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UNIVERSITI TUN HUSSEIN ONN MALAYSIA

FINAL EXAMINATION
SEMESTER I
SESSION 2019/2020

COURSE NAME	:	ROBOTICS
COURSE CODE	:	BDC 40603
PROGRAMME CODE	:	BDD
EXAMINATION DATE	:	DECEMBER 2019 / JANUARY 2020
DURATION	:	3 HOURS
INSTRUCTION	:	ANSWER **FOUR** QUESTIONS ONLY

THIS QUESTION PAPER CONSISTS OF **TEN (10)** PAGES

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Q1 The first three links of a revolute joint robot manipulator are shown in **Figure Q1**. The lengths of the links 1, 2 and 3 are R_1, R_2 and R_3 respectively.

(a) Using the Denavit-Hartenberg method, validate that the forward kinematic equations for the manipulator are as given below:

$$P_x = R_2 C_1 C_2 + R_3 C_1 C_{23}$$
$$P_y = R_2 S_1 C_2 + R_3 S_1 C_{23}$$
$$P_z = R_1 + R_2 S_2 + R_3 S_{23}$$

where $C_1 = \cos(\theta_1)$, $S_{23} = \sin(\theta_2+\theta_3)$ and so on.

(12 marks)

(b) Let $R_1 = R_2 = R_3 = 1$ unit. When the robot is in the configuration given by $\theta_1 = 0°$, $\theta_2 = 45°$ and $\theta_3 = 45°$, the tool is required to exert the following forces/moments on the work piece: $f_x = 1.0$ unit along the x-axis, $f_y = -2.0$ units along the y-axis, and $f_z = 4.0$ units along the z-axis. Develop the steps and determine the moments about the z-axes, that would be transmitted to the links of the manipulator.

(13 marks)

Q2 (a) Briefly explain why the inverse kinematic solution is important in controlling a robot manipulator. Comment on the advantages and disadvantages of using the inverse Jacobian method for obtaining the inverse kinematic solutions.

(5 marks)

(b) A three degree of freedom planar manipulator with two rotary joints (O_1 and O_2) and a translatory joint (J) is shown in **Figure Q2**. R_2 has a constant length of 5 units and r_1 has a variable length. Produce the forward kinematic equations for the manipulator.

(4 marks)

(c) Generate the joint coordinates (θ_1 , θ_2, r_1) when the tool tip is at the (P_x , P_y) = (9, 9) position, with the tool pointing at an angle of 60° measured from the positive x-axis.

(6 marks)

(d) It is now required to move the tool to the position given by (P_x, P_y) = (9.2, 9.3), with the tool pointing at an angle of 61°, measured from the positive x-axis. Generate the corresponding joint coordinates using the inverse Jacobian method.

(10 marks)

Q3 (a) For certain mobile robot applications, navigation methods are well suited to provide solutions, while other mobile robot areas benefit from path planning methods. Design examples for both types of areas and contrast the two methods.

(8 marks)

(b) **Figure Q3** shows the confined workspace of a point-like mobile robot. In the free space (white areas) the robot can move freely; the black areas represent obstacles. Decompose the robot's free space using the **exact cell decomposition method**.

To solve this question, make use of the attached workspace diagram in the "template sheet" (at the end of this paper). Insert the required cells. Assign labels to those cells.

(3 marks)

(c) Construct a connectivity graph whose nodes represent the cells extracted from the decomposed free space and whose links represent the adjacency relation between neighbouring cells.

(3 marks)

(d) Apply the **breadth-first search algorithm** manually to the connectivity graph constructed under c) to find a path from the start position to the goal position. Design the tree structure, which develops, and show the contents of the list that contains the visited nodes at each iteration. Draw the found path into your diagram.

(5 marks)

(e) Consider now a wall-following algorithm which instructs the robot to follow any straight-line object detected on its left, to turn right, if an obstacle in front appears, and to turn left, if the end of the object being followed is reached. The robot does not react to objects on its right.

Predict whether a solution can be found using the wall-following algorithm to solve the problem shown in **Figure Q3**. Consider the two starting conditions, 'start moving left' and 'start moving right', separately.

