

Cleveland State University
Department of Electrical and Computer Engineering
Control Systems Laboratory

Experiment #7

Properties and Tuning of Three-Mode (PID) Controllers

INTRODUCTION

Many industrial processes employ standard controllers to control such things as temperature, pressure, flow rate, liquid level, etc. These controllers are referred to as three mode controllers because they can be operated in what is called a proportional mode, or in an integral mode, or in a derivative mode, or in any combination of these three modes simultaneously. Hence another name for such a controller is a proportional plus integral plus derivative (or P+I+D or PID) controller. The purpose of this experiment is to familiarize you with the operation of a PID controller and to teach you a method for tuning it, i.e. a method for selecting its gains.

We will use a liquid level system as the system to be controlled with the PID controller, but this liquid level system is simply a vehicle for teaching the characteristics and use of a PID controller; its operation in and of itself is of secondary interest.

In the next section we describe the physical layout and general operation of the liquid level system and the controller. After that, a section is devoted to a detailed explanation of the modes of controller operation. A third section describes the procedure to be used for proper tuning of the controller. Subsequent sections deal with the conduct of the experiment.

Liquid Level System

The liquid level system to be controlled is shown in schematic form in Figure 1. Water is pumped from a plastic water storage tank located on the floor to a glass tank located in the upper left section of the overall apparatus. The water is then returned to the storage tank, making this a completely self contained system. The objective of control is to maintain the water level in the glass tank at some desired level; the plastic storage tank is there simply to re-use the water and make the system self contained.

The level in the glass tank is maintained constant by opening and closing the control valve (see Figure 1); the control valve is an automatic valve which can be manipulated by the PID controller. Note that all other valves in Figure 1 are manual valves which are opened and closed by hand. Figure 1 also shows a level sensor at the bottom of the tank (all future references to “tank” will mean the glass tank). The tank has level marks ranging from zero (meaning zero level) to 100, in steps of 10, and the engineering units of level in this experiment are these marks. The level sensor is a pressure sensitive device which produces an electrical current proportional to pressure (hence level) in the tank. It is calibrated so that as the level varies from zero to 100, the sensor output current varies linearly from 4 ma to 20 ma. This current signal is the level feedback signal used by the PID controller.

The control valve is actually a pneumatic valve which opens and closes as an air pressure to

the valve is varied. However, the controller output is an electrical current which varies between 4 ma and 20 ma. To accommodate this difference in signal type, a current-to-air converter (mounted on the valve) changes the 4-20 ma controller output variation into a 3-15 psi air pressure variation which is applied to the valve. The valve also requires a constant 20 psi air source (which is supplied by the building air supply). Figure 1 also shows a flow meter which is used to measure the flow into the tank.

