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THE NATIONAL UNIVERSITY OF IRELAND, CORK

COLÁISTE NA hOLLSCOILE, CORCAIGH
UNIVERSITY COLLEGE, CORK

SUMMER EXAMINATIONS, 2006

B.E. DEGREE (ELECTRICAL)

MECHATRONICS AND INDUSTRIAL AUTOMATION
EE4009

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Time Allowed: *3 hours*

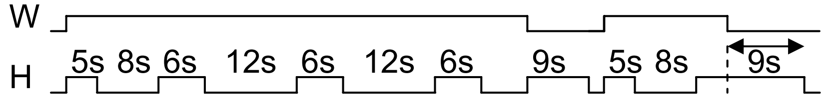
Answer *five* questions.

All questions carry equal marks.
The use of a Casio fx570w or fx570ms calculator is permitted.

1. A process requires that a hooter H be controlled based on the level of a warning signal W. Use a ladder diagram to show how a PLC could be used to generate the signal H.

   When W is set, H should turn on for 5 seconds and then stay off for 8 seconds, followed by a square wave sequence with on periods of 6 seconds followed by off periods of 12 seconds. When W becomes inactive, H should go (or remain) active for 9 seconds.

   This is exemplified by a typical trace:



[*20 marks*]

2. For each the following types of work cells:

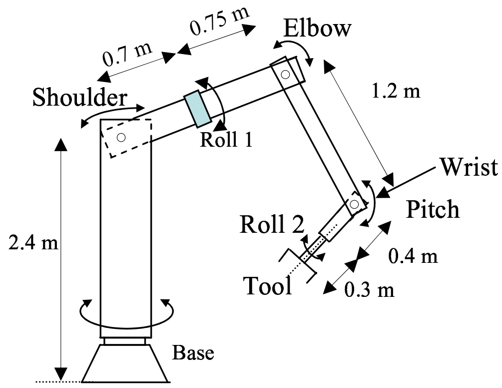
   (a) Robot-centred cell, [*4 marks*]

   (b) In-line cell, [*12 marks*]

   (c) Mobile robot cell, [*4 marks*]

   describe the operation of the cell, highlighting any major advantages and disadvantages. For in-line cells, treat cells with intermittent, continuous and non-synchronous transfer mechanisms separately. Use diagrams to illustrate your answer, as appropriate, and include a typical application of each of the three major cell types.

3. A six axis robot is similar in structure to the Alpha II robot but an extra roll joint is included to provide more flexible kimenatics. This robot has no offsets in a direction perpendicular to the plane of the paper. A gripper acts as the end effector, as shown.



   If the dimensions of the system are as on the diagram, use the Denavit-Hartenberg algorithm and matrix (available as Appendix I at the end of this paper) to

   (a) Assign suitable frames to the robot, using a link-coordinate diagram. [*11 marks*]

   (b) Tabulate the kinematic parameters associated with the robot. [*5 marks*]

   (c) Write down an expression for $T_{\text{base}}^{\text{wrist}}$ for this robot, i.e. T_0^4, based on your frame assignments. Your answer can take the form of a product of a number of matrices, i.e. you are *not* required to perform the multiplication. [*2 marks*]

   (d) Perform a sanity check on T_2^3. [*2 marks*]

4. (a) Describe the operation of a resolver-to-digital converter circuit for estimation of rotary shaft position and velocity. Include a labelled diagram of the converter. It is *not* necessary to give a detailed description of the resolver itself. [*10 marks*]

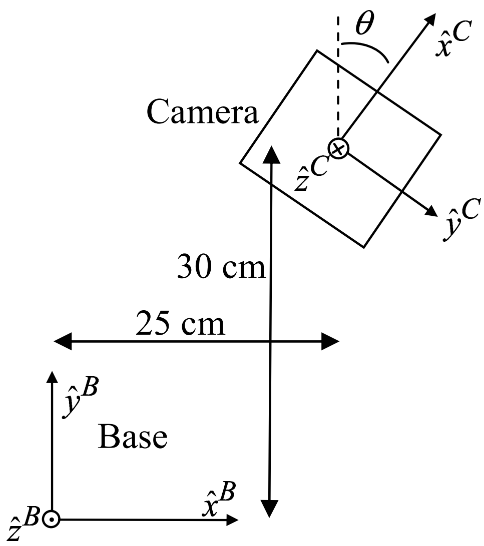
   (b) Derive a Laplace-domain expression giving the piston position, $Y(s)$, as a function of the spool valve position, $X(s)$, and the load force, $F_l(s)$, for an idealised hydraulic servo-valve. Assume an incompressible fluid, load mass M, load damping B and piston cross-sectional-area A. It can also be assumed that the spool valve is close to its central position.

   Aide Memoire: Volumetric flowrate q:

$$q = C_d \pi d\ x\,(P_s - P)^{0.5}\ (2/\rho)^{0.5}$$

   A linearisation of the flow equation may be used. [*10 marks*]

5. The x-y coordinates of the origin of the camera frame, C, relative to the base, B, of an industrial vision system are known. It is also known that the image plane of the camera is horizontal (as is the base plane). However, both the vertical placement of the image plane (i.e. height above base plane) and the orientation of the camera about its $\hat{z}$-axis are not known. The camera position and its orientation in the x-y plane are shown in the following plan view:



A test point (defined in the base frame) $A = [20,\ 20,\ 0]^T$ has image $A^i = [0.258698,\ -0.086233,\ 0]^T$. When the camera is lowered by exactly 1 cm (with no rotational variation), the new image is at $[0.265165, -0.088388,\ 0]^T$ in the camera frame.
The camera has a focal length of 1 cm.