(6 marks)

Q4 A smooth trajectory for a manipulator joint can be calculated employing linear functions with parabolic blends. Use this type of function to solve this question.

Here, the trajectory of one particular joint of a robotic manipulator is specified as follows: Path points: $\theta_1 = 50°$, $\theta_2 = 100°$, $\theta_3 = 10°$. The duration of the two segments should be $t_{d12} = 2$, $t_{d23} = 4$ seconds, respectively. The magnitude of the acceleration to use is as follows: 100, 75 and 50°/sec^2 at the first, second and third path point, respectively. The manipulator is motionless at the start of the trajectory and at the end of the trajectory.

(a) Construct a sketch showing the angular position versus time for this trajectory. Show in your sketch positions θ_1, θ_2, θ_3, duration times t_{d12}, t_{d23}, blend times t_1, t_2, t_3, and linear times t_{12}, t_{23}.

(5 marks)

(b) Hence, determine the sign of all accelerations, all segment velocities, all blend times, and all linear times.

(14 marks)

(c) Calculate the maximum blend time at the second path point for this trajectory considering that only $\ddot{\theta}_2$ will change while all other values remain unchanged. Predict what will be the value of the new acceleration at the second path point?

(4 marks)

(d) Evaluate how can the trajectory be forced through the second path point?

(2 marks)

Q5 (a) Briefly explain how the homogeneous coordinate transformation matrices can be used to specify the position and orientation of the end effector of a robot arm. Give two other distinct applications of homogeneous coordinate transformation matrices.

(5 marks)

(b) In **Figure Q5**, it is required to mate the wedge-shaped block with the assembly to make a rectangular box. The wedge-shaped block is to be placed on the assembly so that ***p*** and ***r*** are touching, and ***s*** and ***q*** are touching, and the final assembly is a rectangular block. The coordinates of points ***p*** and ***r*** are (-4,10,2) and (4,4,2) respectively. The lines ***pq*** and ***rs*** are both parallel to the x-axis. Co-ordinate frames are assigned to each object as follows. The coordinate frame F_1 is attached to the wedge-shaped block with its origin at ***r***, x_1 pointing in the ***rs*** direction and z_1 pointing in the z direction. The coordinate frame F_2 is attached to the assembly with the origin at ***p***, x_2 pointing in the ***pq*** direction and z_2 pointing in the negative z direction.

(i) Generate transformation matrices T_0^1 and T_0^2 for frames F_1 and F_2 respectively, with respect to the world coordinate frame.

(5 marks)

(ii) Formulate the composite transformation matrix, T_1^2, which solves the assembly problem in **Figure Q5**, using T_0^1 and T_0^2. Verify your solution by deriving T_1^2, considering the movements needed to make F_1 coincident with F_2.

(10 marks)

(iii) Use the composite transformation matrix, T_1^2, to transform point ***s*** and hence verify that the assembly is completed.

(5 marks)

-END OF QUESTIONS –

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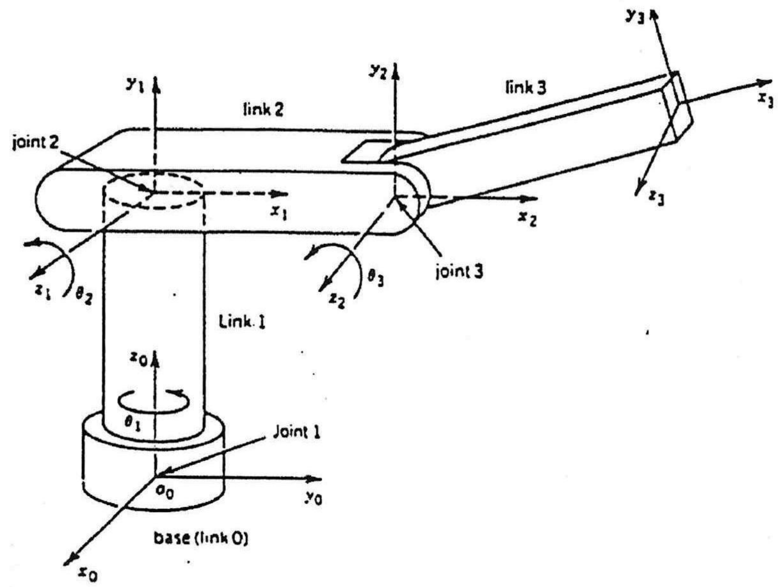

