MECH 420 SENSORS AND ACTUATORS
Assignment 3

Problems 3.3, 3.6, 3.7, 3.8, 3.17, 3.21, and 3.30 from the textbook

Problem 1 (Problem 3.3 from Textbook)

A tactile (distributed touch) sensor (see Chapter 6) of the gripper of a robotic manipulator consists of a matrix of piezoelectric sensor elements placed 2 mm apart. Each element generates an electric charge when it is strained by an external load. Sensor elements are multiplexed at very high speed in order to avoid charge leakage and to read all data channels using a single high-performance charge amplifier. Load distribution on the surface of the tactile sensor is determined from the charge amplifier readings, since the multiplexing sequence is known. Each sensor element can read a maximum load of 50 N and can detect load changes in the order of 0.01 N.

(a) What is the spatial resolution of the tactile sensor?
(b) What is the load resolution (in N/m^2) of the tactile sensor?
(c) What is the dynamic range?

Problem 2 (Problem 3.6 from Textbook)

Consider a simple mechanical dynamic device (single-degree-of-freedom) that has low damping. An approximate design relationship between the two performance parameters T_r and f_b may be given as $T_r f_b = k$, where T_r is the rise time in nanoseconds (ns) and f_b is the bandwidth in megahertz (MHz). Estimate a suitable value for k.

Problem 3 (Problem 3.7 from Textbook)

List several response characteristics of nonlinear dynamic systems that are not generally exhibited by linear dynamic systems. Additionally, determine the response y of the nonlinear system $\left[\frac{dy}{dt}\right]^{1/3} = u(t)$ when excited by the input $u(t) = a_1 \sin \omega_1 t + a_2 \sin \omega_2 t$. What characteristic of a nonlinear system does this result illustrate?

Problem 4 (Problem 3.8 from Textbook)

Consider the "static" (or "algebraic") system represented by $y = pu^2 + c$. Sketch this input-output relationship for $p = 1$ and $c = 0.2$. What is the response of this device on application of a sine input $u = \sin t$? How would you linearize this device without losing its accuracy and the operating range?

Problem 5 (Problem 3.17 from Textbook)

(a) Consider a multi-degree-of-freedom robotic arm with flexible joints and links. The purpose of the manipulator is to accurately place a payload. Suppose that the second natural frequency (i.e., the natural frequency of the second flexible mode) of bending of the robot, in the plane of its motion, is more than four times the first natural frequency.

Discuss pertinent issues of sensing and control (e.g., types and locations of the sensors, types of control, operating bandwidth, control bandwidth, sampling rate of sensing information) if the primary frequency of the payload motion is:

(i) One-tenth of the first natural frequency of the robot
(ii) Very close to the first natural frequency of the robot
(iii) Twice the first natural frequency of the robot

(b) A single-link space robot is shown in Figure P3.17. The link is assumed to be uniform with length 10 m and mass 400 kg. The total mass of the end effector and the payload is also 400 kg. The robot link is assumed to be flexible, although the other components are rigid. The modulus of rigidity of bending deflection of the link in the plane of robot motion is known to be $EI = 8.25 \times 10^9$ N · m^2. The primary natural frequency of bending motion of a uniform cantilever beam with an end mass is given by $\omega_1 = \lambda_1^2 \sqrt{\frac{EI}{m}}$, where m = mass per unit length, λ_1 = mode shape parameter for mode 1. For [beam mass/end mass] = 1.0, it is known that $\lambda_1 l = 1.875$, where l = beam length. Give a suitable operating bandwidth for the robot manipulation. Estimate a suitable sampling rate for response measurements to be used in feedback control. What is the corresponding control bandwidth, assuming that the actuator and the signal-conditioning hardware can accommodate this bandwidth?

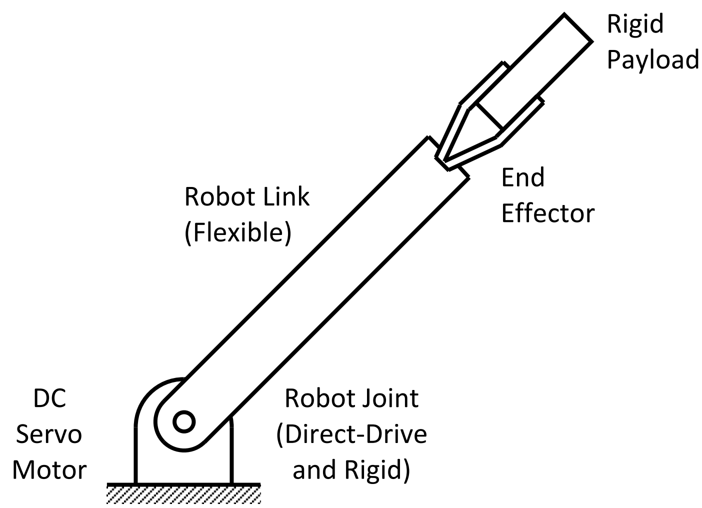

Figure P3.17: A single-link robotic manipulator.

Problem 6 (Problem 3.21 from Textbook)

(a) Explain why mechanical loading error due to tachometer inertia can be significantly higher when measuring transient speeds than when measuring constant speeds.

(b) A DC tachometer has an equivalent resistance $R_a = 20\ \Omega$ in its rotor windings. In a position plus velocity servo system, the tachometer signal is connected to a feedback control circuit with equivalent resistance 2 kΩ. Estimate the percentage error due to electrical loading of the tachometer at steady state.

