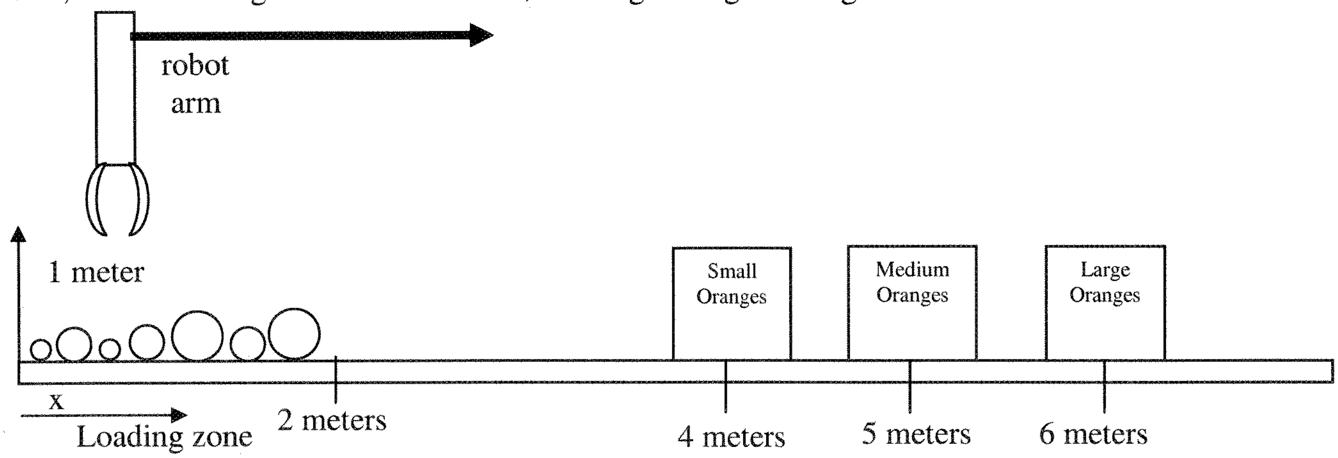
MAE 106 Mechanical Systems Laboratory
Winter 2006 Design Exam

You are a control engineer working with a team of engineers for an orange processing plant. Your team's goal is to design a robotic arm that sorts oranges by size. The arm will place small oranges in small crates, medium oranges in medium crates, and large oranges in large crates.



One engineer on your team is designing a vision system that will guide the robot arm to an orange in a "loading zone" then lift the orange directly upward 1 meter. Your job is to design the controller that will then move the robot arm above the appropriate crate, and drop the orange into the crate. Your controller will receive information about the size of the orange from sensors in the gripper. You are given the above schematic and the following information and equipment to work with:

- the loading zone is 2 meters wide.
- crates are 0.6 meters wide.
- the robot arm behaves like a mass (M = 10 kg) and a damper (B = 1 Ns/m).
- the robot arm is controlled by a DC brushed motor attached to a lead screw, and powered by a current amplifier. A one volt input into the current amplifier gives 10 N of motor force to move the robot.
- you have access to the voltage signal from a potentiometer that measures the horizontal position of the robot arm. The pot voltage is zero at x = 0 m, and 10 volts at x = 10 m.
- once the robot arm grabs the orange and lifts it to a height of 1 meter, your controller receives a 0-10 Volt step change in voltage from a subsystem designed by an engineer in charge of high level path planning. The magnitude of the voltage dictates where the robot arm must move to before it drops the orange. For example, for a small orange, the step change in voltage is 4.0 volts, and for a large orange, the voltage is 6.0 volts.
- the maximum allowed stiffness of your controller is K_p = 10 N/m. This limit has been specified by the safety engineer on the design team, in order to keep the robot relatively "soft" so that it doesn't damage anything if it accidentally runs into an orange, crate, or person.
- you want the robot to move as fast as possible but still drop the orange in the correct crate.
- you must implement your controller using op-amps, resistors, and capacitors.

Design a controller to control the robotic arm. You will get full credit if you:

1) Show a control law for the robotic conveyor belt that relates the motor force (F) to the desired (x_d) and measured robot position (x). Use the symbols K_p and K_d for proporitional and derivative gains.
2) What are the closed loop dynamics of the system?
3) Choose gain values for your control law. State units.
4) What is the maximum time that it will take for your robot to move an orange?
5) What gain value should the proportional gain stage of your op amp circuit have, if you were to design an op amp circuit to implement this controller?

