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SUMMER EXAMINATIONS, 2005

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 servosystem requires accurate position and velocity information to allow precise trajectory following. The shaft of the motor being controlled is coupled to an incremental encoder.

   (a) i. Describe, with the aid of a diagram, the operation of an observer-based system for obtaining reliable velocity and position measurements. (There is no need to describe the encoder itself). [*7 marks*]

   ii. Derive formulae that enable the gain terms of your observer structure to be chosen and describe the factors to be taken into account when choosing the observer parameters. [*6 marks*]

   iii. Describe how the observer can be designed to operate satisfactorily for different inertial loads, assuming that a good estimate of each load is available. [*2 marks*]

   (b) Compare the quality of position and velocity information available from the above system (assuming that a good motor model is available for use within the observer) with that from a resolver/resolver-to-digital-converter (RDC) combination. (Give as many advantages and disadvantages of the two systems as possible). [*3 marks*]

   (c) Similarly, compare the quality of the velocity estimate provided by the observer with that from a simple pulse count tachometer. [*2 marks*]

2. 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 $d_1 = 50$ cm, $a_2 = 40$ cm, $a_3 = 30$ cm, $d_5 = 10$ cm.
The required numeric tool matrix for the robot is

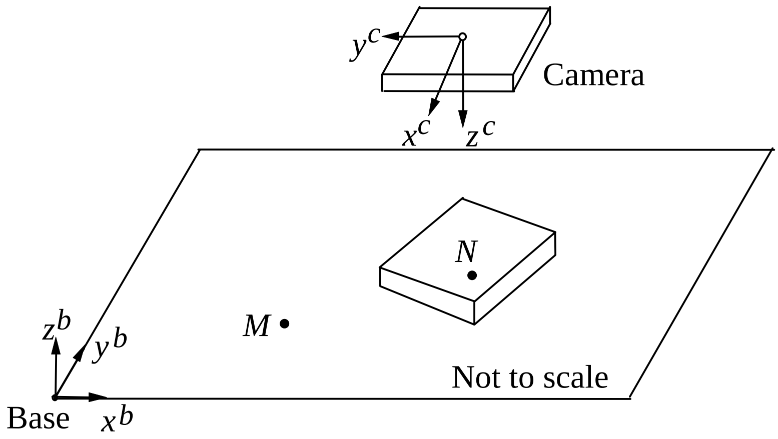
$$T_{\text{base}}^{\text{tool}} = \begin{bmatrix} 0.1001 & 0.7405 & 0.6645 & -47.164 \\ 0.9085 & -0.3409 & 0.2418 & -17.165 \\ 0.4056 & 0.5793 & -0.7071 & 78.977 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(distances in cm).

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

(b) Assuming that the global tool pitch angle, Θ_{234}, equals $+45^o$ and that the elbow angle, Θ_3, is $+30^o$, find a shoulder joint angle, Θ_2, corresponding to the above numeric tool matrix. [*8 marks*]

3. Consider the following vision system for robotic control.



Points M and N are used for camera calibration purposes and are specified in the base frame of the robot, $\{L_b\}$. Points M^i and N^i are the images of M and N. The focal length of the camera is 5 cm. Note that the two test points are at different heights relative to the base. Specifically note that N has an z co-ordinate of 5 cm relative to the base.

The test points (defined in the base frame) are $M = [20,\ 10,\ 0]^T$ and $N = [35,\ 25,\ 5]^T$. These have images $M^i = [-3.3333,\ -1.1111,\ 0]^T$ and $N^i = [-1.8750,\ +0.6250,\ 0]^T$ in the camera frame, $\{L_c\}$. Determine the homogenous transformation, T_b^c. [*20 marks*]

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

   (a) Physical profiles. [*5 marks*]

   (b) The DP communications profile. [*11 marks*]

   (c) The role of Applications profiles, with examples. [*4 marks*]

