis when grasping the cube to pick it up. It can take 'X', 'Y' or 'Z' values, which refer to the positive directions of the relevant axis.

α – the orientation of the gripper fingers when grasping the cube. It represents the angle of rotation of the gripper around its axis. α can take values of '2', '1', '0' or '–', which represent counter-clockwise rotations of 180°, 90°, 0°, and –90° accordingly.

F – the direction of the gripper axis when releasing the cube to place it down after the rotation; it can receive values {X, Y, Z} with the same meaning as S.

$\boldsymbol{\beta}$ – the angle of rotation of the gripper around its axis, with the same meaning as α.

In the example illustrated in Fig. 1, the robot is positioned in the Cartesian coordinate system XYZ and executes a manipulation defined by the RML code "X0Z1". The robot is manipulating a cube with an arrow drawn on one of its faces. The right finger of the robot gripper is marked in black to help view its rotations.

The manipulation starts with the robot picking up the cube while the gripper axis is positioned parallel to the X-axis and not rotated (Fig. 1A left). The cube is placed on the table when the gripper is positioned in the negative direction of the Z-axis and rotated 90° around its axis (Fig. 1A right). As it refers only to the gripper orientation, RML can be

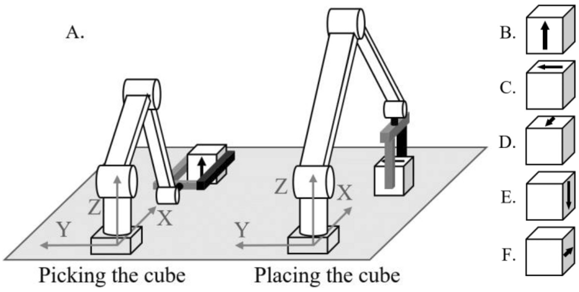

Fig. 1. A. The manipulation defined by the RML code "X0Z1"; B–F. Orientations of the cube.

applied to any robot, regardless of its degrees of freedom (DOF). The next section presents the use of RML to explore the affordances of the Scorbot-ER5 and Baxter robots for rotating the oriented cube.

2.3 Manipulations with Scorbot-ER5

The 5-degrees-of-freedom (DOF) vertical articulated mechanical arm of the robot has five revolute joints, as illustrated in Fig. 1A. Under the constraints described in Section 2.2, and because of its kinematic structure, the Scorbot-ER5 is limited in its ability to approach and grasp a cube. In fact, only six grasp affordances and five rotation affordances can be utilized. The robot can approach the cube along the X-axis (Fig. 1A left) and grasp it horizontally in two ways differing from each other by the 180° turn of the gripper around its axis. The robot can also approach the cube along the negative direction of the Z-axis (Fig. 1A right) and grasp the cube in four ways, each differing by a 90° rotation of the gripper around the axis. After the cube is picked up, it can be rotated and placed on the table in five different orientations. So, to rotate the cube, the robot can perform a total of 30 different pick-and-place manipulations.

These manipulations allow the cube to be placed in 12 different final orientations (including the initial one), while each orientation can be obtained in 2, 4, or 6 ways. For example, the manipulation represented by the X2Z- code will have the same effect on the orientation of the cube as the X0Z1 code illustrated in Fig. 1A. Both manipulations are taking the cube from the orientation shown in Fig. 1B to the orientation in Fig. 1C. In another example, there are four combinations to rotate the cube from the orientation illustrated in Fig. 1B to the orientation in Fig. 1D, by using the manipulations X0Z2, X2Z0, Z0X2, and Z2X0.

As only 12 of 24 existing orientations can be obtained through one pick-and-place manipulation of Scorbot-ER5, the remaining 12 orientations can only be imparted through a sequence of manipulations. For example, the cube can't be rotated by one manipulation from orientation in Fig. 1B to that in Fig. 1E and requires a sequence of manipulations such as X2X0, Z0Z1 as presented in Fig. 2.

2.4 Manipulations with Baxter

The Baxter is a *cobot* (collaborative robot) intended to perform various production tasks through safe interaction with humans in a shared workspace [24]. The robot embodies the core concepts of modern robotics intelligence technology. Baxter has two arms, each with 7 degrees of freedom joints shown in Fig. 3.

We examined Baxter's affordances to manipulate a cube placed in various locations of the workspace and found there isn't any location in which the cube can be approached and grasped from more than three directions. We also realized that placing the cube in the front-left direction of the robot makes it easier for the left robot arm to grasp and manipulate the cube, as illustrated in the example of a robot manipulation presented in Fig. 4.

Thus, Baxter has eight affordances to grasp and seven affordances to rotate the cube (vs. six affordances to grasp and five affordances to rotate the cube with Scorbot-ER5). Baxter can approach the cube not only along the X and Z axes, like the Scorbot-ER5, but also along the direction of the Y-axis. From this direction, the Baxter can grasp the cube horizontally in two ways different by a 180° turn of the gripper around its axis. In total, the Baxter can rotate the cube through 56 different pick-and-place manipulations, which allow it to

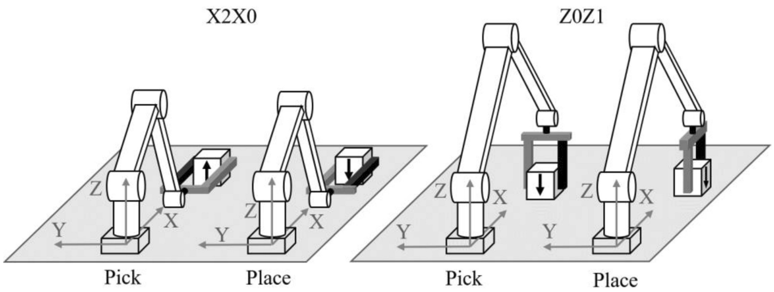

Fig. 2. Rotation of an oriented cube through a sequence of manipulations.

