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Positioning Issues in the Study of Robotic Manipulations*

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A new approach to studying robot manipulations in the workplace is proposed. New instructional principles for modelling the positioning of parts in the robot pick-and-place operations are established. An algorithm of automatic assembly of block-structured bodies by the robot is developed and run on various groups of students.

INTRODUCTION

PRESENT research on instructional robotics deal mostly with robot-manipulator kinematics [1] and its graphic simulations by computer [2]. Existing teaching aids focus mainly on robotic construction, and little attention is paid to robotic manipulations planning [3].

At the same time technological progress requires thorough knowledge and skills in robot manipulating, based on spatial mechanism analysis [4]. So there is a need for new pedagogical approaches based on active interaction with robots, and practical usage. These approaches can be realized by the educational robotic systems based on the new generation of educational robots [5, 6].

Thus robot manipulations in workspace have become an important part of robotics study, especially for students who do not major in this subject.

Even a modern robot cannot define manipulations with the aim of solving a given task automatically, if the task is formulated in an unstructured environment [7]. So the planning of manipulations is carried out by the operator. This activity includes the definition of positions and orientations of the robot and requires a high level of spatial comprehension.

In this paper a new approach is proposed for studying robot manipulations. A two-fingered, five degrees of freedom robot-manipulator is used (Fig. 1). A method of the robot manipulation planning is developed for changing orientations of objects in block-structured environments. This method allows, in a formal manner, the description of orientations and their transformations by the robot regarding objects which are simple blocks, block compositions and their assemblies.

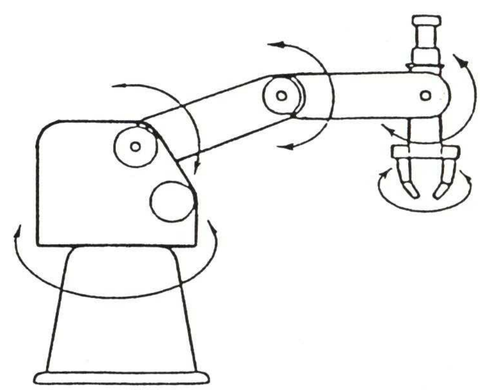

Fig. 1. The SCORBOT-5 instructional robot.

When studying assembling manipulations, we take into account the task of automatic assembly of a Soma cube puzzle [8], which might be an interesting challenge for students. We have carried out this task using the robot, but our algorithms of assembly planning [9] and assembly sequences (described in this paper) are valid also for a variety of objects in block-structured environments.

The design of pick-and-place of a part by a robot is based on the solution of the following problem. Given the initial position and final destination of the part and positions of its grasp, it is required to determine the sequence of robotic manipulations to move the part from its initial location to the final destination.

This problem is solved by determining the intermediate robot positions and the sequence of commands in order to move the part from the current position to the next one.

We will note one important feature of pick-and-place operation by a robot. While grasping the part, it is fixed in the robot's gripper. So when moving the

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part it changes its position in space, but relative to the gripper it remains in a fixed position. Therefore, if the part's orientation with relation to the gripper, in the initial and final destinations, is the same, then the part can be moved to the final destination by means of moving along an appropriate trajectory without re-grasp. But if these orientations have to be different, then additional robotic manipulations are necessary to provide the new orientation relative to gripper.

The problem of assembling a set-up or a structure from parts, leads to repeated pick-and-place operations executed by the robot. The particular feature of these operations is that they must satisfy the restrictions raised by the other parts orientations and relative positions of the assembly.

INSTRUCTIONAL ASPECTS OF PICK-AND-PLACE MANIPULATIONS

To study pick-and-place manipulations by robot, we will refer to three aspects:

(1) translation of parts along trajectories;
(2) rotation of parts;
(3) robotic assembly.

Students may learn these core operations of the robot mainly through interactive demonstrations (using the robot), practical work with instructional programs of graphic simulation and, consequently, programming of robotic manipulations.

The first section (1) does not differ principally from the corresponding section of any common introductory robotic course [2]. The main didactic objective in this section is to learn the kinematic scheme and related robot commands. The instructional program and the graphic simulation program of the SCORBOT software [5, 6] are used. Simple robotic manipulations using four basic commands could be:

MOVE	⟨POSITION⟩
OPEN	⟨GRIPPER⟩
CLOSE	⟨GRIPPER⟩
DELAY	⟨TIME⟩

THE ROTATION ISSUE

In the common introductory robotic course, there is not enough attention paid to objects rotation study. We consider it necessary to treat this issue in any instructional program, since rotation is integrated in manipulation operations, and orienting objects in space gives a good spatial comprehension training for students. Therefore, an analytic description of rotation is needed.

