Robot manipulations and development of spatial imagery

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Abstract — This paper considers spatial learning in an environment where manipulations of objects are carried out by robot operations. Handiwork is replaced by handling a manipulator by means of computer commands. The proposed robotics curriculum focuses on spatial learning through practice in kinematics of spatial mechanisms, and designing and programming robot manipulations. The curriculum refers to three aspects of studying robot manipulations: robot kinematics and "point-to-point" motion, rotation of objects and robotic assembly of puzzles. It provides the learners with diverse learning activities in spatial perception, mental rotation and visualization. The learning activities are strongly supported by the RoboCell environment for educational robotics. The curriculum has been implemented at school and tertiary levels. Our teaching experience supports the conclusion that the proposed curriculum can provide improvement in performing spatial tasks. Pre-course and post-course tests indicated significant students’ progress in the tasks related to the categories of spatial ability which were practiced in the course.

Index Terms — Puzzles, RoboCell, robot manipulations, spatial learning.

INTRODUCTION

Learning practice in physical and virtual environments commonly depends on visual information and relies on the abilities of spatial perception, reasoning, and visualization. Cognitive scientists believe that spatial skills can be developed through experience and exercises [2]. In many educational studies of spatial instruction, including [4-5], students dealt with graphic representations and paper-and-pencil tests. Less attention was paid to spatial learning through physical world practice, especially when physical operations were aided by tools. The literature on this subject [9] points out that both imagery functions help people to anticipate the displacement of objects that results from tool use, and that people's actions can facilitate their imagery.

This paper considers a learning environment where all manipulations of spatial objects are performed by operating a robot system. Students must consciously apply spatial reasoning and problem solving skills in order to adjust the movements of the robot-manipulator to the desired tasks. We propose a curriculum which focuses on solving spatial puzzles by means of a robot, and offers spatial learning through constructionistic practice [13, 14] in real and virtual manipulating of robot movements. Application of the instructional robot-manipulator and spatial puzzles is based on the methodology of constructionism and extends the ideas of Papert [ ] from practice with flat "Turtle" movements towards experimenting in kinematics of spatial mechanisms and manipulations with 3D objects. A new direction in exercising with puzzles is achieved when the tasks are reformulated as practical problems of a robot-handling design [17,18]. Such tasks encourage the student to find solutions which can be performed by the robot, and design appropriate manipulation procedures.

SPATIAL REASONING OF MANIPULATIONS IN ROBOCELL

Experiential learning in the course is supported by RoboCell which is a technologically rich environment for designing various computer-aided manufacturing systems and processes [9]. Components of the RoboCell include the following:

- Robot-manipulators, and computer-controlled milling and welding machines.
- Conveyor belts, sensors, storage and other peripheral devices controlled by machine controllers.
- Work tables, parts and other functional objects for handling production processes in the RoboCell.
- Software for robot and machine programming and operation.
- Software for the design of simulated learning environments and 3D animation of automatic control processes.

An instructional robot manipulator Scobot is a central component of the RoboCell. A mechanical arm of the Scobot has five degrees of freedom: rotation of the base, the shoulder and the elbow, as well as pitch and roll of the gripper. Programming robot movements is based on point-to-point control, when the basic commands are to move the mechanical arm from a present position to the next one and open/close the gripper. The route between the two positions may be chosen as
linear, circular, or defined by default. Thus, in order to arrange a robot manipulation, the learner has to design the trajectory of the robot motion, to assign a sequence of intermediate positions (points) and to program point-to-point translations.

Robot manipulation design also includes the subtask of rotating objects. The mechanical arm is primitive in comparison with the human hand. Therefore, rotating an object by the robot requires the operator to design the manipulation as a multi-step sequence of primitive mechanical arm movements.

The designer of a robot operation, aiming at performing an assembly task, needs to solve spatial problems which for human hand actions are accomplished at the subconscious level. The pick-and-place operation for each part has to be designed in a way that is executable by the mechanical arm, without disturbing the stability of the entire set-up. The designer must also create a special technological system (workcell) which integrates the robot with part feeders, conveyors, sensors and other machines, in order to provide automatic supply, transportation, and handling of parts in the production process. Designing a robot workcell includes determining the spatial locations of the various devices in the workspace and their interaction throughout the production process.