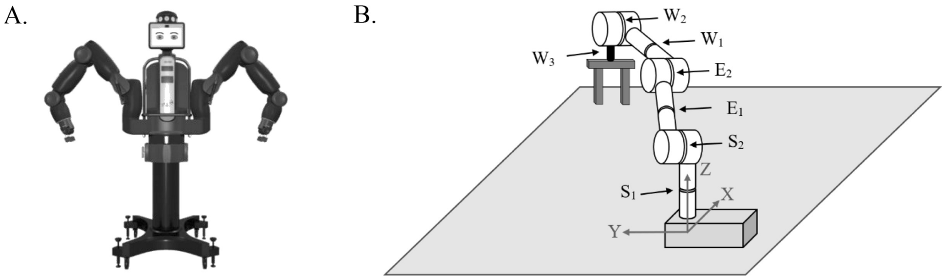

Fig. 3. A. The Baxter; B. Baxter's arm joints: shoulder S_1 roll and S_2 pitch; elbow E_1 roll and E_2 pitch; wrist W_1 roll, W_2 – pitch, and W_3 roll.

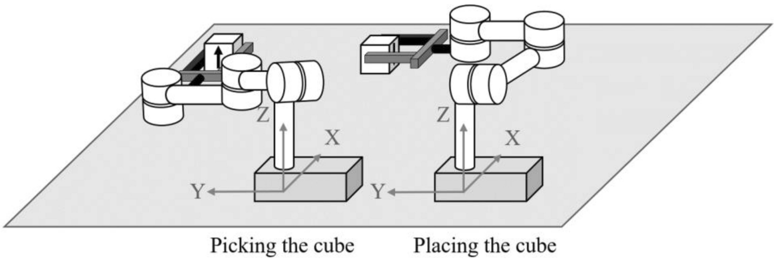

Fig. 4. Baxter performing manipulation X0Y2.

place the cube in 18 different and final orientations (including the initial one). That is six orientations more than allowed by Scorbot-ER5. For example, the rotation of the cube from the orientation shown in Fig. 1B to that in Fig. 1E requires from Scorbot-ER5 two pick-and-place manipulations (Fig. 2) but requires only one manipulation from Baxter. Moreover, Baxter can perform this manipulation in four different ways described by the RML codes X0Y2, X2Y0, Y0X2, and the code Y2X0 illustrated in Fig. 4.

However, for each initial orientation, there are six final orientations of the cube that cannot be imparted by Baxter in one pick-and-place manipulation. For example, the rotation from the orientation shown in Fig. 1B to that in Fig. 1F can only be executed through a sequence of manipulations.

3. Educational Context

In this paper, we discuss two versions of the 6-hour workshop – the first version was conducted in 2015–16 and the second in 2018–19. Each version included a lecture and two laboratory sessions in which student participants performed robot operation exercises. The first version of the workshop was held in the RobLab, where the students operated Scorbot-ER5 in physical and virtual modes. In the second version, the students practiced with both Scorbot-ER5 and Baxter in the virtual mode in the faculty computer class. The description of the first version of the workshop has been published [23], and the second version is presented below.

3.1 The Lecture

The lecture exposed the students to industrial robotics and introduced the structure and principles of operation of Scorbot-ER5 and Baxter. The students learned the kinematics of each robot, the ways to define positions of the mechanical arm by coordinates, and the ways to program pick-and-place manipulations. The first laboratory exercise was then presented. In this assignment, the students were given a plan of a block structure and were asked to operate the virtual Scorbot-ER5 to assemble the structure from blocks consisting of 1, 2, and 3 cube units. The criteria for evaluation were the minimal number of robot movements and used parts, correct calculation of block positions, and accuracy of the robotic assembly. The first exercise was the same in both versions of the workshop.

Next in the lecture, the affordances of Scorbot-ER5 and Baxter in manipulating the oriented cube were considered. The RML language was introduced to the students, and examples of using RML codes to plan robot manipulations were given. The assignment for the second laboratory exercise was then presented. The manipulated objects are identical cubes with digits from 1 to 6 on their faces, as shown in Fig. 5. The digits on the faces of the cube are irregularly oriented to intensify the training of spatial awareness in planning robot manipulations. Two 3-digit numbers were given to the students to specify the assignment. They had to

Fig. 5. Different views and the envelope of the cube.

place the three cubes in the initial positions so that the digits on their top faces present together the first number. Then they had to operate the robot to rotate and place the cubes in the final positions, in which their top faces show together the second number.

The digits in the second number were selected relative to that of the first number, to provide tasks of growing complexity. The first digit was chosen so that both Scorbot-ER5 and Baxter have the affordance to rotate the first cube to the desired orientation by a single pick-and-place manipulation (complexity level 1). The second digit was such that to allow rotation of the second cube to the desired orientation in one pick-and-place operation of Baxter. Still, it required two operations of Scorbot-ER5 (complexity level 2). The third digit was selected so that the rotation of the third cube required two pick-and-place operations from both robots (complexity level 3). After the lecture, the students visited the laboratory to watch a demo of the two physical robots operated to manipulate objects.

3.2 The Exercises with Scorbot-ER5

RoboCell is a software platform that simulates the operation of Scorbot-ER5 in a virtual environment [37]. This software enables the user to design a realistic virtual work cell and import into it custom 3D objects to be manipulated by the robot. The user controls the robot by entering commands in a command-line prompt and can then extend the set of standard commands by adding custom commands based on subroutines written in the robot control language. RoboCell allows the user to view robot movements in the work cell during the execution of commands, including zooming in and out, and taking a different point of view.

