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UNIVERSITI TUN HUSSEIN ONN MALAYSIA

FINAL EXAMINATION
SEMESTER II
SESSION 2018/2019

COURSE NAME	:	INDUSTRIAL ROBOTIC
COURSE CODE	:	BND 33003/ BND 43003
PROGRAMME CODE	:	BND
EXAMINATION DATE	:	JUNE/ JULY 2019
DURATION	:	3 HOURS
INSTRUCTION	:	ANSWER **ALL** QUESTIONS

THIS QUESTION PAPER CONSISTS OF **NINE (9)** PAGES

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Q1 (a) Describe the RIA definition of a robot.

(3 marks)

(b) Two classifications of the robots are according to the types of control and coordinate systems. Explain these **TWO (2)** classifications.

(6 marks)

(c) State **TWO (2)** advantages and **TWO (2)** disadvantages of a revolute manipulator.

(4 marks)

(d) Explain the definition of the work envelope/volume.

(3 marks)

(e) Draw the approximate workspace for the robot as shown in **Figure Q1 (e)**.

(4 marks)

Q2 (a) A point P in space is defined as ${}^{B}P = (2,3,5)^T$ relative to frame B which is attached to the origin of the reference frame A and is parallel to it. Apply the following transformations to frame B and find ${}^{A}P$.

(i) Rotate 90° about x-axis, then

(ii) Rotate 90° about local a-axis, then

(iii)Translate 3 units about y- axis, 6 units about z- axis, and 5 units about x- axis.

(5 marks)

(b) In a robotic setup, a camera is attached to the fourth link of a robot with five degrees of freedom. The camera observes an object and determines its frame relative to the camera's frame. Using the following information, determine the necessary motion the end effector has to make to get the object.

$$ {}^{4}T_{cam} = \begin{bmatrix} 0 & 0 & -1 & 2 \\ 0 & -1 & 0 & 0 \\ -1 & 0 & 0 & 4 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad {}^{4}T_{H} = \begin{bmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 3 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$$ {}^{cam}T_{obj} = \begin{bmatrix} 0 & 0 & 1 & 1 \\ 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad {}^{H}T_{E} = \begin{bmatrix} 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 2 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

(8 marks)

(c) Suppose that a robot is made of a Cartesian and RPY combination of joints. Calculate the necessary RPY angles to achieve the following:

$$B = \begin{bmatrix} 0.354 & -0.674 & 0.649 & 4.33 \\ 0.505 & 0.722 & 0.475 & 2.5 \\ -0.788 & 0.160 & 0.595 & 8 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(7 marks)

Q3 For the Standford Arm robot as shown in **Figure Q3**:

(a) Assign the coordinate frames based on D-H representation.

(8 marks)

(b) Fill out the parameters table.

(8 marks)

(c) Write the ${}^{U}\boldsymbol{T}_{H}$ matrix in terms of the A matrices.

(4 marks)

Q4 (a) The position of point B of **Figure Q4(a)** is as follows:

$$x_B = l_1 \cos\theta_1 + l_2 \cos(\theta_1 + \theta_2)$$
$$y_B = l_1 \sin\theta_1 + l_2 \sin(\theta_1 + \theta_2)$$

Calculate the Differential motion of B, its Jacobian and its Differential of joints in matrix form.

(5 marks)

(b) The last column of the forward kinematic equation of the simple revolute arm is:

$$\begin{bmatrix} P_x \\ P_y \\ P_z \\ 1 \end{bmatrix} = \begin{bmatrix} C_1(C_{234}a_4 + C_{23}a_3 + C_2a_2) \\ S1(C_{234}a_4 + C_{23}a_3 + C_2a_2) \\ S_{234}a_4 + S_{23}a_3 + S_2a_2 \\ 1 \end{bmatrix}$$

Calculate the Jacobian of P_y of the above robot.