We will take a cube with an arrow on one of its sides (Fig. 2) as the simplest oriented object. Four different directions of the arrow on each of the six cube sides define all 24 orientations of the cube. It can move from one orientation to another by rotation of the cube around its symmetry axes.

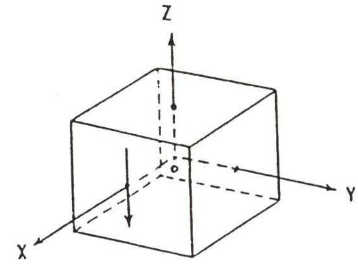


Fig. 2. A cube oriented by an arrow.

To get an analytic description of rotations, we will introduce the coordinate system as shown in Fig. 2, where the distance between the origin and each of the cube sides is one.

The arrow position is described by coordinates of its origin $(\mathbf{x}_1, \mathbf{y}_1, \mathbf{z}_1)$ and end $(\mathbf{x}_2, \mathbf{y}_2, \mathbf{z}_2)$ points

$$\mathbf{S} = \begin{bmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \end{bmatrix}$$

For example, for the arrow shown in Fig. 2

$$\mathbf{S} = \begin{bmatrix} 1 & 0 & 1 \\ 1 & 0 & -1 \end{bmatrix}$$

As known, multiplication of a matrix such as **S** by the matrices

$$\mathbf{T}_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & -1 & 0 \end{bmatrix}, \quad \mathbf{T}_y = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ -1 & 0 & 0 \end{bmatrix}, \quad \mathbf{T}_z = \begin{bmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

corresponds to the rotation (counter-clockwise) of the cube around **X**-, **Y**-, **Z**-axes by 90°. Any combination of rotations corresponds to multiplication of **S** by a product of the matrices.

Actually the same result of a rotation around any axis can be obtained by a certain combination of rotations around the other axes. For example, it is easy to check that

$$\mathbf{T}_x = \mathbf{T}_z \times \mathbf{T}_y \times \mathbf{T}_z^{-1}, \qquad \mathbf{S} \times \mathbf{T}_x = \begin{bmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

This is illustrated in Fig. 3.

CUBE ROTATION POSSIBILITIES BY ROBOT

We will now consider the issue of the cube rotation by the robot, regarding every rotation as a single pick-and-place operation. We describe all possible rotations of the cube by the robot without re-grasp by means of a three-symbol code. The first symbol points out the initial direction of the gripper axis and assumes the values **Z**, **X** or **Y**. Since our robot is unable (for technical reasons, see Fig. 1) to place the gripper axis in parallel to *Y*, we will use **Y** as the first symbol for those cases where the normal to the gripper plane (see Fig. 4) is parallel to **Y**-axis.

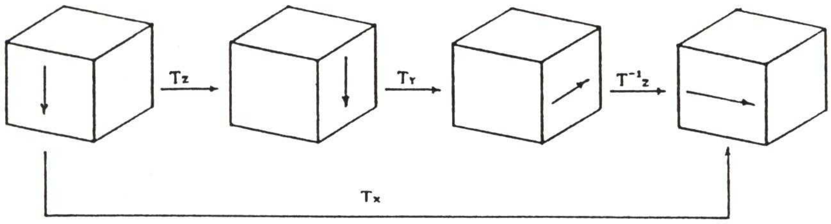


Fig. 3. Different rotations leading to the same result.

In this state the gripper axis remains in a vertical direction. The second symbol shows the new axis position of the gripper. Therefore, only Z or X directions are possible. The third symbol M defines the cube rotation angle M = 0, 1, 2, − (minus) corresponding to the rotation of the gripper counter-clockwise by the angle M × 90°.

Thus the code ZZ1 means the grasp from above and rotation around Z-axis by 90° counter-clockwise. This manipulation provides the rotation shown in Fig. 4a. The code ZX0 means the grasp from above, turning the gripper to the position in which its axis is parallel to X-axis, and no more rotation (see Fig. 4b).