Exercise 1

For the first exercise, we created a virtual work cell containing the robot, three block feeders, and blocks of different lengths (Fig. 6A).

Each pair of the students were given a plan (top view) of a structure and had to choose suitable blocks, determine their dispositions in the assembly, and operate the robot to assemble the structure (Fig. 6B). The exercise was given in the first laboratory practice session in both versions of the workshop. The students performed the task in the faculty computer class, where the RoboCell software was installed.

Exercise 2

The second exercise was implemented in physical and virtual environments. To provide practice with oriented cubes in virtual mode, the Intelitek Co. extended the functionality of the RoboCell for our purposes, and allowed the importing and manipulating of cubes, which had pictures on their faces. For this exercise, we used the modified software to create a work cell containing the robot, three oriented cubes, and stands on which the cubes are placed (Fig. 7A). For each RML code applicable for Scorbot-ER5, we prepared a subroutine that

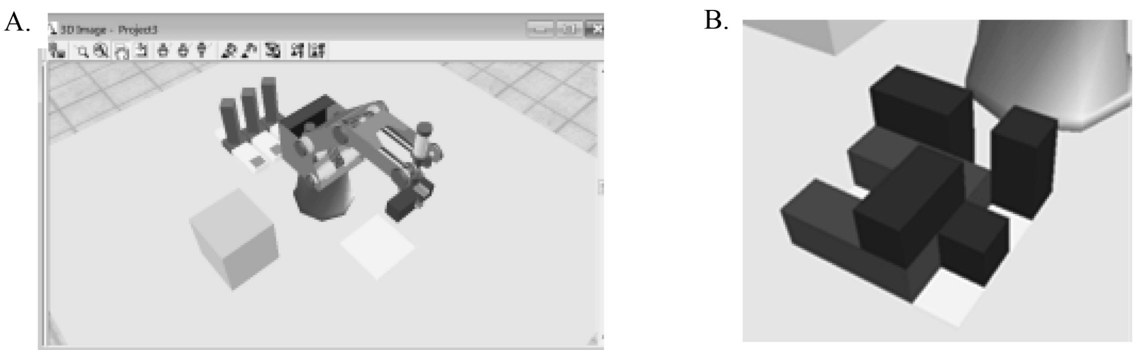

Fig. 6. A. Scorbot-ER5 virtual work cell for Exercise 1; B. Assembled structure.

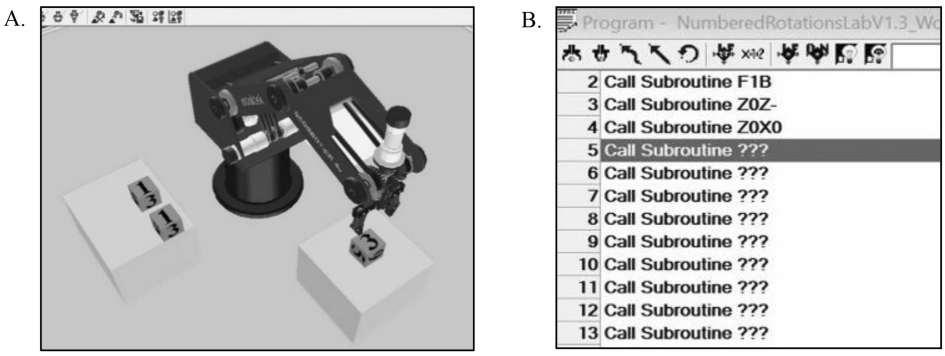

Fig. 7. A. Scorbot-ER5 virtual work cell for Exercise 2; B. Command prompt.

executed the appropriate manipulation. By entering the RML code in the Call Subroutine command line, the user prompts the subroutine, and the corresponding pick-and-place manipulation is executed (Fig. 7B). The same subroutine commands were used to operate Scorbot-ER5 in the physical mode.

This assignment with Scorbot-ER5 was given in both versions of the workshop. In the first version, the students performed the task with virtual and real robots in the RobLab. The robot work cell included a robot and tables for placing the cubes. The manipulated objects were three identical cubes with digits from 1 to 6 irregularly oriented on their faces (Fig. 5). In the assignment, the students were given two 3-digit sequences that determined the initial and final orientations of the cubes. In the second version of the workshop, the students performed the same task but used the virtual Scorbot-ER5 in the faculty computer class. In the second version, we provided physical demonstration cubes, identical to those rotated by the robot, to students who had experienced difficulties in planning robot rotation manipulations. The students rotated the demonstration cubes by hands to test the intended movements of the robot arm.

3.3 The Exercise with Baxter

Baxter is operated and controlled via the Robot Operating System (ROS) running in a Linux environment. The ROS allows users to develop custom programs for the robot. The programs can be run either on a physical robot or on a virtual model of the robot within the Gazebo simulator. The developed virtual work cell included a readymade model of Baxter, models of oriented cubes, and stands for placing the cubes (Fig. 8A). In the simulation environment, the user could choose the desired point of view by rotating the entire work cell and zooming in or out. For example, the mechanical arm holding the cube can be viewed from the viewpoint in front of the robot (Fig. 8B), or from the perspective of the robot's head camera (Fig. 8C).