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

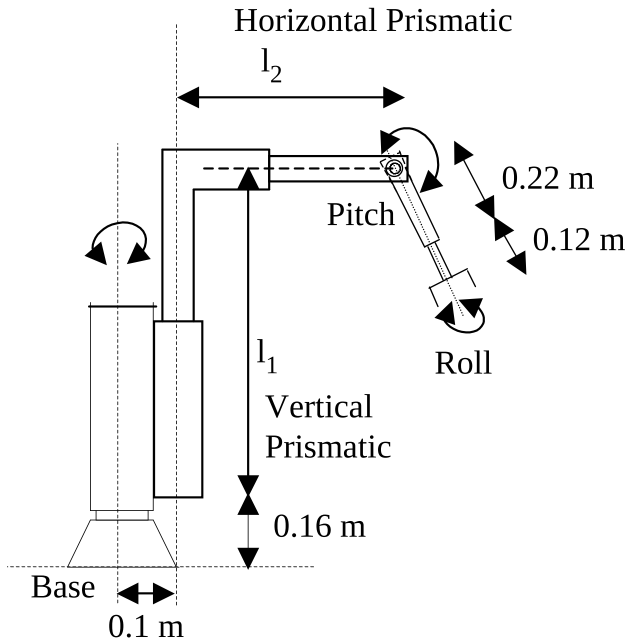
$$p_x(t) = 5 + 5t, \quad p_y(t) = 25 - 5t, \quad 0 \le t < 5;$$
$$p_x(t) = 55 - 5t, \quad p_y(t) = 0, \quad 5 \le t < 10;$$

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, where feasible, but by adding a parabolic blend with a knot point at $t = 5$ s. Note that the duration of the blend region will differ for the x and y components of the motion, with each of the x and y blends taking place at the 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? [*12 marks*]

   (b) What will be the position error in the $x - y$ plane at $t = 5$ s? [*8 marks*]

6. 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 0.2 m to 0.5 m, and l_2 from 0.15 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:

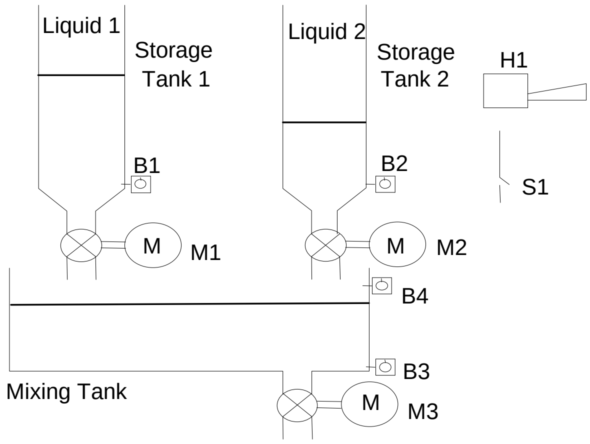
(a) Assign suitable frames to the robot, using a link-coordinate diagram. [*11 marks*]

(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_0^3, 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_0^1. [*2 marks*]

7. A process requires the mixing of two liquids as shown below. Use a ladder diagram to show how a PLC could be used to control this process.



Equipment description:

The Liquid 1 tank has a low-level sensor B1 (normally closed when no liquid present) and a motorised discharge valve M1 that is controlled via a contactor K1.
The Liquid 2 tank has a similar low-level sensor B2 and a motorised discharge valve M2 that is controlled via a contactor K2.
The mixing tank has low-level (empty) and high-level sensors, B3 and B4, which are normally open when no liquid is present. The mixing tank has a motorised discharge valve M3 under the control of a contactor K3.
A hooter, H1, is available to supply an audible warning.
A single on/off switch S1 is also provided.

Operational Specifications:

(a) The system is enabled when S1 is closed.

(b) When the mixing tank is empty, as indicated by B3, liquid is discharged from both liquid storage tanks, until the liquid in the mixing tank has reached the high level, as given by B4. The contents of the mixing tank are then discharged immediately until the mixing tank is empty. The process then repeats.

(c) The process should stop immediately if the level of either of the storage tanks goes low. A hooter warning should be sounded, the duty cycle of which should be: on for 10 seconds, off for 5 seconds, and this intermittent pattern should repeat for as long as the active warning is to be given. (This should be programmed under the assumption that the PLC software is equipped with on-delay timers.) The warning continues until either (i) both storage tanks are no longer low, or (ii) S1 is opened.

(d) It can be assumed that the mixing tank is initially empty when S1 is closed.

[*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:

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