The code XZ- means the grasp in the direction of X-axis, then turning the gripper to the vertical position and clockwise rotation by 90° (Fig. 4c). The code XX2 describes a half-roll of the cube around X-axis (Fig. 4d). The code YX1 marks the grasp from above as indicated in Fig. 4e, turning

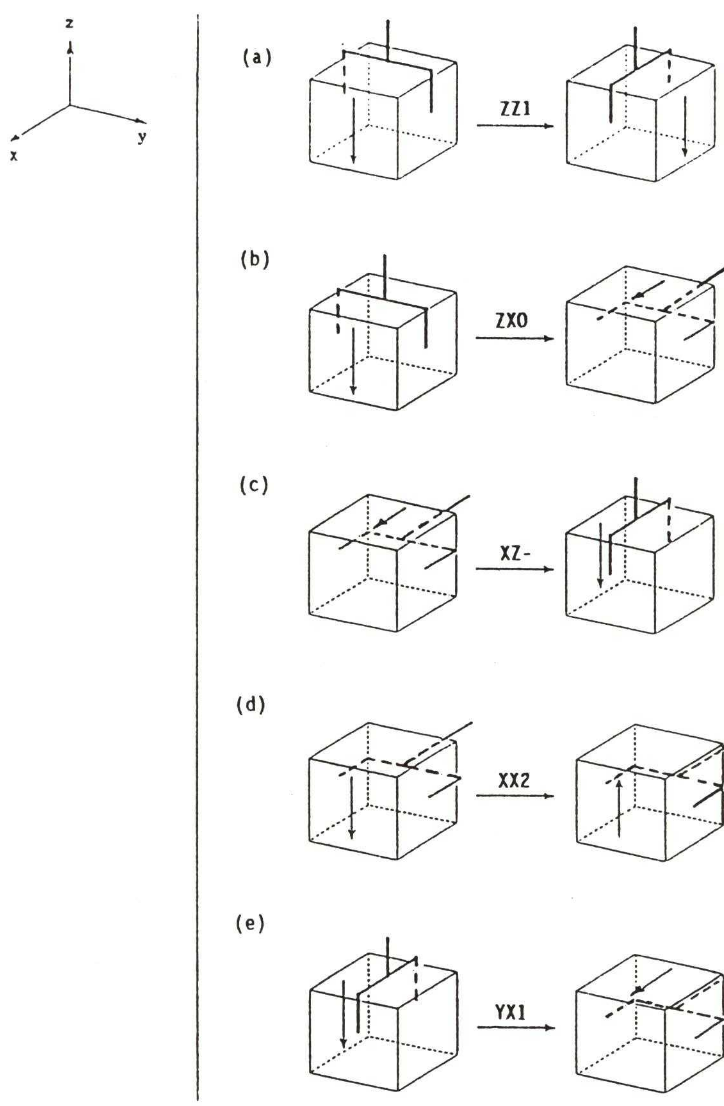


Fig. 4. Possible one-step rotations by the robot and their codes.

the gripper to the horizontal position in X-axis direction and 90° counter-clockwise rotation.

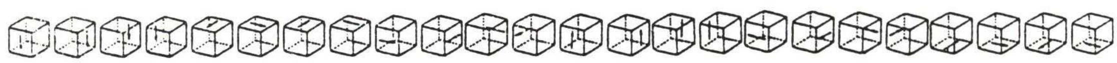
The cube rotation codes for all initial and final orientations are shown in Table 1. The list of all initial orientations is in the left vertical column of the table and final orientations are in upper line. The codes of the operation are at the crossroads. The code is 0 if rotation is impossible in one step (without re-grasp). The code is I if the initial and the final positions coincide.

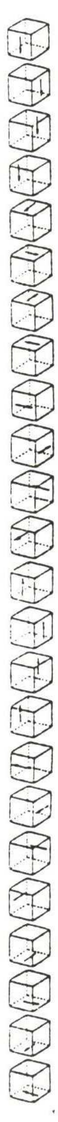
As follows from Table 1, twelve final orientations are in the one-step reach from every initial orientation. However, all 24 final orientations can be obtained by two steps, each of them through several alternative ways. For example, according to Table 1 the rotation from position 1 to position 17 without re-grasp is impossible, whereas with one re-grasp it is possible in several ways:

1 → 4 → 17 (ZZ–, XZ1);
1 → 18 → 17 (YX1, ZZ–);
1 → 21 → 17 (XZ0, YX1);
1 → 22 → 17 (XZ–, XZ2);
1 → 23 → 17 (XZ2, YX–);
1 → 24 → 17 (XZ1, ZX0);

Among the different routes, we can choose the optimal one concerning either the time and precision of the manipulation, or the restrictions of the robot's movements. For example, grasping in horizontal position is undesirable for manipulation time and precision reasons. So route 1 → 18 → 17 (YX1, ZZ–) is optimal.

