OLLSCOIL NA hÉIREANN, CORCAIGH

THE NATIONAL UNIVERSITY OF IRELAND, CORK

COLÁISTE NA hOLLSCOILE, CORCAIGH

UNIVERSITY COLLEGE, CORK

SUMMER 2000

B.E. (ELECTRICAL) DEGREE

MECHATRONICS AND INDUSTRIAL AUTOMATION EE4009

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Full marks for complete answers to *five* questions.
The use of approved calculators is permitted.

3 hours

1. A PLC controls traffic flow in two directions by turning on the red, amber and green lights, R1, R2, A1, A2, and G1, G2, as appropriate. Design a ladder-diagram controller based on the fact that both sets of lights have identical timing: red for 60 seconds, then green for 50 seconds, followed by amber for 4 seconds. The two sets of lights are coordinated to produce the following (six phase) sequence: both lights red for 3 s, one goes green for 50 s, then amber for 4 s, then both are red for 3 s, then the other goes green, etc. (Note that this controller has no inputs. You can assume that all outputs, including timer outputs, latch outputs, are open (off) when the controller is initially activated).
   Suggested approach: Start by generating six flags, P1 to P6, representing phases 1 to 6, and then use these to generate the actual output signals required to control the lights.

2. A camera (with a focal length of 1 cm) is located 21 cm above a base frame. The x and y coordinates of the camera relative to the base frame are not known. However, it is known that

$$R_{\text{base}}^{\text{camera}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix}$$

(a) If the image of a test point with coordinates $[10, 10, 0]^T$ in the base frame is $[0.5, 0, 0]^T$, what is the location of the camera relative to the base.

(b) If the camera is moved in the y and z directions, but its orientation and its location in the x direction remain unchanged, and if the new image of the test point is $[0.4444, 0.05555, 0]^T$, how far was the camera moved in each direction.

3. (a) Derive a Laplace domain expression relating the piston position, $Y(s)$, to 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 can be used.

(b) Briefly, compare the performance of counting/timing-based and observer-based methods of rotary shaft velocity estimation when employing an incremental encoder for digital position detection purposes. (Note: A detailed description of the hardware/software components of these measurement techniques is not required).

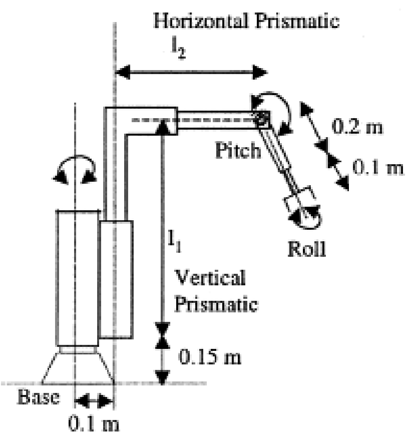
4. Describe the Profibus fieldbus system under the following headings:

(a) Physical profiles

(b) The DP communications profile.

(c) The role of Applications profiles, with examples.

5. A five-axis robot is of a modified cylindrical structure, where the vertical prismatic joint is offset by 0.1 m, as shown in the diagram. The offset is in the plane of the paper only. The minor (pitch and roll) joints are of standard type, the pitch joint of the wrist having a horizontal axis. You can assume that the joints also have no offsets in a plane perpendicular to the paper. A gripper acts as the end effector, as shown. The prismatic length l_1 can vary from 0.3 m to 0.6 m, and l_2 from 0.2 m to 0.4 m. 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.

(b) Tabulate the kinematic parameters associated with the first three joints of the robot (i.e. those from the base to the wrist).

(c) Write down an expression for $T_{\text{base}}^{\text{wrist}}$ for this robot, based on your frame assignments; (i.e. you need not write down the transformations relating frames from tool to wrist). Your answer can take the form of a product of a number of matrices, i.e. you are *not* required to perform the multiplication.

(d) Perform a sanity check on T_1^2.

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

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

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

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

Derive the inverse kinematic equations and comment on the uniqueness, or otherwise, of your solution.

7. A two-dimensional $x - y$ positioning system is nominally required to follow the 10 second trajectory defined by

$$p_x(t) = 2 + 5t, \quad p_y(t) = 6 - t, \quad 0 \leq t < 6;$$
$$p_x(t) = 62 - 5t, \quad p_y(t) = 12 - 2t, \quad 6 \leq t < 10;$$

where positions are given in cm. A cartesian system is used so that motion in each of the x and y directions is controlled by separate motors, the characteristics of each of which limit the absolute value of the acceleration to 5 cm s^{-2}. This limitation is taken into account by maintaining the same linear segments as above, but by adding a parabolic blend with a knot point at $t = 6$ s. Note that the duration of the blend region will differ for the x and y componenets of the motion, with both blends taking place at limiting acceleration of the relevant motors.

(a) What is the equation of the x-coordinate of the trajectory during the blend region, as a function of time?

(b) What will be the position error in the $x - y$ plane at $t = 6$ s.

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 2; 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 8; else, stop.

DENAVIT-HARTENBERG MATRIX:

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