(c) If the conditions were not steady, how would the electrical loading be affected in this application (Part (b))?

Problem 7 (Problem 3.30 from Textbook)

(a) Compare and contrast the "Absolute Error" method with the "square-root-of-sum-of-squares" (SRRSS) method in analyzing error combination of multicomponent systems. Indicate situations where one method is preferred over the other.

(b) Figure P3.30 shows a schematic diagram of a machine that is used to produce steel billets. The molten steel in the vessel (called tundish) is poured into the copper mould having a rectangular cross section. The mould has a steel jacket with channels to carry cooling water upward around the copper mould. The mould, which is properly lubricated, is oscillated using a shaker (electro-mechanical or hydraulic) to facilitate stripping of the solidified steel inside it. A set of power-driven friction rollers is used to provide the withdrawal force for delivering the solidified steel strand to the cutting station. A billet cutter (torch or shear type) is used to cut the strand into billets of appropriate length.

The quality of the steel billets produced by this machine is determined on the basis of several factors, which include various types of cracks, deformation problems such as rhomboidity, and oscillation marks. It is known that the quality can be improved through proper control of the following variables: Q = coolant (water) flow rate; v = speed of the steel strand; s = stroke of the mould oscillations; and f = cyclic frequency of the mould oscillations. Specifically, these variables are measured and transmitted to the central controller of the billet casting machine, which in turn generates proper control commands for the coolant-valve controller, the drive controller of the withdrawal rollers, and the shaker controller.

A nondimensional quality index q has been expressed in terms of the measured variables, as $q = \left[1 + \frac{s}{s_o}\sin\frac{\pi}{2}\left(\frac{f}{f_o + f}\right)\right] / (1 + \beta v/Q)$ where s_o, f_o, and β are operating parameters of the control system and are exactly known. Under normal operating conditions, the following conditions are (approximately) satisfied: $Q \approx \beta v$, $f \approx f_o$, $s \approx s_o$. *Note*: If the sensor readings are incorrect, the control system will not function properly, and the quality of the billets will deteriorate. It is proposed to use the "Absolute Error" method to determine the influence of the sensor errors on the billet quality.

i. Obtain an expression for the quality deterioration δq in terms of the fractional errors $\delta v/v$, $\delta Q/Q$, $\delta s/s$, and $\delta f/f$ of the sensor readings.

ii. If the sensor of the strand speed is known to have an error of ±1%, determine the allowable error percentages for the other three sensors so that there is equal contribution of error to the quality index from all four sensors, under normal operating conditions.

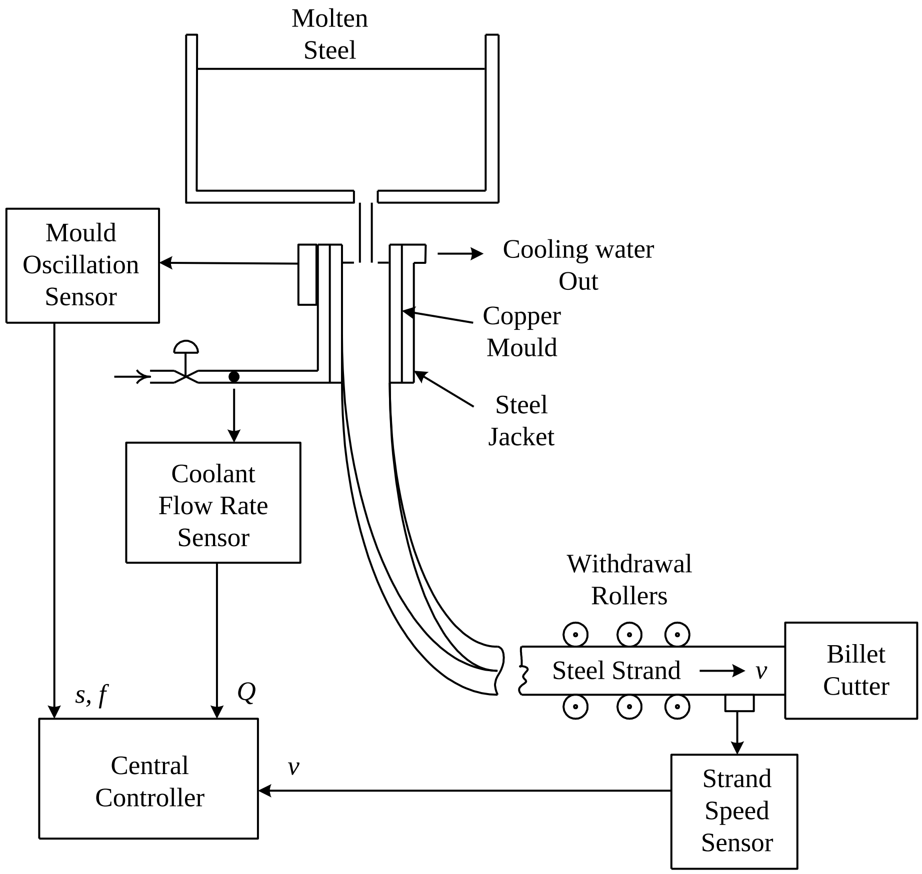

Figure P3.30: A steel-billet casting machine.