We also developed a graphic user interface (GUI) to control the robot in the work cell. The GUI panel (Fig. 9A) is used to specify the exercise by entering the 3-digit number that determines the initial orientations of the cubes. Another panel (Fig. 9B) serves to operate the robot and run pick-and-place manipulations determined by the RML codes. The cubes are moved from the source to the buffer stand,

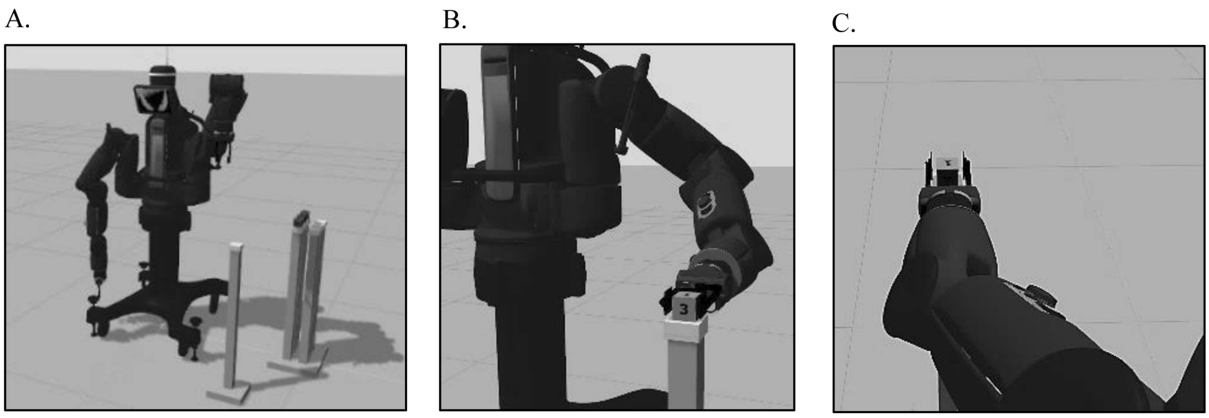

Fig. 8. A. Virtual workcell; B. Observer's point of view; C Baxter's point of view.

A. B.

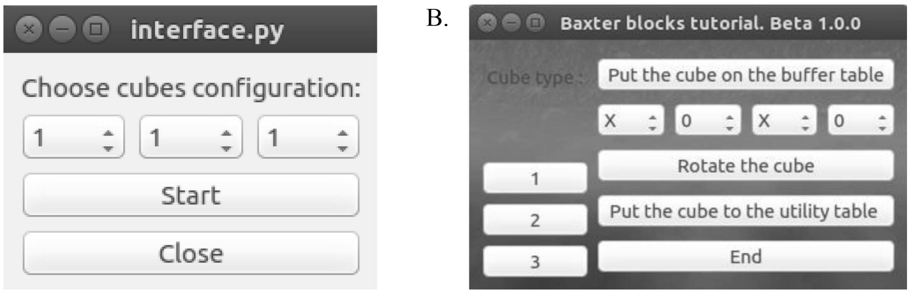

Fig. 9. The control interfaces: A. Configuration GUI; B. Robot control GUI.

rotated to the required orientation, and then placed on the target stand. The Gazebo simulator allows the user to observe robot movements during the execution of commands and to view the effect of the manipulation on the cube orientation. The program records the number of pick-and-place manipulations and the time it takes to bring each of the cubes to the desired orientation. The data on students' performances was collected in a log file and served for the analysis of student performance.

The students only performed this assignment with virtual Baxter in the second version of the workshop. They worked in the faculty computer class where virtual machines with Linux, ROS, and Gazebo were installed. Students who experienced difficulties in planning rotation manipulations were allowed to use physical demo cubes.

4. Evaluation

4.1 Research Setting

This research was conducted in the framework of the mandatory first-year course, Introduction to Industrial Engineering and Management. The course provides students with an overview of different aspects of IEM and includes our robotics workshop on industrial robotics. The research goal was to examine how the students learn through exploration of robot affordances and evaluate how the learning impacts their appreciation of the role of robotics in IE, interest in industrial robotics, and spatial awareness.

The research questions were:

1. How did the students learn spatial affordances of conventional and modern robot manipulators?
2. How did the workshop contribute to the students' spatial awareness, their interest in industrial robotics, and their exposure to the role of robotics in industrial engineering?

The research used a multi-case study method and was based on experience gained through past research of learning in different robotic environments [38, 39]. We found this method appropriate for our empirical studies, in which we developed robotic environments and instructional strategies, and evaluated the influence of their characteristics on learning outcomes.

4.2 Sampling

Our research included two case studies that involved 226 first-year students of the Technion Faculty of Industrial Engineering and Management who participated in the course. The majority of the students were 20–23 years old. Less than 5% of them had previously learned robotics in school or other settings. The first case study was conducted in 2015–2016 and involved 89 students who participated in the first version of the workshop. 58% of them were female and 42% male students. The second case study in 2018–2019 included 137 students who participated in the second version of the workshop, among them 53% female and 47% male. The first study was presented in detail in a previous paper [23]. In this paper, we present the second case study, compare evaluations of the workshop provided by the participants of the two case studies, and identify contributions of the practice with Baxter.

We applied the comparative case studies (CCS) method. According to Goodrick [40], the CCS method is appropriate when the intervention is implemented in different contexts within a certain framework, and the research aims to explore how the features of the contexts contribute to the targeted outcomes. Accordingly, our study evaluated and compared learning outcomes and student perceptions of learning with Scorbot-ER5 only and with Scorbot-ER5 and Baxter robots.

Our research also involved 28 second-year students majoring in industrial engineering, who took the workshop as part of the course a year before.

4.3 Measures

The data collection tools used in this study included observations during laboratory sessions, records of robot operation performance, the spatial perception questionnaire conducted at the end of the second session, laboratory reports, and the workshop evaluation questionnaire. The observations of student learning provided insights into how the students performed the robot operation tasks. After the laboratory session, we made notes about the use of visualization techniques and RML codes, and about students' strategies for planning robot manipulations.