Name: SOLUTION

Lab Day and Time:

Circle your TA: Laura Marchal Daisuke Aoyagi Julius Klein

Answer Sheet – Put your answers in the boxes, and show your work to the right of the boxes.

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1) Answer:

$F = -K_p(x - x_d) - K_d\dot{x}$

$F = -K_p(x - x_d) - K_d(\dot{x} - \dot{x}_d)$ } acceptable

$F = K_p(x_d - x) + K_d\dot{x}$

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2) Answer:

$M\ddot{x} + (B+K_d)\dot{x} + K_p x = K_p x_d$

Robot behaves like:

$F = M\ddot{x} + B\dot{x}$

Closing the loop: $M\ddot{x} + B\dot{x} = -K_p(x - x_d) - K_d\dot{x}$

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3) Answer:

$K_p = 10\ N/m$ $K_d = 12.6\ Ns/m$

(if $\zeta = 1$, $K_d = 19\ Ns/m$)

Desire robot to move up to 6 meters as fast as possible but still drop orange in .6 m wide crate. Worst case overshoot and still suceed:

$\frac{0.3m \text{ overshoot}}{6m \text{ amplitude}} = 5\%$ settling criteria

$t_s|_{5\%}$ is minimized at $\zeta = .68$

$\zeta = \frac{B + K_d}{2\sqrt{K_p M}} = .68 = \frac{1 + K_d}{2\sqrt{(10)(10)}} \Rightarrow K_d = 12.6\ Ns/m$

Half credit if you choose $.68 < \zeta \le 1$

$\zeta = 1 \Rightarrow \frac{1 + K_d}{2\sqrt{(10)(10)}} \Rightarrow K_d = 19\ Ns/m$

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4) Answer:

4.4 sec

(if $\zeta = 1 \rightarrow 3.0$ sec)

$t_s|_{5\%} \approx \frac{3}{\zeta\omega_n} = \frac{3}{(.68)(1)} = 4.4$ sec } Acceptable answers

$\omega_n = \sqrt{\frac{K}{M}} = \sqrt{\frac{10}{10}} = 1$ rad/s

If you chose $\zeta = 1$: $t_s|_{5\%} \approx \frac{3}{\zeta\omega_n} = \frac{3}{(1)(1)} = 3.0$ sec

Strange: Why is settling time faster with more damping?

It really isn't! $t_s|_{5\%} \approx \frac{3}{\zeta\omega_n}$ is only an approximation.

At $\zeta = .68$, $t_s|_{5\%} = 2T = \frac{2}{(.68)(1)} = 2.9$ sec

At $\zeta = 1$, $t_s|_{5\%} = 4.7T = \frac{4.7}{(1)(1)} = 4.7$ sec

"The whole story" see graph at left from Ogata p 234

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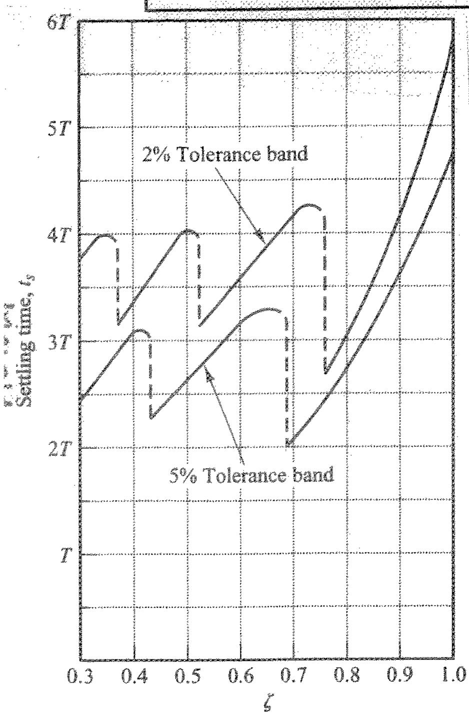
5) Answer:

$\frac{K_p}{10} = 1$



$F = -K_p(x - x_d)$ controller

$V = -G(V - V_d)$ op amp

$F = 10Gx = K_p x$

$G = \frac{K_p}{10}$