(6 marks)

(c) The last column of the forward kinematic equation of a simple revolute arm is:

$$A1 = \begin{bmatrix} C_1 & 0 & S_1 & 0 \\ S_1 & 0 & -C_1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad A2 = \begin{bmatrix} C_2 & -S_2 & 0 & C_2a_2 \\ S_2 & C_2 & 0 & S_2a_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A3 = \begin{bmatrix} C_3 & -S_3 & 0 & C_3a_3 \\ S_3 & C_3 & 0 & S_3a_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad A4 = \begin{bmatrix} C_4 & 0 & -S_4 & C_4a_4 \\ S_4 & 0 & C_4 & S_4a_4 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A5 = \begin{bmatrix} C_5 & 0 & S_5 & 0 \\ S_5 & 0 & -C_5 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad A6 = \begin{bmatrix} C_6 & -S_6 & 0 & 0 \\ S_6 & C_6 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Calculate the ${}^{T6}J_{24}$ element of the Jacobian for the above revolute robot.

(9 marks)

Q5 (a) Derive the equations of motion for the 1-DOF system shown in **Figure Q5(a)**.

(6 marks)

(b) The kinetic energy and the potential energy of a two link system shown in **Figure Q5(b)** are given below. Use the Lagrangian mechanics to calculate the equation of motion of the system.

$$K = \frac{1}{2}(m_1 + m_2)l_1^2\dot{\theta}_1^2 + \frac{1}{2}m_2 l_2^2\left(\dot{\theta}_1^2 + \dot{\theta}_2^2 + 2\dot{\theta}_1\dot{\theta}_2\right) + m_2 l_1 l_2 C_2\left(\dot{\theta}_1^2 + \dot{\theta}_1\dot{\theta}_2\right)$$

$$P = -(m_1 + m_2)gl_1C_1 - m_2 g l_2 C_{12}$$

(14 marks)

- END OF QUESTION –

FINAL EXAMINATION

SEMESTER/SESSION	:	SEM II /2018/2019	PROGRAMME	:	BND
COURSE NAME	:	INDUSTRIAL ROBOTIC	COURSE CODE	:	BND 33003/BND 43003

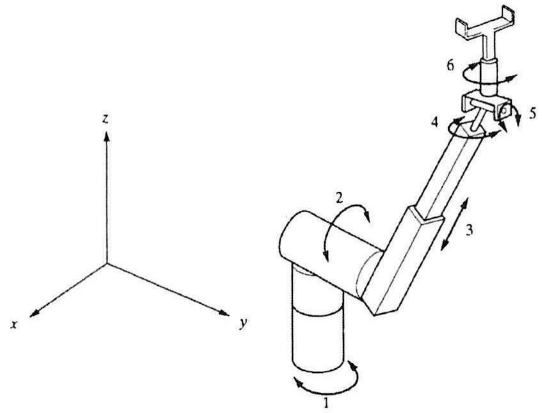


Figure Q1(e)