Table 1. The cube rotation codes for all initial and final orientations





	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	I	ZZ1	ZZ2	ZZ-	ZX0	0	0	0	0	0	0	YX	XX2	0	0	0	0	YX1	0	0	XZ0	XZ-	XZ2	XZ1
2	ZZ-	I	ZZ1	ZZ2	YX-	0	0	0	XZ-	XZ0	XZ1	XZ2	0	0	0	XX2	0	ZX0	0	0	0	0	YX1	0
3	ZZ2	ZZ-	I	ZZ1	XZ2	X2-	XZ0	XZ1	0	0	0	YX1	0	0	XX2	0	0	ZY2	0	0	0	0	ZX0	0
4	ZZ1	ZZ	ZZ-	I	YX1	0	0	0	0	0	0	ZX0	0	XX2	0	0	XZ1	XZ2	XZ-	XZ0	0	0	YX-	0
5	XZ0	XZ1	XZ2	XZ-	I	ZZ1	ZZ2	ZZ-	0	0	YX-	XZ-	0	0	YX-	0	0	0	ZX0	0	0	0	0	0
6	0	0	YX1	0	ZZ-	I	ZZ1	ZZ2	XZ0	XZ1	XZ2	XZ-	0	0	YX-	0	0	0	ZX0	0	0	0	0	XX2
7	0	0	ZX0	0	ZZ2	ZZ-	I	ZZ1	0	0	YX1	0	XZ0	XZ1	XZ2	XZ-	0	0	YX-	0	XX2	0	0	0
8	0	0	YX-	0	ZZ1	ZZ2	ZZ-	I	0	0	ZX0	0	0	0	YX1	0	XZ0	XZ1	XZ2	XZ-	0	XX2	0	0
9	0	YX1	0	0	0	ZX0	0	0	I	ZZ1	ZZ2	ZZ-	0	0	0	YX-	XX2	0	0	0	XZ1	XZ0	XZ-	XZ2
10	0	ZX0	0	0	0	YX-	0	0	ZZ-	I	ZZ1	ZZ2	XZ-	XZ0	XZ1	XZ2	0	0	0	XX2	0	0	0	YX1
11	0	YX-	0	0	XZ1	XZ2	XZ-	XZ0	ZZ2	ZZ-	I	ZZ1	0	0	0	YX-	0	0	XX2	0	0	0	0	ZX0
12	XZ1	XZ2	XZ-	XZ0	0	YX1	0	0	ZZ1	ZZ2	ZZ-	I	0	0	0	ZX0	0	XX2	0	0	0	0	0	YX-
13	XX2	0	0	0	0	0	ZX0	0	0	YX1	0	0	I	ZZ1	ZZ2	ZZ-	0	0	0	YX-	XZ2	XZ1	ZX0	XZ-
14	0	0	0	XX2	0	0	YX-	0	0	ZX0	0	0	ZZ-	I	ZZ1	ZZ2	XZ-	XZ0	XZ1	XZ2	YX1	0	0	0
15	0	0	XX2	0	XZ0	XZ1	XZ2	XZ-	0	YX-	0	0	ZZ2	ZZ-	I	ZZ1	0	0	0	YX1	ZX0	0	0	0
16	0	XX2	0	0	0	0	YX1	0	XZ1	XZ2	XZ-	XZ0	ZZ1	ZZ2	ZZ-	I	0	0	0	XZ0	YX-	0	0	0
17	0	0	0	YX-	0	0	0	ZX0	XX2	0	0	0	0	YX1	0	0	I	ZZ1	ZZ2	ZZ-	XZ-	XZ2	XZ1	XZ0
18	XZ-	XZ0	XZ1	XZ2	0	0	0	YX-	0	0	0	XX2	0	ZX0	0	0	ZZ-	I	ZZ1	ZZ2	0	YX1	0	0
19	0	0	0	YX1	XZ-	XZ0	XZ1	XZ2	0	0	XX2	0	0	ZY2	0	0	ZZ2	ZZ-	I	ZZ1	0	ZX0	0	0
20	0	0	0	ZX0	0	0	0	ZY1	0	XX2	0	0	XZ1	XZ2	XZ-	XZ0	ZZ1	ZZ2	ZZ-	I	0	ZY2	0	0
21	ZX0	0	0	0	0	0	XX2	0	YX-	0	0	0	XZ2	XZ-	XZ0	XZ1	ZY1	0	0	0	I	ZZ-	ZZ2	ZZ1
22	YX1	0	0	0	0	0	0	XX2	ZX0	0	0	0	YX-	0	0	0	XZ2	XZ-	XZ0	XZ1	ZZ1	I	ZZ-	ZZ2
23	XZ2	XZ-	XZ0	XZ1	XX2	0	0	0	YX1	0	0	0	ZX0	0	0	0	YX-	0	0	0	ZZ2	ZZ1	I	ZZ-
24	YX-	0	0	0	0	XX2	0	0	XZ2	0	XZ0	XZ1	YX1	0	0	0	ZX0	O	0	0	ZZ-	ZZ2	ZZ1	I