Figure Q1

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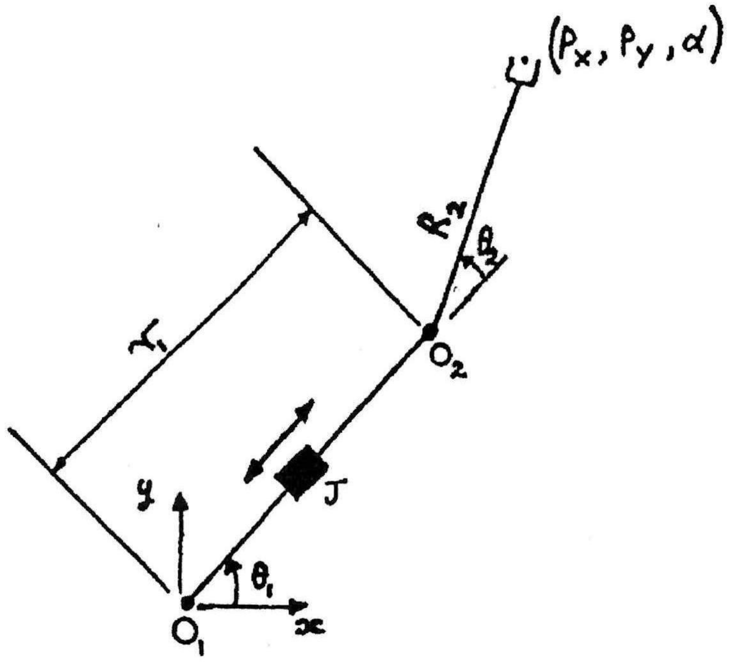

Figure Q2

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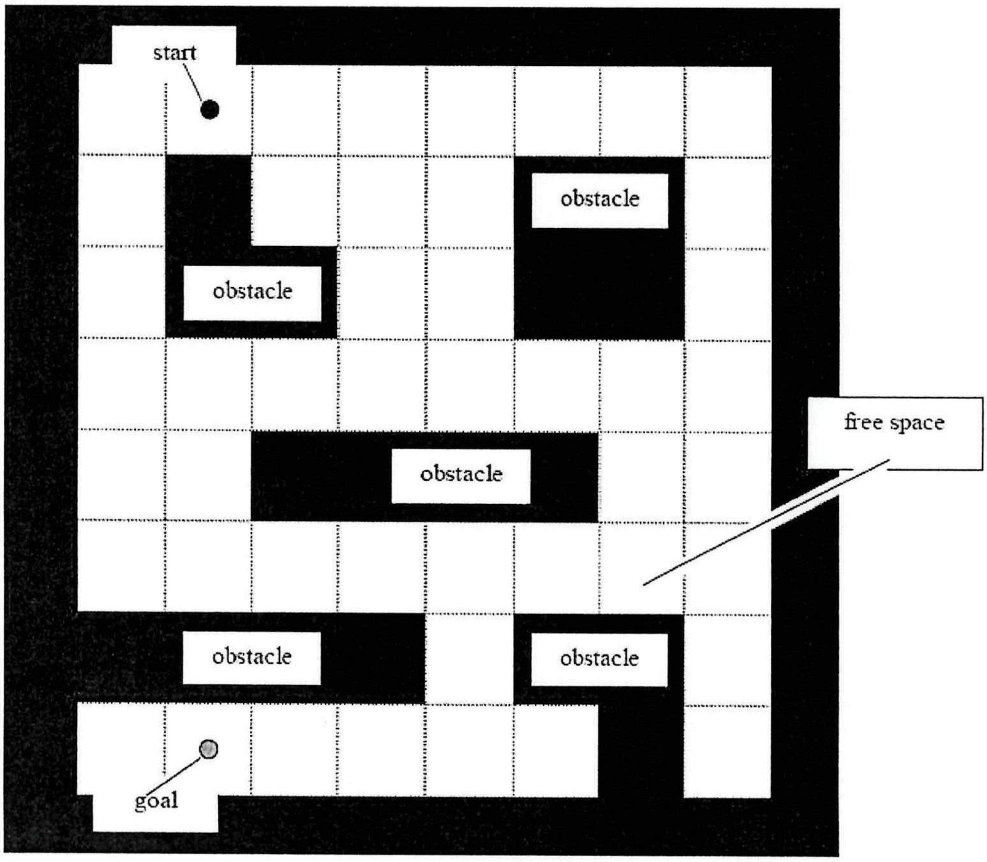