Observing activities in manipulating robot movements mentioned above has led to the conclusion that they are, in essence, activities in spatial reasoning, and therefore can be used for developing spatial skills. This has motivated the design of a curriculum which focuses on spatial learning through manipulating robot movements. The learning strategy realized in the curriculum refers to four aspects of studying robot manipulations: robot kinematics and "point-to-point" motion, rotation of objects, robotic assembly, and design of workcells.

MECHANICAL ARM KINEMATICS

The basic spatial task of point-to-point motion control is to perceive various positions of the mechanical arm and to describe them analytically by means of coordinates. The students start by studying the structure of the mechanical arm, the stepper motor, and driving rotations in joints. Then, the three-dimensional system of Cartesian coordinates is introduced. The students practice determining coordinates of various points in the robot's workspace and depict points given by coordinates. Our teaching experience in schools shows that students properly grasp the concept of 3D coordinates through the robotics curriculum, although it often precedes the study of this concept in the mathematics course.

The next step is for students to study the basics of kinematics of mechanisms. The concepts of kinematic pairs, degrees of freedom, crank and articulated mechanisms are considered. The students also practice analysis and synthesis of mechanical linkages, and define their positions by multidimensional coordinates. The students then learn robot control commands for defining the mechanical arm positions via coordinates, and practice programming pick-and-place manipulations with block parts in simulated and real environments. A sheet of squared paper, covered by transparent perspex and fixed on the workplane, serves for physical measuring of XY coordinates. Some of the learning exercises are reformulated from spatial IQ tests [21] concerning identification, incidence, and adjacency of puzzle pieces, and other spatial tasks. The students are asked to assemble puzzles presented in the test pictures by means of robot operations.

ROTATION OF OBJECTS

Students begin this part of the curriculum by studying rotations of an object around coordinate axes and their combinations. Then they perform the rotation of objects using the robotic arm. We found that many students of different ages have difficulties in the kind of spatial reasoning required for performing this assignment. Therefore, we developed a tutoring package to help students plan object rotations. Rotating the object through pick-and-place manipulation depends only on the orientation of the gripper in the initial and final positions and not on the object's shape. Hence, rotating objects by the robot is practiced on a simple object such as an oriented block. A block with an arrow drawn on one of its sides was used throughout the study of rotations as a test object - an "object-to-think-with".

The first stage of the study focuses on rotations of the oriented block around the coordinate axes by angles (multiples of 90°) and their combinations. The students learn to describe a rotation around an axis analytically in the form $R^N_M$. Here $M$ is one of the coordinate axes (X, Y, or Z) and N indicates a rotation angle, $N = 90°$, $N$ is positive for a counterclockwise rotation and negative in the opposite case. These descriptions are used by the students to perform two spatial tasks: to find a final position of the oriented block after a given combination of rotations, and to find a combination of rotations which transforms a block from a given initial to a given final position.

At the second stage the students study rotations of the oriented block by the robot. Every rotation of the oriented block is considered as a single pick-and-place operation and described by means of a triple-index code. The first index points out the initial direction of the gripper axis when grasping the object, the second index determines the final direction of the gripper axis when placing the object, and the third index defines the angle of rotating the gripper around its axis during the manipulation. Thus, the code ‘XZI’ denotes grasping the block with the gripper oriented in the X-axis direction, moving the
block up, turning the gripper to the vertical (Z) position and counterclockwise rotating it through angle \(\theta = 90^\circ\), and placing the block on the table.

It can be shown that some of the block’s rotations cannot be performed by one pick-and-place operation, but need a sequence of two operations over a number of different routes [8]. We have developed a software package for practical learning of rotation operations by means of a robot.

The first learning task requires finding a sequence of pick-and-place operations, transferring the oriented block from the initial to the given final position. To carry out this task, the student chooses the function ‘robot planning’ from the menu. At the beginning, all 24 possible positions of the oriented block are displayed on the screen. The student selects the initial and final positions. The program presents all the possible robot operations for executing the task, showing the positions of the block and gripper as well as the codes of the operations. The learner examines all the routes and finds the optimal one for the task. When the planning is completed, the learner turns to the second task – programming the operation. This includes defining by a control language a sequence of intermediate positions of the mechanical arm, and a sequence of commands for moving the arm from one position to another. Using the package, the learner verifies the program in the graphic simulation mode and then runs it, so that the task is carried out by the robot.