In the second version of the workshop, to track the learning process in performing Exercise 2, we measured the execution time of rotation manipulations with each of the three oriented cubes. We measured the time spent by the student team to find, define by code, and implement the pick-and-place manipulation. We also recorded all robot control commands used to execute the assignment. For practice with Scorbot-ER5, measurements and recordings were carried out manually, while for Baxter they were done automatically by the robot control program.

The data on spatial difficulties experienced by the students when performing the spatial manipulation assignments were collected by questionnaires conducted in the two case studies. In the first case study, the workshop evaluation questionnaire included two open-ended questions in which the students were asked to describe the difficulties they encountered in performing spatial manipulations with Scorbot-ER5 in physical and virtual environments.

In the second case study, the spatial perception questionnaire included questions about the spatial difficulties that were described by the students in the first case study. These difficulties regarded the robot manipulation language, performing the tasks with minimum manipulations, and taking the robot's view of the workspace.

The questions asked to evaluate on the 5-point Likert scale (from 1 = no difficulty to 5 = great difficulty), to what degree the students encountered each of the difficulties in Exercise 2.

An additional question referred to student practice in mimicking the way the robot manipulates the virtual cube by rotating the physical cube by hand. We asked to what extent this mimicking helped them reduce the difficulties in planning rotation manipulations. Reliability analysis was carried out on the spatial perception questionnaire. Cronbach's alpha value of the 5-item scale was 0.84.

The laboratory reports handed by the students included the sequence of commands created to perform the robot manipulation assignment and two screenshots showing the robot workspace from two different viewpoints at the end of the manipulation.

An evaluation questionnaire was administered in both case studies and addressed the extent to which the workshop exposed the students to the role of robotics in industrial engineering, raised their interest in industrial robotics, and fostered awareness of the spatial skills required in robot operation. It included three multiple-choice questions in a 5-point Likert scale with 1= no contribution, 2 = low contribution, 3 = medium contribution, 4 = high contribution, and 5 = strong contribution. The students were asked to explain their answers. Cronbach's alpha value of the 3-item scale showed the evaluation questionnaire had an acceptable reliability, $\alpha = 0.77$.

More data from the students' evaluation of the workshop was collected from second-year students who took the Production Systems Engineering course. This course was given for students majoring in manufacturing and service systems engineering and included intensive practice for the programming and operation of modern robots. We conducted a short questionnaire and asked the students to reflect on their participation in our workshop which they took year ago. The students were requested to evaluate the workshop contribution to their decision to major in the production and service systems engineering track, and their understanding of the subjects learned in the production systems engineering course.

4.4 Data Analysis

When answering the first research question, we focused our attention on how the students performed the robot operation tasks, what spatial difficulties they experienced, and whether they realized the necessity of spatial skills for operating robots. We assessed student performance by task reports and records of robot operation. In the reports, we checked if the initial and final positions of the cubes and the presented sequence of commands match the manipulation tasks assigned for Scorbot-ER5 and Baxter. The records served to assess the time it took to plan and perform the rotation of each cube. We summarized the assessment results of all the teams in an assignment sheet. In the sheet, we included the following parameters for each of the three cubes: the indicator of correct performance, the number of rotation manipulations, the degree of task complexity, and the time spent to perform the rotations.

Based on this data, we assessed for each team the performance of the rotation of each cube by a quantitative score calculated as follows:

$$Score = 80 \times \left(\frac{R_{max} - R}{R_{max} - R_{min}}\right) + 20 \times \left(\frac{T_{max} - T}{T_{max} - T_{min}}\right).$$

Here R_{max} is the largest number of rotation manipulations used by the class, R_{min} is the minimal number of rotation manipulations required to perform the cube rotation task. T_{max} and T_{min} are the times it took the slowest and the fastest teams to accomplish the cube rotation task. R is the number of rotation manipulations made by the assessed team, and T is the time it took to perform the rotation. The score values range from 0 to 100, while 100 is achieved for the minimal number of rotation manipulations performed in minimum time. We gave the higher weight (80) to the number of rotation manipulations as the assignment required to minimize it.

We analyzed observed student performance, looking for patterns looked for patterns of student performance in the exploration of robot affordances related to using the visualization techniques and RML codes, and to the strategies to plan manipulations.

We identified specific difficulties noted by the students. This was done by content analysis of the answers to the relevant questions of the workshop evaluation questionnaire. Then, we quantitatively analyzed the data of the spatial perception questionnaire related to the level of the specific difficulties perceived by the students. We calculated the percentage of the students who reported the difficulties and compared the level of difficulties in operating Scorbot-ER5 and Baxter. A Mann-Whitney U test compared the difference in the perception of the difficulties between the male and female students.

We answered the second research question based on the workshop evaluation questionnaire administered in both case studies. Workshop's contributions to the exposure of the students to the role of robotics in industrial engineering and their interest in industrial robotics and spatial awareness were analyzed quantitatively. We calculated the percentage of students who highly evaluated these contributions and compared the evaluations given in the first and second case studies using Mann-Whitney U test and Pearson correlation coefficient. We selected a representative set of explanations given by the students on their evaluations. We used the explanations to support the results of the quantitative analysis.

We analyzed the answers of the second-year students, provided a year after they took the first workshop, with a focus on its contribution to their majoring choice and decision to take the advanced robotics course.

5. Results and Discussion

5.1 Learning Robot Affordances

Concerning the first research question, our findings relate to the students' performance in robot operation assignments and the spatial difficulties they faced.