Thus, Table 1 proposed here, allows one to determine the sequence of robot manipulations for any change of the cube orientation.

This table can also be used to change the orientation of any object consisting of cubic units. For this purpose it is sufficient to mark one side of any cubic unit by an arrow. Then the arrow position describes the whole object's orientation, and the sequence of robotic manipulations, defined through Table 1, is valid for the object. What is needed is merely to point out grasp positions and to provide stable locations of the object.

The study of this section starts from interactive demonstrations, i.e., with student involvement, of different rotations by robot. The instructional program is developed for study rotations and their codes. The student chooses initial and final orientations of the cube using a graphic menu and gets all possible routes of motion including intermediate orientations, grasp positions and codes. He chooses the rational route based on this information. Then the student programs various rotations of parts by robotic language using the instructional program for robot movements simulation.

THE SOMA-CUBE PUZZLE ASSEMBLY

The section devoted to automatic assembly reviews the study of object pick-and-place by robot. We chose the 3-dimensional Soma cube puzzle [8] as an object of robotic assembly. Developed algorithms are suitable for geometrical objects, consisting of elementary identical cubes or parallelepiped elements, joined by sides. This set of objects leads to simple mathematical models and to effective methods of robot trajectory calculations. On the other hand, it also raises a wide spectrum of problem-solving activities for students.

The Soma cube puzzle is a $3 \times 3 \times 3$ cube (Fig. 5a) dissected into six parts composed of 4 units and one piece of 3 units. They are shown in Fig. 5b. Several bodies assembled from these parts are depicted in Fig. 5c.

It is known [9] that automatic assembly of a body by a robotic system, requires the solution of two main problems:

(1) assembly planning—to check the feasibility of assembling, to select parts and define their positions;
(2) assembly sequences—to define an assembly order and to produce a corresponding sequence of robotic manipulations.

The algorithm of assembly planning by Soma parts, is described in [10]. Here we will discuss some issues concerning Soma cube assembly sequences.

ASSEMBLY ORDER OF SOMA PARTS

The problem of assembly order of Soma parts is formulated as follows: an assembly plan is given, so all the parts and their initial locations in the assembly are specified. It should be checked first if the assembling is executable by the proposed plan and if so, then find an appropriate sequence of parts packing.

The robot gripper in its horizontal position is directed radially and cannot maintain parallel orientations of parts. So we assume that the robot places the parts through top-to-bottom movements. Thus we come to the 'from top-to-bottom' principle of assembling, discussed below.

We numerate the parts and introduce the 'relation of order' of their assembling. We will say that part **i** is on top of part **j**, if there is a cubic unit of part **i** above any unit of part **j**. This relation of order can be represented by a directed graph. The parts are designated by the graph vertices of the same numeration. The direction of edge is (**i**, **j**), that is, from the vertex **i** to **j**, if part **i** is situated above part **j**. Consideration of examples (Fig. 6) shows that for some constructions the graph is cyclic. Note, that if element **i** is on top of element **j**, then **i** can be placed by robot only after **j**. So the loop means, that during assembly, the placing operation of part **i** precedes