From our experience, the codes help students to formulate and examine their mental operations, while the oriented block helps them visualize their solutions. This approach also provides an effective way of studying the subject by students with a limited mathematical and technical background. After practicing rotations of the oriented block, the study is continued with more advanced objects. Learners apply RoboCell to practice rotation of blocks with drawings on their faces, and complex 3D shapes. The learners make objects and their 3D models and perform rotations in real and simulated RoboCell environments. Figure 1 shows a fragment of the rotation manipulation of a block performed in the simulation mode. A cylindrical pallet in the figure is used for pick-and-place operations when the gripper axis is oriented horizontally.

**ROBOTIC ASSEMBLY AND DESIGN OF WORKCELLS**

Soma puzzles are assembled from parts, each consisting of identical block elements joined at the sides. This set of parts is highly suitable for assembling by a mechanical arm and allows students a wide spectrum of problem solving activities. A Soma puzzle assignment in the course is to assemble a given setup from Soma parts by the robot. In the first stage of performing the assignment the learner examines the possibilities of assembling the setup. He/she examines various groups of parts in their different orientations in order to find dispositions that compose the setup (if they exist). Then, for each of the dispositions, the learner checks if it can be assembled by the robot. After determining the group of parts and their dispositions in the setup, the learner performs the second stage of the assignment. This includes programming robot operations to pick the parts from their initial positions and place them in the setup, and running the assembly manipulation.

In the last section of the curriculum the learners design computer aided manufacturing processes, using a robot in combination with other components of the RoboCell environment. The assignment is to design a system (workcell) which receives, transports and sorts parts, and arranges them in sets on assembly pallets. At the first step of designing a workcell the learner selects the RoboCell components to be involved in the manufacturing process and defines their spatial locations. Then he/she specifies operations to be carried out by each of the RoboCell components and schedules them in a complete production plan. At the last step the learner programs operations of the RoboCell components and runs the automated manufacturing process. A workcell plan is presented in Figure 2. It was developed for the assignment in which two types of parts, namely red and green cubes initially stored in two feeders were to be finally set up on two black pallets. Locations of the feeders and pallets on the work table were given.

By measuring the distances between the feeders and the pallets and dimensions of the mechanical arm the learner ascertained that there was no room on the table to fix the arm base from which it could reach the feeders and the pallets. To solve this problem, the learner put the mechanical arm on a slide-base with its movements along the slide-base controlled by a computer. In addition, a conveyor was used in order to save robot operation time. The manipulation was designed as follows. First, the robot moved to the feeder area, took the parts from the feeders and put them on the conveyor belt. Then, at the same time, the robot moved along the slide-base and the parts were transported to the pallet area. Two special sensors attached to the conveyor detected the arrival of the red and green cubes to their destination where the robot picked up the cubes and placed them on the pallet. The workcell was designed and tested in the simulation mode using the RoboCell software and then set up physically.

**LEARNING OUTCOMES**

Pilot teaching, based on proposed learning materials, included lectures and workshops for different groups of learners: junior high and senior high school students, pre-service and in-service teachers, undergraduate students and aircraft
technicians. High school and college student projects were guided. Below we will consider cases in which students' progress was measured by pre-course and post-course spatial tests.

**ORT Akko Middle School**

A 12-hours course “Principles of Robot Spatial Motion” was delivered to seventh grade students. The learning population consisted 40 female and 21 male students (N=61) divided into four groups. The mechanical arm kinematics section of the curriculum was studied. The learning practice included defining spatial positions of a 3D object (cube) and the robot (Scorbot) by means of coordinates, and programming robot pick-and-place manipulations.