5.1.1 Student Performance

All the groups of students successfully performed the two workshop exercises, in each of which they rotated three cubes from an initial to a designated orientation. The results of the exercise, performed with Baxter, are presented in Table 1. The first, second, and third columns present the order of the cubes, the level of complexity of the rotation tasks, and the minimum possible number of manipulations needed to execute the rotation, as defined in Section 3.1. The fourth and fifth columns present parameters of students' performance: the average number of manipulations to rotate each cube, and the average time spent to perform the rotation.

The table shows that while the level of complexity of the rotation tasks grew from cube to cube, the parameters of student performance improved. The average task performance time decreased from about 4 minutes for the first cube to about 3 minutes for the second cube, and remained almost the same for the third cube even though its rotation required more manipulations. The average number of manipulations used by the students to rotate the first and second cubes was about the same despite the increased rotation complexity of the second cube. The average number of 2.10 manipulations used to rotate the third cube indicates a considerable improvement, as it is much closer to the minimum number than for the first and second cubes.

Fig. 10 presents distributions of the scores given to the student teams for operating rotations of the cubes. The three histograms show the distribution of the scores for rotating each of the three cubes. The histograms indicate that the task scores of above 70 were achieved by 78% of the teams for the first cube, 50% for the second cube, and 86% for the third cube. This result provides an additional

Table 1. Cube rotation results

Cube	Level of rotation task complexity	Minimal possible number of manipulations	Average number of manipulations	Average time of performance (sec)
First	1	1	1.54	241
Second	2	1	1.52	179
Third	3	2	2.10	182

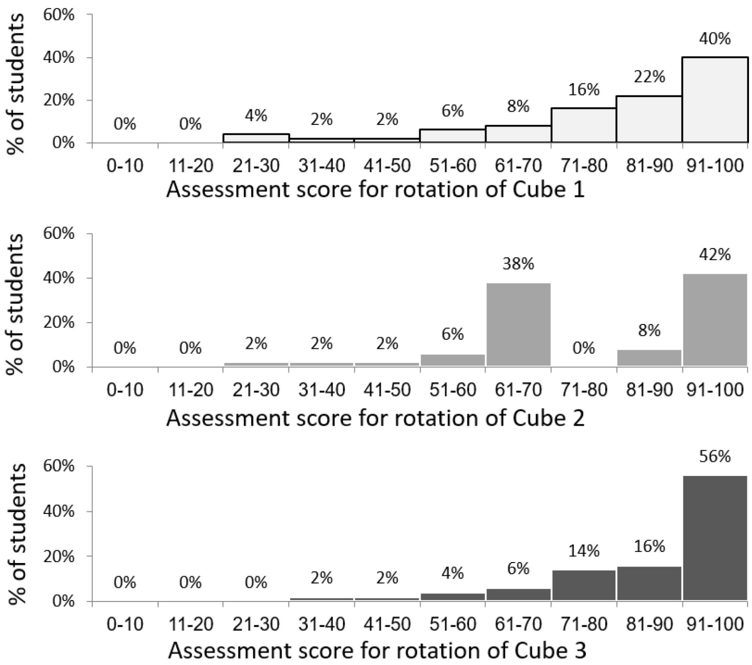

Fig. 10. Distribution of assessment scores for rotations of the three cubes.

indication of the learning progress. The scores for rotation of the second cube turned out to be lower than that of the first one. In our opinion, this is because the second task still had to be done in a single operation, while its complexity level increased from 1 to 2 (see Section 3.1). In the second task, the students learned to design a sequence that included rotations of the cube around the three coordinate axes. The high grades in the third task indicate that the students successfully applied this knowledge to plan even more complex manipulations.

The observations indicated that the students used several visualization techniques: mimicking gripper operations by hand movements, exploring spatial codes by rotating the physical cube in hand, and using the simulator to visualize the workspace from the robot's viewpoint and display the hidden faces of the cube. In the evaluation questionnaire, the students expressed satisfaction with the visualization techniques that helped them to perform the assignment. The absolute majority of the students highly evaluated the contribution of mimicking gripper operations (86%), hand rotating the physical cube (83%), and using the simulator (74%).

The observations helped us determine the strategies that the students used to plan rotation manipulations using the RML codes. One of the revealed strategies was that the students explored the spatial codes from the given list, one by one until they found the manipulation that moves the cube to the required orientation. If the students did not find such a manipulation, then they planned a sequence of two manipulations. In this sequence, the first manipulation brought the desired digit to the upper face of the cube, and the second one rotated the cube around the Z-axis to the required orientation. In another strategy, the students examined the robot affordances to grip the cube. For each affordance, they checked if there is an operation that starts with this grasping and rotates the cube to the required orientation. If the students found such operation, they composed its RML code according to the initial and final gripper orientation. As indicated by the workshop evaluation questionnaire, about half of the student teams followed the first strategy, while another half preferred the second strategy.

5.1.2 Spatial Difficulties

As noted in Section 4.3, in the second case study, we evaluated the difficulties that were identified and categorized in the first case study. The first column of Table 2 presents the four spatial difficulties in performing robot manipulations. The second column shows the percentage of participants in the second study who reported the difficulties.

As indicated, the exercise of rotating the oriented cubes by the robot challenged the students, and most of them faced difficulties performing it. The largest number of students experienced difficulties in finding optimal sequences of rotation manipulations, and the smallest number faced difficulties in perceiving the orientations of digits on the hidden faces of the cube. Our explanation of this result is that finding the optimal sequences of manipulations

Table 2. Students who encountered difficulties in rotation manipulations

Difficulties	Students (%)
Using RML codes to plan robot manipulations	72
Finding optimal sequences of rotation manipulations	78
Planning rotations based on allocentric views of the robot	71
Perceiving the orientations of digits on the hidden faces of the cube	61

requires complex reasoning of robot affordances while perceiving a digit on the hidden face of the cube requires only its mental rotation.