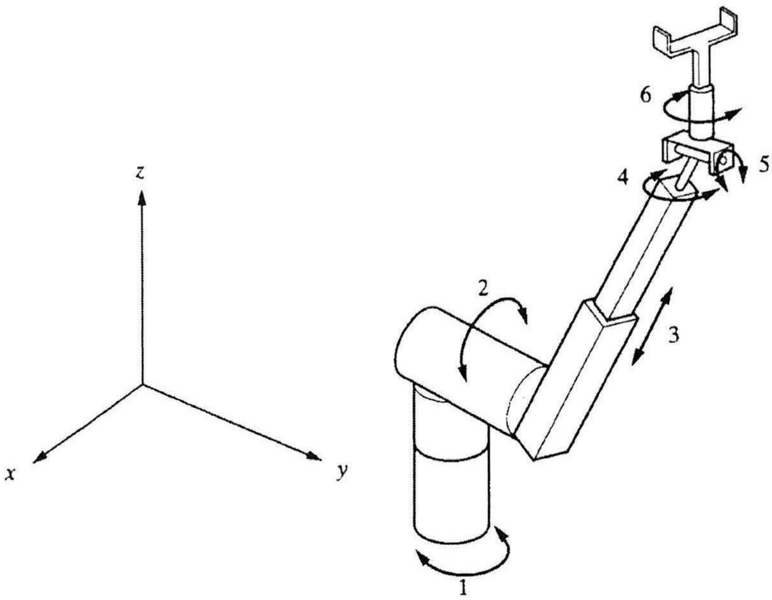


Figure Q3

FINAL EXAMINATION

SEMESTER/SESSION	:	SEM II /2018/2019	PROGRAMME	:	BND
COURSE NAME	:	INDUSTRIAL ROBOTIC	COURSE CODE	:	BND 33003/BND 43003

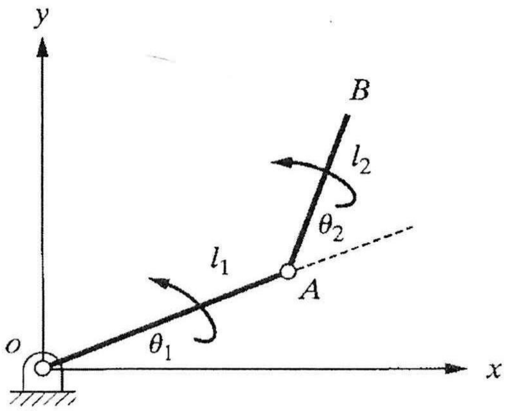


Figure Q4(a)

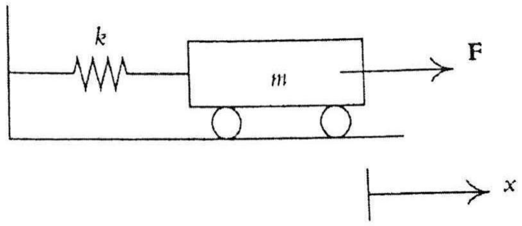


Figure Q5(a)

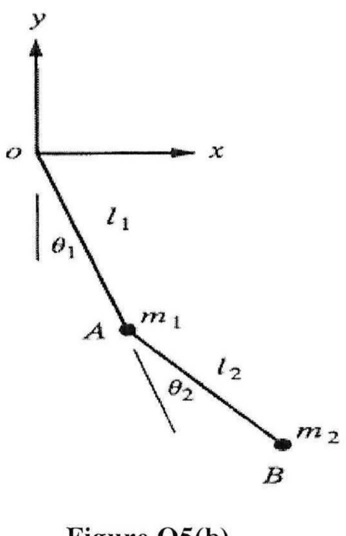


Figure Q5(b)

FINAL EXAMINATION

SEMESTER/SESSION	:	SEM II /2018/2019	PROGRAMME	:	BND
COURSE NAME	:	INDUSTRIAL ROBOTIC	COURSE CODE	:	BND 33003/BND 43003

FORMULAE

New location of frame due to the pure translation

$$F_{new} = Trans(d_x, d_y, d_z) \times F_{old}$$

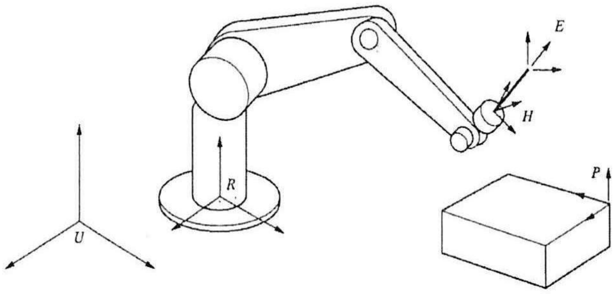
Six constraint equations:

(1) $\bar{n} \bullet \bar{o} = 0$
(2) $\bar{n} \bullet \bar{a} = 0$
(3) $\bar{a} \bullet \bar{o} = 0$
(4) $|n| = 1$
(5) $|o| = 1$
(6) $|a| = 1$

Rotation portion of the matrix

$$T^{-1} = \begin{bmatrix} n_x & n_y & n_z & -\bar{P}.\bar{n} \\ o_x & o_y & o_z & -\bar{P}.\bar{o} \\ a_x & a_y & a_z & -\bar{P}.\bar{a} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Transformation from reference frame U to end effector:



$${}^{U}T_{E} = {}^{U}T_{R}\,{}^{R}T_{H}\,{}^{H}T_{E} = {}^{U}T_{P}\,{}^{P}T_{E}, \qquad {}^{R}T_{H} = {}^{U}T_{R}^{-1}\,{}^{U}T_{P}\,{}^{P}T_{E}\,{}^{H}T_{E}^{-1}$$

- ${}^{U}T_{R}$ is the transformation of frame $\boldsymbol{R}$ relative to $\boldsymbol{U}$.
- ${}^{H}T_{E}$ is the transformation of the end effector relative to robot's hand.
- ${}^{U}T_{P}$ is the transformation of the part relative to the universe.
- ${}^{P}T_{E}$ is the transformation of the end effector relative to the part's position.
- ${}^{R}T_{H}$ is the transformation of the robot's hand relative to the robot's base (unknown).