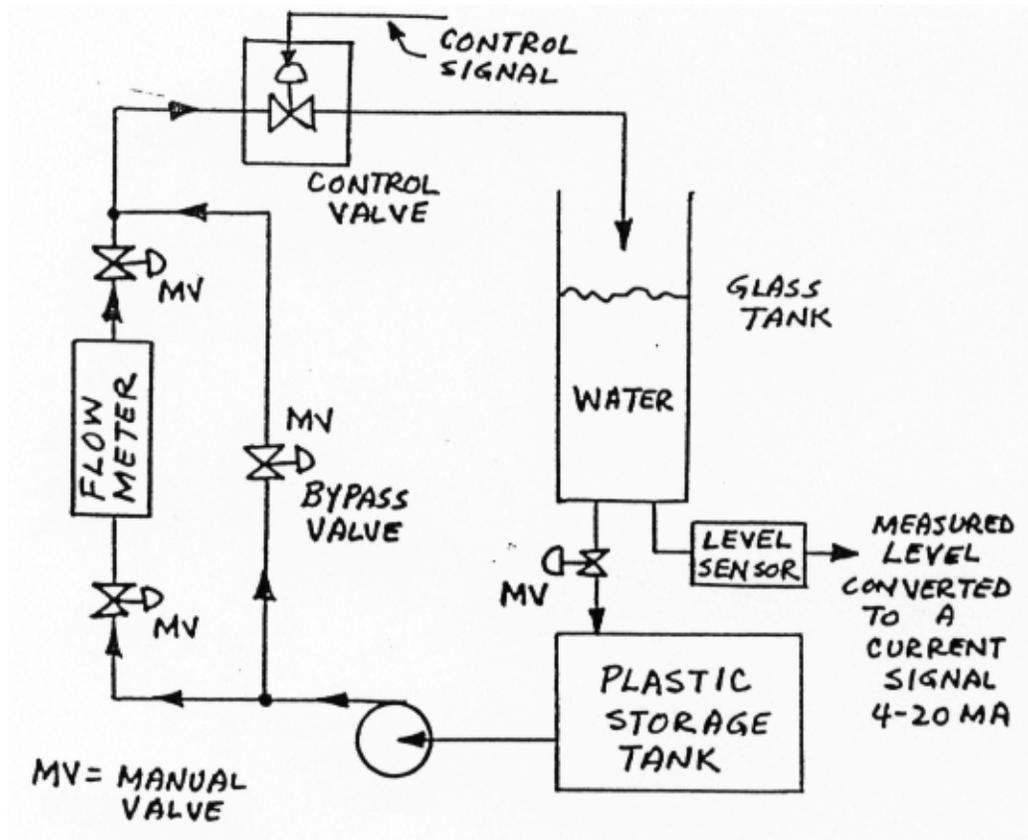


Figure 1: Liquid Level System

Figure 2 shows a block diagram of the overall control loop. A detailed representation of the controller and the current to air converter, showing the different signal types, is given in Figure 3. The set point (or desired level) is determined from the face of the controller; thus, in Figure 3, the set point dial is shown as being inside the controller. The output of the controller is a 4-20 ma signal which is changed by the current to air converter to a 3-15 psi signal before it is applied to the control valve. Again, the current to air converter is the round, black device physically mounted to the green control valve housing. The level signal feedback to the controller is a 4-20 ma signal representing level; this signal is scaled inside the SLC controller back from ma to tank level in marks as shown in Figure 3.

The controller can be operated in either automatic or manual. When in automatic, it functions as described above, i.e. it controls the process and outputs a correction to the valve--a correction which depends on the error between the level set point and the measured level. When the controller is in manual, the controller output to the valve is set by the operator who can change the control signal from the face of the controller; in the manual mode the controller output does not depend on the control error. Thus, in manual, the operator can adjust the controller output as she wishes in order to open and close the valve; but in manual the controller does not respond to

any set point change or any variation in measured level.