In the spatial perception questionnaire administered in the spring semester 2018, we asked the students to evaluate spatial difficulties in robot operation separately for Scorbot-ER5 and Baxter. The 25 participants of that workshop were part of the 137 students involved in the second case study. The results show that the percentage of students who experienced difficulties in operating Baxter was lower than in operating Scorbot-ER5 for using RML codes (65% vs. 72%), finding optimal rotations (60% vs. 76%), and taking allocentric views (60% vs. 80%). As indicated by the Mann-Whitney U test, these differences were not significant ($p > 0.05$).

The students' written reflections provided in the questionnaire referred to the difference in their experiences with Scorbot-ER5 and Baxter. Repeated reflections on the practice with Scorbot-ER5 were:

> "The Scorbot simulation is more detailed."

> "While working, I had to look from the robot's perspective and see the moves that the robot had to take to carry out the task."

A repeated reflection related to Baxter was:

> "This experimentation required taking the robot's perspective, perceiving its position in the space, understanding the relationship between its arm and the cube, and thinking on how to move the arm to grab, rotate, and place the cube."

Over 90% of the students who had the opportunity to rotate the oriented cube by hand noted that it alleviated their difficulties in planning robot movements using the RML codes. This note took a special meaning when planning the manipulations of Baxter, as illustrated by the following reflection:

> "Baxter's movement is more like a human hand movement. Practice with it contributed more to spatial vision since movements of a human hand can simulate robot movements."

We compared the difficulty scores reported by the male and female students using the Mann-Whitney U test. Interestingly, the test only indicated a significant difference in perceiving the orientations of digits on the hidden faces of the cube. The scores given by male students (M = 2.36, SD = 1.0) were lower than that of female students (M = 3.0, SD = 1.0), $U = 1000.5$, $p < 0.01$.

5.2 Contribution of the Workshop

Concerning the second research question on the workshop's contribution, our findings relate to students' exposure to the role of robotics in industrial engineering, interest in industrial robotics, and spatial awareness. We note that the students in both case studies, with rare exceptions, had not studied robotics previously and had no experience working with robots before the workshop.

The first column of Table 3 presents the three aspects of the workshop's contribution. The other columns summarize the evaluations for each of the aspects provided by the students in the two case studies.

The majority of the students in the first (78%) and second (82%) case studies noted the contribution of the workshop to the exposure of the role of robotics in industrial engineering. However, only 16% in the first case study, versus 46% in the second study, evaluated this contribution as high.

We compared the workshop contribution evaluated by the participants of the two case studies using the Mann-Whitney U test (see Table 4). We found that the scores in the second study, which included practice with Scorbot-ER5 and Baxter, were significantly higher than those in the first study (training with Scorbot-ER5 only).

A Pearson correlation was computed to assess the relationship between the contribution to the appreciation of the role of robotics in IE and the two other contribution aspects. Table 5 shows a cross-tabulation of Pearson's correlations among the three aspects of the contribution. As found, the

Table 3. Students' evaluation of the contribution of the workshop (%)

Aspects of the contribution	Contribution score 3–5		Contribution score 4–5	
	Case study 1	Case study 2	Case study 1	Case study 2
Appreciation of the role of robotics in IE	78	82	16	46
Interest in industrial robotics	54	72	29	47
Awareness of spatial problems	46	85	23	62

Table 4. Descriptive statistics of the workshop contribution in the case studies

Aspects of the contribution	Mean (S.D.)		Mann-Whitney U Test	
	Case study 1	Case study 2	U	$p <$
Appreciation of the role of robotics in IE	2.9 (0.9)	3.3 (0.9)	3518	0.01
Interest in industrial robotics	2.6 (1.3)	3.2 (1.1)	3463	0.01
Awareness of spatial problems	2.4 (1.2)	3.6 (1.0)	2245.5	0.001

Table 5. Pearson's correlations among the aspects of the contribution.

Aspects of the contribution	Appreciation of the role of robotics in IE		Interest in industrial robotics		Awareness of spatial problems	
	Case study 1	Case study 2	Case study 1	Case study 2	Case study 1	Case study 2
Role of robotics in IE			0.45*	0.62**	0.53*	0.39**
Interest in industrial robotics	0.45*	0.62**			0.51*	0.46**
Awareness of spatial problems	0.53*	0.39**	0.51*	0.46**		

Note: *$p < 0.001$ (N = 80); **$p < 0.001$ (N = 118).

correlations among all three factors, in both case studies, were medium to strong with p < 0.001.

The students noted the contribution of the workshop in their reflection given in the evaluation questionnaire. They appreciated the exposure to the role of robotics in industrial engineering in the following words:

> "I have never seen an industrial robot at work, let alone operated one. The workshop contributed a lot to my exposure to, and becoming familiar with, industrial engineering." "The workshop practice made me understand the role of the industrial engineer in optimizing industrial processes."

Regarding the contribution to interest in industrial robotics, they wrote:

> "The workshop contributed to my interest in industrial robotics, as I learned about system thinking and the role and importance of robotics in industrial engineering."
>
> "The workshop taught me how diverse and interesting the field of industrial robotics is."

The repeated reflections on the contribution to spatial awareness were:

> "The practice in operating the robot made me understand the need to take into account spatial considerations and be aware of the whole robot workspace."
>
> "The workshop made me aware of the need to understand the coordinates system in which the robot works."