Representation of the rotation matrix

$$Rot(x,\theta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\theta & -sin\theta \\ 0 & sin\theta & cos\theta \end{bmatrix}, \quad Rot(y,\theta) = \begin{bmatrix} cos\theta & 0 & sin\theta \\ 0 & 1 & 0 \\ -sin\theta & 0 & cos\theta \end{bmatrix}, \quad Rot(z,\theta) = \begin{bmatrix} cos\theta & -sin\theta & 0 \\ sin\theta & cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Cylindrical Coordinates

$${}^{R}T_{P} = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} C\alpha & -S\alpha & 0 & rC\alpha \\ S\alpha & C\alpha & 0 & rS\alpha \\ 0 & 0 & 1 & l \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Spherical Coordinates

$${}^{R}T_{P} = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} C\beta C\gamma & -S\gamma & S\beta C\gamma & rS\beta C\gamma \\ C\beta S\gamma & C\gamma & S\beta S\gamma & rS\beta S\gamma \\ -S\beta & C\beta C\gamma & C\beta & rC\beta \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

FINAL EXAMINATION

SEMESTER/SESSION	:	SEM II /2018/2019	PROGRAMME	:	BND
COURSE NAME	:	INDUSTRIAL ROBOTIC	COURSE CODE	:	BND 33003/BND 43003

Roll, Pitch , Yaw (RPY) Angles

$\Phi_a = ATAN2(n_y, n_x)$, $\Phi_o = ATAN2(-n_z, (n_x C\Phi_a + n_y S\Phi_a))$,

$\Phi_n = ATAN2((-a_y C\Phi_a - a_x S\Phi_a), (-o_y C\Phi_a - o_x S\Phi_a))$

Eulers Angles

$\Phi = ATAN2(a_y, a_x)$, $\Psi = ATAN2(-n_x S\Phi + n_y C\Phi, -o_x S\Phi + o_y C\Phi)$,

$\theta = ATAN2(a_x C\Phi + a_y S\Phi), a_z)$

Denavit-Hartenberg Representation

- θ represents the rotations about the z-axis.
- d represents the distance on the z-axis between two successive common normals.
- a represents the length of each common normal (also called joint offset).
- α represents the angles between two successive z-axis (also called joint twist)

Representation of A matrices

$$^{n}T_{n+1} = A_{n+1} = Rot(z,\theta_{n+1}) Tran(0,0,d_{n+1}) Trans(a_{n+1},0,0)(Rot(x,\alpha_{n+1})$$

$$= \begin{bmatrix} C\theta_{n+1} & -S\theta_{n+1}C\alpha_{n+1} & S\theta_{n+1}S\alpha_{n+1} & a_{n+1}C\theta_{n+1} \\ S\theta_{n+1} & C\theta_{n+1}C\alpha_{n+1} & -C\theta_{n+1}S\alpha_{n+1} & a_{n+1}S\theta_{n+1} \\ 0 & S\alpha_{n+1} & C\alpha_{n+1} & d_{n+1} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Jacobian Matrix

$$D = JD\theta$$

$$\begin{bmatrix} dx \\ dy \\ dz \\ \delta x \\ \delta y \\ \delta z \end{bmatrix} = \begin{bmatrix} \\ \\ Robot \\ Jacobian \\ \\ \\ \end{bmatrix} \begin{bmatrix} d\theta 1 \\ d\theta 2 \\ d\theta 3 \\ d\theta 4 \\ d\theta 5 \\ d\theta 6 \end{bmatrix}$$