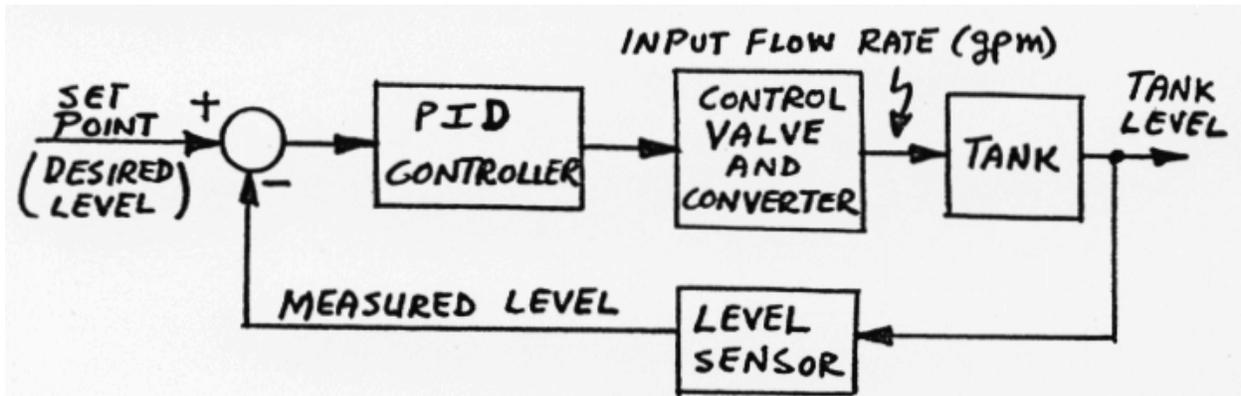


Figure 2: Liquid Level Control Loop

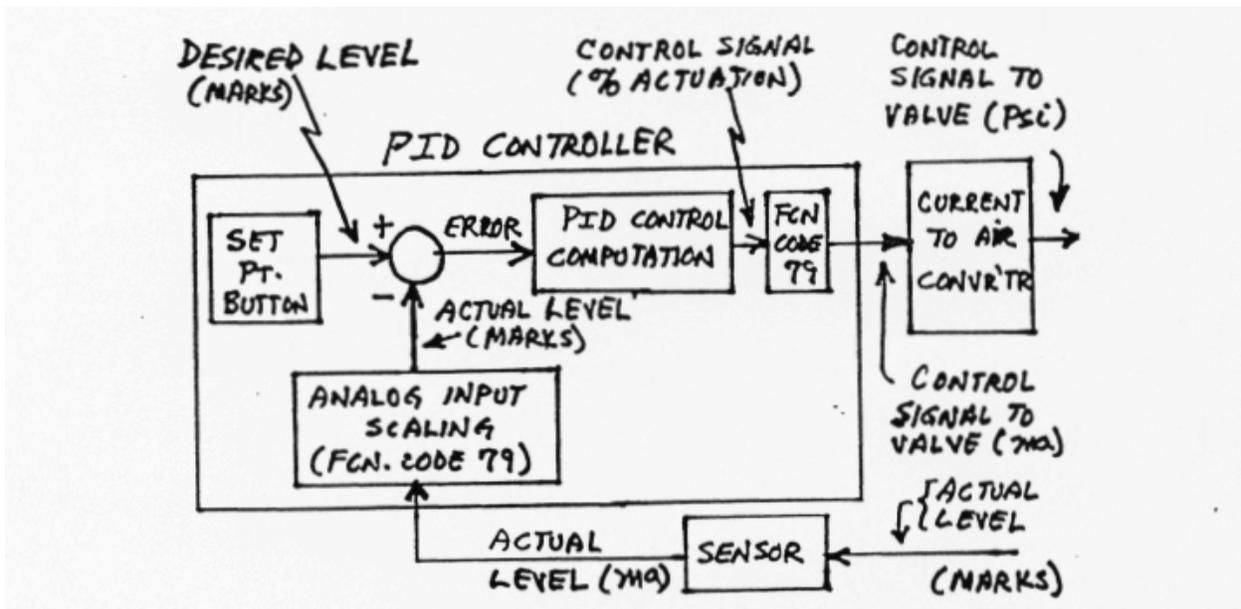


Figure 3: PI Controller and Valve

The tanks, level sensors, valves, piping, etc. are all mounted within a silver angle-iron frame against the wall; the controller, patch panel and associated electronics and power supplies are mounted in a black angle iron frame which is bolted to the tank frame. This is represented in Figure 4. Based on Figure 3 and the discussion above, it should be clear that the signals that travel between the process and the patch panel and controller are those shown in Figure 4. The level sensor output must be patched to the controller input, and the controller output must be patched to the current-to-air converter and control valve input.

In this experiment you will use the SLC controller. This controller has four analog inputs and two analog outputs: use analog input #1 and analog output #1. Analog input #1 will be "level" in the tank, so connecting the strip-chart recorder to the analog input #1 measurement jacks will allow you to record level.