In their reflections, the students repeatedly appreciated the practice with both Scorbot-ER5 and Baxter:

> "Training with each of the robots has its advantages – when working with Scorbot we must consider its inflexibility. On the other hand, with Baxter, a lot of affordances have to be taken into account to find the operation with the minimum amount of robot manipulations."

The questionnaire, administered to the sophomore students, revealed additional aspects relating to the contribution of the robotics workshop. 75% of the students noted that the experience in the workshop influenced their decision to major in the production and service systems engineering track; above 90% pointed out that the knowledge acquired in the workshop helped them in learning the production systems engineering course. From the reflection of one of the students:

> "The workshop exposed me to the topic of robotics and provided an initial experience in robot operation. When starting to learn the Production Systems Engineering course, I felt I had some background and confidence."

5.3 Implications

Engineering education is increasingly aware of the need and importance of preparing students for a professional life in the current era of the rapid and global digital transformation of industry and society [8, pp. 137–154]. This transformation requires engaging engineering students in learning the new technologies and foster the development of the skills associated with the fourth industrial revolution. In this context, our research proposes and explores how to expose students, majoring in industrial engineering, to the emerging concepts and technologies in the first-year introductory course.

In our past study [22], we implemented a robotics workshop in which students operated conventional robot manipulators, while the assigned tasks promoted the training of spatial skills. In the current research, we significantly reworked the workshop and included practice in operating the modern Baxter robot in addition to practice with a conventional robot. We also developed the Robot Manipulation Language that the students used to plan and execute rotation manipulations with Scorbot-ER5 and Baxter. These innovations enabled to expose the students to the functionality of the modern robot, facilitate practice in operating robots, and prompt the students to practically explore the concepts of robot affordances and spatial awareness.

By integrating the workshop in the introductory engineering course, we introduced the students to industrial robotics and its central role in modern automated manufacturing. Through robot operation activities, we tried to arouse the students' interest in industrial robotics and foster their spatial awareness as a generic ability needed by an engineer.

For the students, the practice with Baxter was the first-time meeting with a modern CPS. The skills of operation of CPSs are of high demand in Industry 4.0, where people interact with robots in a shared space. High-level robot operation has become a critical component of the manufacturing process [41]. Understanding the functionality of robot systems in the workspace underlie the industrial engineer's ability to manage and optimize this process. Therefore, we here emphasize the need to develop skills of perception of robot affordances and spatial awareness in industrial engineering students. The present research is the first, to our knowledge, to examine how first-year IEM students learn through exploration of robot affordances and evaluate the learning impact.

6. Conclusion

In this study, we developed and implemented a workshop that engaged first-year IEM students in the exploration of robot affordances, while the objective was to answer two research questions. The first question related to how the students learned robot affordances. In the answer, we addressed the learning process, students' performance in the robot operation exercises, and the spatial difficulties they faced.

As found, the students learned to perceive affordances through step-by-step practice. In the first exercise with Scorbot-ER5, the learning focused on the direct and inverse kinematics of the mechanical arm. The students explored the affordances of the robot to bring the gripper endpoint to a required position, while the gripper axis remained vertical. In the second exercise, the students explored the affordances of Scorbot-ER5 and Baxter to rotate oriented cubes. The learning of affordances focused on selecting suitable orientations of the gripper axis during picking and placing the cubes. With the Scorbot-ER5, because of its kinematic limitations, the student could only use the vertical (Z) and horizontal (X) directions of the gripper axis and rotate the gripper around its axis. With Baxter, the students could utilize an additional horizontal direction (Y).

Assessment of the student performance results showed that all the groups of students successfully completed the workshop exercises, the absolute majority of them with high scores. The results of the exercise with Baxter indicated that student performance improved from task to task. Even though the last task was the most complex, the students completed it in less average time and, much less excess manipulations.

The evaluation showed that the student experienced spatial difficulties in exploring the affordances of the robots. We identified and categorized four types of such spatial difficulties: using the robot manipulation language, optimization of rotation sequences, taking an allocentric perspective, and perceiving hidden faces of the cube. We found that some visualization techniques helped the students to cope with the difficulties. They included using a physical cube, mimicking gripper operations by hand movements, and changing the observer's viewpoint of the workspace in the simulator. We also found that the students overcame the difficulties in finding optimal rotation sequences by examining all the available actions one by one or by "breaking" the task into several easier tasks.

To answer the second research question, in the evaluation of the workshop, we focused on its contribution to students' spatial awareness, exposure to the role of robotics in industrial engineering, and their interest in industrial robotics. Our study showed that most of the students in both case studies appreciated the contribution of the workshop to all three above mentioned aspects. We also note that student evaluation of the workshop contribution in the second study was significantly higher than in the first one. The students particularly appreciated the combination of learning practice with both conventional and modern robots. They noted that the training with Scorbot-ER5 effectively introduced them to the principles of industrial robot operation. At the same time, the learning experience with Baxter exposed them to the new spatial capabilities of modern robots.

Some of the students evaluated the contribution of the workshop from a general perspective. They noted that the workshop was the only experience of this kind in the course, and the practice in planning and optimization of production processes was very relevant for their future profession. Reflections of sophomore students who reported that the workshop influenced them to choose to major in manufacturing and service systems engineering, provide an additional indication of its contribution.

We believe that the skills of exploring the functionality of robots and designing appropriate affordances for the operation of engineering systems are necessary for industrial engineers. Our study demonstrated that these skills can be developed in IE students starting from the first year of studies. The results of the study encourage us to continue to research and engage students in the inquiry of affordances of cyber-physical systems offered by the new technologies associated with the fourth industrial revolution.

Acknowledgement – This study was supported by the Israel Science Foundation grant.

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