Universiti Tun Hussein Onn Malaysia

UNIVERSITI TUN HUSSEIN ONN MALAYSIA

FINAL EXAMINATION
SEMESTER I
SESSION 2016/2017

TERBUKA

COURSE NAME	:	INDUSTRIAL ROBOT
COURSE CODE	:	BND 41203
PROGRAMME	:	4 BND
EXAMINATION DATE	:	DECEMBER 2016 / JANUARY 2017
DURATION	:	3 HOURS
INSTRUCTION	:	ANSWER **ALL** QUESTIONS

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

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 cylindrical configuration as shown in **Figure Q1 (e)**.

(4 marks)

Q2 (a) A frame B as given below is rotated 90^o about the z-axis, then translated 5 and 3 units relative to the n-axis and o-axis respectively, then rotated another 90^o about the n-axis, and finally, 90^o about the x-axis. Find the new location and orientation of the frame.

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

(5 marks)

(b) In a robotic setup, a camera is attached to the fifth link of a robot with six 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:

$${}^{5}T_{cam} = \begin{bmatrix} 0 & 0 & -1 & 2 \\ 0 & -1 & 0 & 0 \\ -1 & 0 & 0 & 4 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad {}^{5}T_{H} = \begin{bmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

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

(8 marks)

(c) Suppose that we now desire to place the origin of the hand of a spherical robot at $[3,5,7]^T$. Calculate the joint variables of the robot.

(7 marks)

Q3 A robot arm with six degrees of freedom has been designed for applying paint on flat wall as shown in **Figure Q3**.

(a) Assign coordinate frames as necessary 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 Jacobian of a robot at a particular time is given below. Compute the linear and angular differential motions of the robot's hand frame for the given joint differential motions.

$$J = \begin{bmatrix} 2 & 0 & 0 & 0 & 1 & 0 \\ -1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} D_\theta = \begin{bmatrix} 0 \\ 0.1 \\ -0.1 \\ 0 \\ 0 \\ 0.2 \end{bmatrix}$$

(2 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_x and P_y of above robot.

(9 marks)

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

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

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

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

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

(9 marks)

Q5 Derive the equations of motion for the two-link mechanism with concentrated masses in **Figure Q5**.

(20 marks)

- END OF QUESTION –

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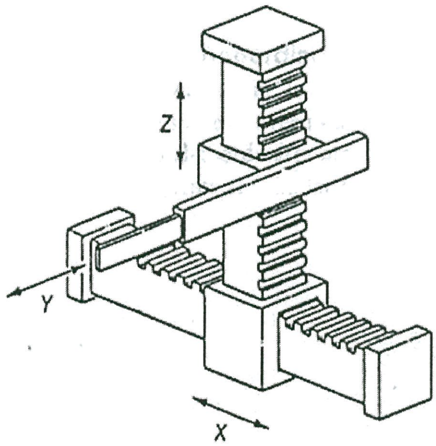

FIGURE Q1 (e)

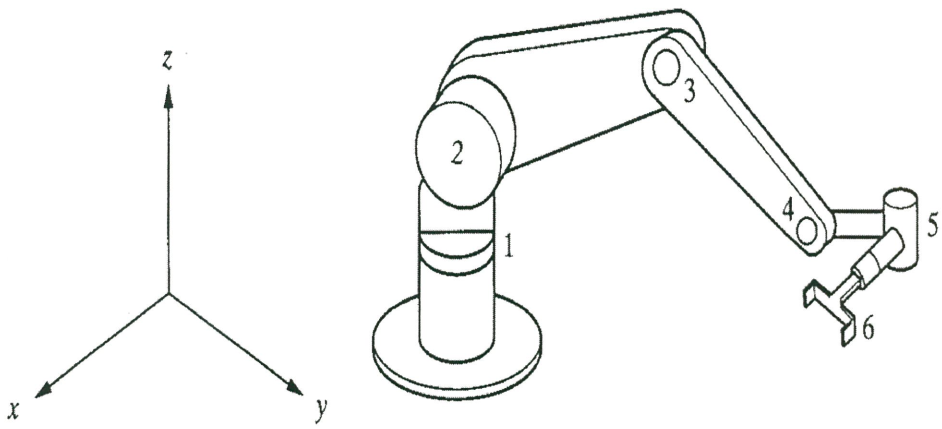

FIGURE Q3

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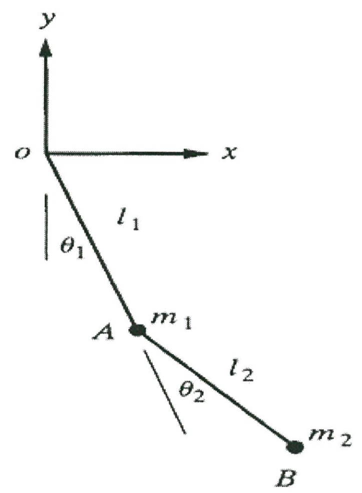

FIGURE Q5

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FORMULAS

New location of frame due to the pure translation

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

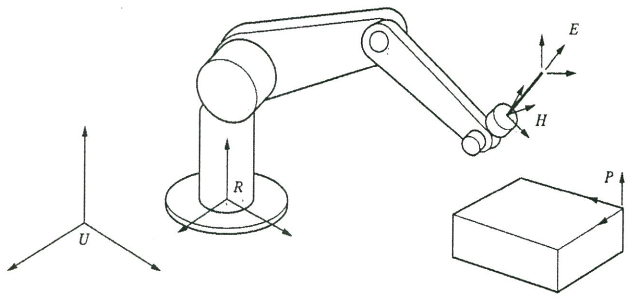
Six constraint equations:

(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 ***R*** relative to ***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

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

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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.**

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- **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

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

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