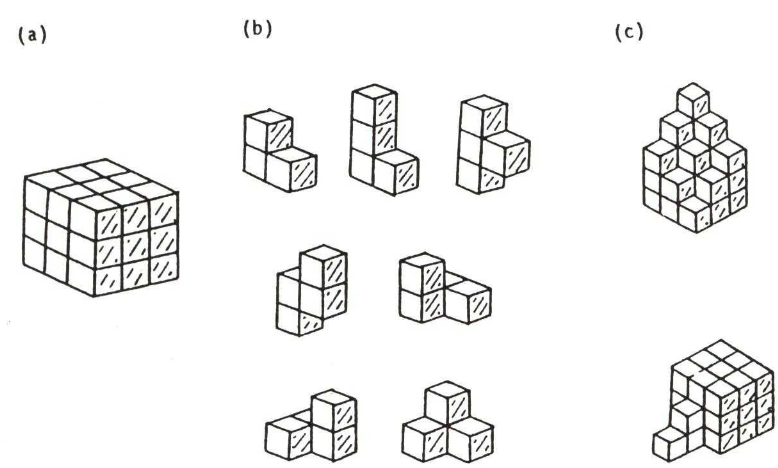


Fig. 5. (a) Soma cube puzzle, (b) the seven parts of the puzzle, (c) the bodies assembled by the parts.

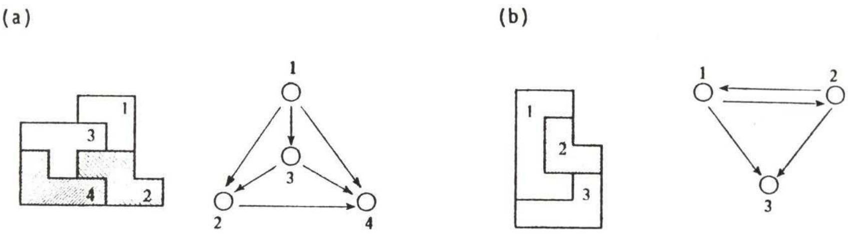


Fig. 6. Assembly plan and its graph representation, (a) acyclic graph, (b) cyclic graph.

and follows that of part **j** (Fig. 6b). This contradiction shows that the given construction cannot be assembled by the robot. Thus, we come to the following statement:

> If a construction can be assembled by the robot, then the graph of the parts assembly is acyclic.

The topological sorting theorem of directed graphs [11] states that we can label the vertices of an **n**-vertex acyclic directed graph **G** with integers from the set (1, 2, . . ., **n**) so that the presence of the edge (**i**, **j**) in **G** implies that **i** < **j**. As a result the graph contains terminal vertices, which are not initial for any edges.

In our case these are the vertices of the lower parts of the construction. They are placed first and do not prevent consecutive assembling of parts.

So we come to the following algorithm of assembly sequence definition using the graph:

(1) Place a part whose vertex in the graph is terminal. If all the vertices are not terminal, then the assembling is impossible; exit.
(2) Remove the vertex, defined in (1), from the graph, with all its adjacent edges.
(3) If the graph contains any vertices, go to (1).

For the example depicted in Fig. 6a the assembly sequence 4, 2, 3, 1 can be defined by this algorithm. For the construction shown in Fig. 6b, the assembly by robot is impossible.

During the assembly process the robot moves every part from its initial place to an interim one. There the robot orients the part properly and then places it into the assembly. Parts already assembled may restrict robotic manipulations and even make placing of a certain part impossible (Fig. 7).

So, in the common case it is needed to define the grasp position of the part by robot with regard to these restrictions.

So far, as the robot places the part from top to bottom, we may assume that the robot grasps the part in its top layer, the nearest to the gripper. Hence, the grasp position depends on the location of the top layer cubes and on the parts assembled previously, having cubes of the same or higher layer.

We will calculate the grasp position by the

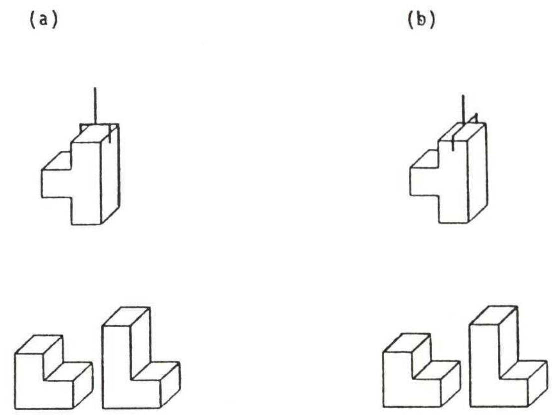


Fig. 7. Placing the part in the grasp position is (a) impossible (gripper interference), (b) possible.