Determine

(a) the (original) height of the camera frame above the base plane, [*9 marks*]

(b) the acute angle θ shown in the diagram, [*11 marks*]

6. A five-axis articulated robot (Alpha II) has a tool matrix of the following form:

$$T_{\text{base}}^{\text{tool}} = T_{\text{base}}^{\text{wrist}} \, T_{\text{wrist}}^{\text{tool}} =$$

$$\begin{bmatrix} C_1C_{23} & -C_1S_{23} & -S_1 & C_1(a_2C_2 + a_3C_{23}) \\ S_1C_{23} & -S_1S_{23} & C_1 & S_1(a_2C_2 + a_3C_{23}) \\ -S_{23} & -C_{23} & 0 & d_1 - a_2S_2 - a_3S_{23} \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C_4C_5 & -C_4S_5 & -S_4 & -d_5S_4 \\ S_4C_5 & -S_4S_5 & C_4 & d_5C_4 \\ -S_5 & -C_5 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} C_1C_{234}C_5 + S_1S_5 & -C_1C_{234}S_5 + S_1C_5 & -C_1S_{234} & C_1(a_2C_2 + a_3C_{23} - d_5S_{234}) \\ S_1C_{234}C_5 - C_1S_5 & -S_1C_{234}S_5 - C_1C_5 & -S_1S_{234} & S_1(a_2C_2 + a_3C_{23} - d_5S_{234}) \\ -S_{234}C_5 & S_{234}S_5 & -C_{234} & d_1 - a_2S_2 - a_3S_{23} - d_5C_{234} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where $d_1 = 80$ cm, $a_2 = 60$ cm, $a_3 = 50$ cm, $d_5 = 30$ cm.
The required numeric tool matrix for the robot is

$$T_{\text{base}}^{\text{tool}} = \begin{bmatrix} 0.4330 & 0.8660 & -0.25 & -22.5 \\ -0.75 & 0.5 & 0.4330 & 38.97 \\ 0.5 & 0.0 & -0.8660 & 207.94 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(distances in cm).

(a) Derive the general (symbolic) inverse kinematic equations for the base, elbow and shoulder joints of this robot. [*12 marks*]

(b) Assuming that the global tool pitch angle, Θ_{234}, equals -150^o and that $0 \leq \Theta_1 \leq 180^o$, find a elbow joint angle, Θ_2, corresponding to the above numeric tool matrix. [*8 marks*]

7. It is desired to perform a piecewise linear interpolation with a parabolic blend for the following three point trajectory in three-dimensional coordinate space. The total time of the traverse is to be 10 s, with $T_1 = T_2 = 5$ seconds. The deviation of the machine from the second knot point (in 3D space) should be 0.125 units.
The three points are:

$$\begin{aligned} w^1 &= [-3,\ 0,\ 0]^T \\ w^2 &= [0,\ 8,\ 0]^T \\ w^3 &= [-3,\ 8,\ 0]^T \end{aligned}$$

Find the x and y components of the trajectory $w(t)$, over the time interval $[0,\ 10]$.

[*20 marks*]

Appendix I
Denavit-Hartenberg Algorithm and Matrix

1. Number the joints from 1 to n starting with the base and ending with the tool yaw, pitch and roll, in that order.
2. Assign a right-handed orthonormal coordinate frame L_0 to the robot base, making sure that z^0 aligns with the axis of joint 1. Set $k = 1$.
3. Align z^k with the axis of joint $k + 1$.
4. Locate the origin of L_k at the intersection of the z^k and z^{k-1} axes. If they do not intersect, use the intersection of z^k with a common normal between z^k and z^{k-1}.
5. Select x^k to be orthogonal to both z^k and z^{k-1}. If z^k and z^{k-1} are parallel, point x^k away from z^{k-1}.
6. Select y^k to form a right-handed orthonormal coordinate frame L_k.
7. Set $k = k + 1$. If $k < n$, go to step 3; else, continue.
8. Set the origin of L_n at the tool tip. Align z^n with the approach vector, y^n with the sliding vector, and x^n with the normal vector of the tool. Set $k = 1$.
9. Locate point b^k at the intersection of the x^k and z^{k-1} axes. If they do not intersect, use the intersection of x^k with a common normal between x^k and z^{k-1}.
10. Compute Θ_k as the angle of rotation from x^{k-1} to x^k measured about z^{k-1}.
11. Compute d_k as the distance from the origin of frame L_{k-1} to point b_k measured along z^{k-1}.
12. Compute a_k as the distance from point b^k to the origin of frame L_k measured along x^k.
13. Compute α_k as the angle of rotation from z^{k-1} to z^k measured about x^k.
14. Set $k = k + 1$. If $k \leq n$, go to step 9; else, stop.

DENAVIT-HARTENBERG MATRIX:

$$T_{i-1}^{i} = \begin{bmatrix} C\Theta_i & -S\Theta_i C\alpha_i & S\Theta_i S\alpha_i & a_i C\Theta_i \\ S\Theta_i & C\Theta_i C\alpha_i & -C\Theta_i S\alpha_i & a_i S\Theta_i \\ 0 & S\alpha_i & C\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$