Figure Q3

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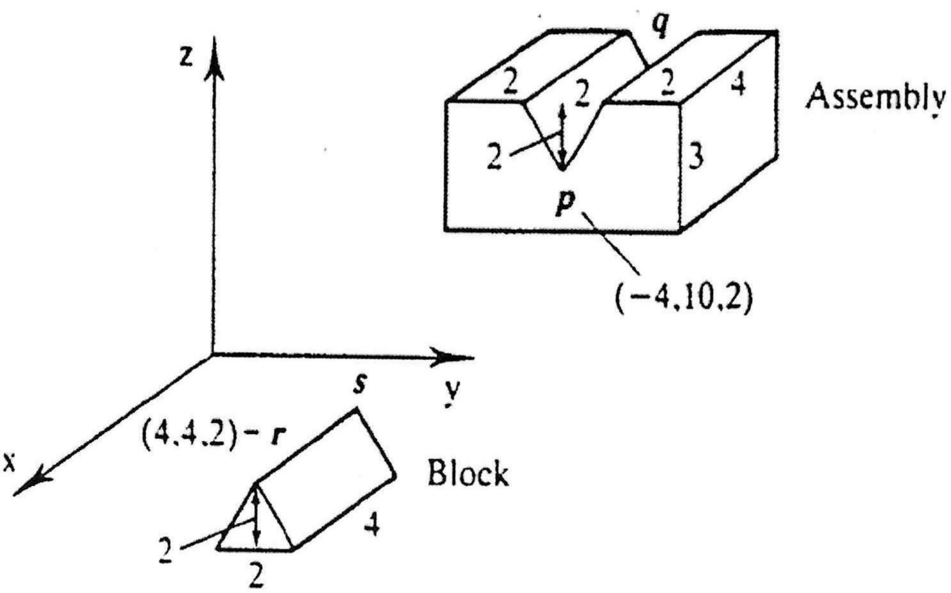

Figure Q5

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General Formulae for Rotation and Transformation Matrices

1) General Rotation Matrices

$$\text{ROT}_{x,\alpha} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c\alpha & -s\alpha \\ 0 & s\alpha & c\alpha \end{bmatrix}, \quad \text{ROT}_{y,\beta} = \begin{bmatrix} c\beta & 0 & s\beta \\ 0 & 1 & 0 \\ -s\beta & 0 & c\beta \end{bmatrix}, \quad \text{ROT}_{z,\gamma} = \begin{bmatrix} c\gamma & -s\gamma & 0 \\ s\gamma & c\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix}.$$

2) D-H Frame Transformation Matrix

The matrix to transform coordinates from a frame *i* to a frame *i*-1 is given by,

$$\text{T}_{i-1}^{i} = \begin{pmatrix} \cos\theta_i & -\sin\theta_i \cos\alpha_i & \sin\theta_i \sin\alpha_i & a_i \cos\theta_i \\ \sin\theta_i & \cos\theta_i \cos\alpha_i & -\cos\theta_i \sin\alpha_i & a_i \sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{pmatrix},$$

where θ_i, d_i, α_i, a_i are four ordered operations to bring frame *(i-1)* into coincidence with frame *i*.
(θ_i = a rotation about z_{i-1}, d_i = a translation about z_{i-1},
α_i = a rotation about x_{i-1}, a_i = a translation about x_{i-1}).

General Inverse Kinematic Formulae

IF	THEN
$a \cos\theta - b \sin\theta = c$ and $a \sin\theta + b \cos\theta = d$	θ = ATAN2 ($ad - bc$, $ac + bd$) and $a^2 + b^2 = c^2 + d^2$