following algorithm, based on a matrix model of the parts collocation. We project on the (**x**, **y**) plane the cubes of the present part having the maximal coordinate $\mathbf{z}_p$, and those cubes of the parts assembled before, for which $\mathbf{z} \geqslant \mathbf{z}_p$ (Fig. 8). We label squares of projections by digits 1 and 2 correspondingly. We also put 0 into the squares bordered by the labelled ones. Then we will find between lines and columns of projections a sequence of units restricted on both sides by zeroes, for which the total length of corresponding squares is less than the maximal spread of the gripper (Fig. 8b). If there are no such sequences, then the placing of the part by robot is impossible. The center of the identified sequence of squares and its orientation define the grasp position. For example, it follows from analysis of the model shown in Fig. 8, that there is a unique sequence in the right column corresponding to the grasp action shown in Fig. 8b. Hence, we find the unique possible grasp position, shown in Fig. 8a.

To conclude the issue of study assembly manipulations of the robot, the study of robotic assembly starts from interactive demonstrations of assembling of various bodies by Soma parts. The instructional program based on graphic simulation is developed to learn assembling sequences. A student with the graphical method gets or designs by himself a body, and assembles it by choosing needed Soma parts, their orientations and positions. Then he programs robotic manipulations for

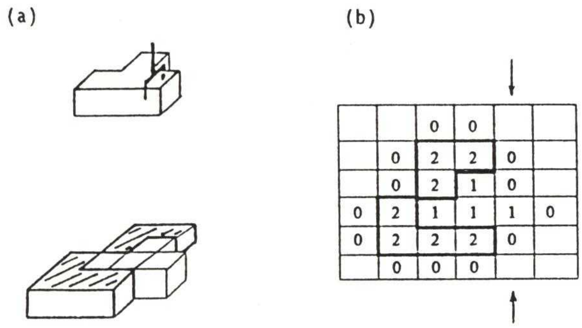


Fig. 8. Calculating the grasp position, (a) correct grasp position, (b) digital model.

assembling various bodies using the instructional program for robot movement simulation.

TEACHING SPATIAL MANIPULATIONS IN A ROBOTICS COURSE

The instructional materials presented above were implemented in an introductory robotic course of 1991–2, at a teacher training professional course for teachers, held at the Department of Education in Technology & Science, at the Technion.

This course included study of robotic manipulations, training in programming of the SCORBOT robotic system and optional work for interested students.

CONCLUSIONS

Studying robot manipulations consists of three stages, which are translation, rotation and assembly, and includes interactive demonstrations, practical work with instructional programs and programming of robot motion.

The suggested formalism for robot rotations allows the assignment of any needed orientation to a part composed of blocks.

The Soma cube puzzle is shown to serve as a teaching aid for robotic assembly. The automatic assembly algorithm for Soma bodies is developed using mathematical means (e.g. matrics, graphs).

The suggested models and algorithms of robotic planning turned out to be quite effective and may be used in practical robot planning.

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REFERENCES

1. W. N. White, D. D. Niemann and P. M. Lynch, The presentation of Lagrange's equations in introductory robotics courses, *IEEE Trans. Ed.*, **32** (1), (1989).
2. T. Raz, Graphics robot simulator for teaching introductory robotics, *IEEE Trans. Ed.*, **32** (2) (May, 1989).
3. D. Sharon, J. Harstein and G. Yantian, *Robotics and Automated Manufacturing*, Pitman, London (1987).
4. Z. Liang and C. J. Quinn, Using CAD software to analyze spatial mechanisms, *Int. J. Appl. Engng Ed.*, **7** (1), 76–80 (1991).
5. Eshed Robotec, Advanced Control Language, reference guide, TelAviv (1991).
6. Eshed Robotec, SCORBOT-ERV plus, user's manual (1991).
7. T. Lozano-Perez and R. H. Taylor, *Geometric Issues in Planning Robot Tasks, Robotics Science*, MIT Press (1989).
8. M. Gardner, *Mathematical Puzzles and Diversions*, Penguin, London (1970).
9. K. S. Fu, R. C. Gonzalez and C. S. G. Lee, *Robotics: Control, Sensing, Vision and Intelligence*, McGraw-Hill, New York (1987).
10. M. Eliahu and I. Verner, The integration of educational robot with Soma-cube puzzle for spatial comprehension training, Proceedings of the 1992 Pacific Conference on Manufacturing, 878–882 (November 1992).
11. K. Thulasiraman and M. N. S. Swamy, *Graphs: Theory and Algorithms*, Wiley, New York (1992).

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