The Jacobian with respect to the last frame

$$\begin{bmatrix} {}^{T6}dx \\ {}^{T6}dy \\ {}^{T6}dz \\ {}^{T6}\delta x \\ {}^{T6}\delta y \\ {}^{T6}\delta z \end{bmatrix} = \begin{bmatrix} {}^{T6}J_{11} & {}^{T6}J_{12} & {}^{T6}J_{13} & {}^{T6}J_{14} & {}^{T6}J_{15} & {}^{T6}J_{16} \\ {}^{T6}J_{21} & {}^{T6}J_{22} & {}^{T6}J_{23} & {}^{T6}J_{24} & {}^{T6}J_{25} & {}^{T6}J_{26} \\ {}^{T6}J_{31} & {}^{T6}J_{32} & {}^{T6}J_{33} & {}^{T6}J_{34} & {}^{T6}J_{35} & {}^{T6}J_{36} \\ {}^{T6}J_{41} & {}^{T6}J_{42} & {}^{T6}J_{43} & {}^{T6}J_{44} & {}^{T6}J_{45} & {}^{T6}J_{46} \\ {}^{T6}J_{51} & {}^{T6}J_{52} & {}^{T6}J_{53} & {}^{T6}J_{54} & {}^{T6}J_{55} & {}^{T6}J_{56} \\ {}^{T6}J_{61} & {}^{T6}J_{62} & {}^{T6}J_{63} & {}^{T6}J_{64} & {}^{T6}J_{65} & {}^{T6}J_{66} \end{bmatrix} \begin{bmatrix} d\theta 1 \\ d\theta 2 \\ d\theta 3 \\ d\theta 4 \\ d\theta 5 \\ d\theta 6 \end{bmatrix}$$

- **If i under consideration is a revolute joint, then:**

  ${}^{T6}J_{1i} = (-n_x p_y + n_y p_x)$, ${}^{T6}J_{2i} = (-o_x p_y + o_y p_x)$, ${}^{T6}J_{3i} = (-a_x p_y + a_y p_x)$

  ${}^{T6}J_{4i} = n_z$, ${}^{T6}J_{5i} = o_z$, ${}^{T6}J_{6i} = a_z$

- **Assuming that any combination of $A_1A_2A_3A_4A_5A_6$ can be expressed with a corresponding n , o , a , p matrix, the corresponding elements of the matrix will be used to calculate the Jacobian.**

FINAL EXAMINATION

SEMESTER/SESSION	:	SEM II /2018/2019	PROGRAMME	:	BND
COURSE NAME	:	INDUSTRIAL ROBOTIC	COURSE CODE	:	BND 33003/BND 43003

- **If i under consideration is a prismatic joint, then:**

  $^{T6}J_{1i} = n_z$, $^{T6}J_{2i} = o_z$, , $^{T6}J_{3i} = a_z$, $^{T6}J_{4i} = 0$, $^{T6}J_{5i} = 0$, $^{T6}J_{6i} = 0$

- **For column i use $^{i-1}T_6$:**

  For column 1, use $^0T_6 = A_1A_2A_3A_4A_5A_6$

  For column 2, use $^1T_6 = A_2A_3A_4A_5A_6$

  For column 3, use $^2T_6 = A_3A_4A_5A_6$

  For column 4, use $^3T_6 = A_4A_5A_6$

  For column 5, use $^4T_6 = A_5A_6$

  For column 6, use $^5T_6 = A_6$

Differential transformation

$$dT = [\Delta][T]$$

Differential operator relative to the fixed frame

$$\Delta = [Trans(dx, dy, dz)Rot(k, d\theta) - I] = \begin{bmatrix} 0 & -\delta z & \delta y & dx \\ \delta z & 0 & -\delta x & dy \\ -\delta y & \delta x & 0 & dz \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

Differential operator relative to the current frame

$$[^T\Delta] = [T]^{-1}[\Delta][T] = \begin{bmatrix} 0 & -^T\delta z & ^T\delta y & ^T dx \\ ^T\delta z & 0 & -^T\delta x & ^T dy \\ -^T\delta y & ^T\delta x & 0 & ^T dz \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

New location and orientation of the frame

$$B_{new} = B_{original} + dB$$

Lagrange function

$$L = K(q, \dot{q}) - P(q)$$

Total kinetic energy

$$K = \sum_{i=1}^{n} \frac{m1(\dot{x}_t^2 + \dot{y}_t^2 + \dot{z}_t^2)}{2}$$

Potential energy

$$P = mgh$$

General Lagrangian equation for the ith particle

$$F_i = \frac{d}{dt}\left(\frac{\delta L}{\delta \dot{x}_i}\right) - \left(\frac{\delta L}{\delta x_i}\right), i = 1,2 \ldots\ldots n$$

$$T_i = \frac{d}{dt}\left(\frac{\delta L}{\delta \dot{\theta}_i}\right) - \left(\frac{\delta L}{\delta \theta_i}\right), i = 1,2 \ldots\ldots n$$