Pre and post spatial tests comprised 12 paper-and-pencil tasks. Five tasks related to perception of a block structure, other five tasks required mental rotations, there were also two visualization tasks. Test results indicated some improvements in performing spatial tasks. The average score (percent of correct answers) rose from 46.5% in the pre-course test to 62.4% in the post-course test. Data analysis indicated significant improvement in the perception and visualization tasks, in which the percent of correct answers rose from 39.8% to 65.3% and from 35.7% to 62.2% (in both cases P_{value}<0.001). Improvement in the percent of correct answers for the mental rotation tasks from 53.1% to 61.2% was found not significant with P_{value}=0.0603. A possible reason for lower performance in mental rotations was that they were not directly addressed in the course.

**Yafia Nazareth Arab Middle School**

A fourteen-hours course was given to 67 eighth graders divided into two groups. It included the study of mechanical arm kinematics similar to that in the ORT Akko course. In addition, the students theoretically learned rotations of an object (cube) around coordinate axes. They observed demonstrations of rotation operations by the robot but did not practice them. Pre and post spatial tests were the same as in the ORT Akko course. As found, the average test score rose significantly from 54.6% in the pre-course test to 66.9% in the post-course test (P_{value}<0.01). The major improvement from 39.7% to 66.7% was achieved in the perception tasks, less significant improvement from 61.1% to 71.1% in the rotation tasks (P_{value}=0.052). Progress in the visualization tasks from 52.4% to 59.9% (not significant) was small probably because students learned in large groups and had limited access to individual practice with the robot.

**Raanana High School**

A 22-hours robotics course was taught in the tenth grade as one of the optional subjects (N=31). The course concentrated on problem solving and hands-on practice in analysis and building mechanisms, and programming their spatial movements using our courseware and the RoboCell. The progress in spatial learning was measured by means of pre-course and post-course tests. Each of the tests included six problems; each problem consisted of a number of similar tasks to be solved in given time limits. The two first problems related mainly to spatial perception, problems 3 and 4 referred to mental rotations, and the last two problems concerned assessed visualization skills. The tests indicated significant progress of the students in performing the tasks. The average test score rose from 61.7% in the pre-course test to 72.2% in the post-course test. Advance in the perception problems was from 76.7% to 86.6%, in the rotation operations from 63.0% to 69.8%, and in the visualization problems from 29.0 to 48.2% (in the three cases P_{value}<0.03). Personal results of the students are presented in the diagram (Figure 3).

Each square mark in the diagram presents test results of one of the students so that its X and Y coordinates are his/her pre-course test and post-course test scores. As shown by the diagram, most of the square marks are located above the dotted diagonal. It means that the majority of students performed on the post-test better than the pre-test. Seven students did not improve their results, with three post-test scores lower than in the pretest. All the marks are to the right of the vertical dotted line and above the horizontal line. This indicates that the lowest score of the students rose from 35.3% to 52.7%. To summarize, our experience of teaching the subject in the three schools indicated noticeable improvements in performing spatial tasks.

Besides implementation in schools, the robotics curriculum was included in the courses 'Teaching Methods for Design and Manufacturing' and 'Technological Aspects of Teaching Science and Technology in Junior High Schools', delivered by the author as part of the teacher training program in the Department of Education in Technology and Science at the Technion.

**CONCLUSIONS**

This paper considers spatial learning in an environment where manipulations of objects are carried out by robot operations. The robot serves a physical tool, or an interface between the human hand and the object. The proposed robotics curriculum focuses on spatial learning through practice in kinematics of spatial mechanisms, and designing and programming robot manipulations. The curriculum refers to three aspects of studying robot manipulations: robot kinematics and "point-to-point" motion, rotation of objects and robotic assembly of puzzles. It combines various instructional methods, such as
interactive demonstrations, models and codes, simulated environments, and robot operations. This provides the learners with diverse learning activities in spatial perception, mental rotation and visualization. The learning activities are strongly supported by the RoboCell environment for educational robotics. Our teaching experience supports the conclusion that the proposed curriculum can provide improvement in performing spatial tasks. Pilot courses were delivered in two middle schools and a high school; progress in spatial learning was measured by pre-course and post-course tests. The tests indicated significant students' progress in the tasks related to the categories of spatial ability which were practiced in the course.

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REFERENCES


FIGURES AND TABLES

FIGURE 1

Rotation of a block in the simulation mode
FIGURE 2
A WORKCELL DESIGNED USING ROBOCELL

FIGURE 3
PERSONAL RESULTS IN THE TESTS