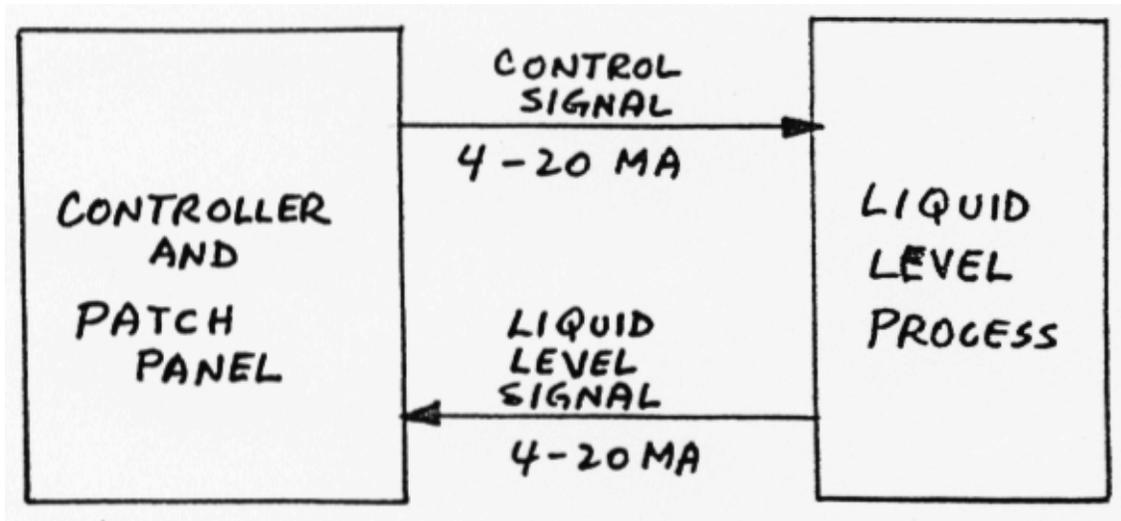


Figure 4: Controller and Process Configuration

Controller Modes of Operation

The SLC controller to be used throughout the experiment is a three mode or PID (proportional plus integral plus derivative) controller. The output of such a controller has a component proportional to the error, a component proportional to the integral of the error, and a component proportional to the derivative of the error. If we let $e(t)$ represent the error and $u(t)$ represent the controller output, then

$$u(t) = K_p e(t) + K_I \int_0^t e(\lambda) d\lambda + K_D \dot{e}(t)$$

or

$$U(s) = K_p E(s) + (K_I / s) E(s) + K_D s E(s)$$

where K_p , K_I and K_D are the proportional, integral and derivative gains respectively. In this experiment we will use only the PI mode (no derivative action; $K_D = 0$). With most industrial PID controllers the error $e(t)$ used in the algorithm is the error expressed as a percent of its full range of variation, and the control output $u(t)$ is interpreted by the device or algorithm that converts that output to ma to be control action in percent of full actuation. Specifically, the output of the controller drives an actuator: 0% actuation ($u(t) = 0$) means the actuator is “shut” or “off”; 100% actuation ($u(t) = 100$) means the actuator is “full-open” or “full-on”. To allow for conversion of the error $e(t)$ from its engineering units (“marks” in this experiment) to a percent of its full range of variation, the SLC controller has a conversion factor multiplying all three terms in the controller. This conversion factor is $K = 100/(e_{\max} - e_{\min})$ so that $Ke(t)$ is error as a percent of its full range of variation. Using this conversion factor, the PI algorithm is then given as

$$u(t) = K [K_p e(t) + K_I \int_0^t e(\lambda) d\lambda]$$

You should, at this point, figure out what the conversion factor K is for this experiment.

The integral gain in industrial PID controllers has the units of 1/minutes or resets/minute or repeats/minute. To understand where these units come from suppose that at some time t_1 there is a step change of Δe in the error $e(t)$ as shown in Figure 5. The controller output will immediately jump by a value $M_P = KK_P(\Delta e)$ due to the proportional part of the controller.

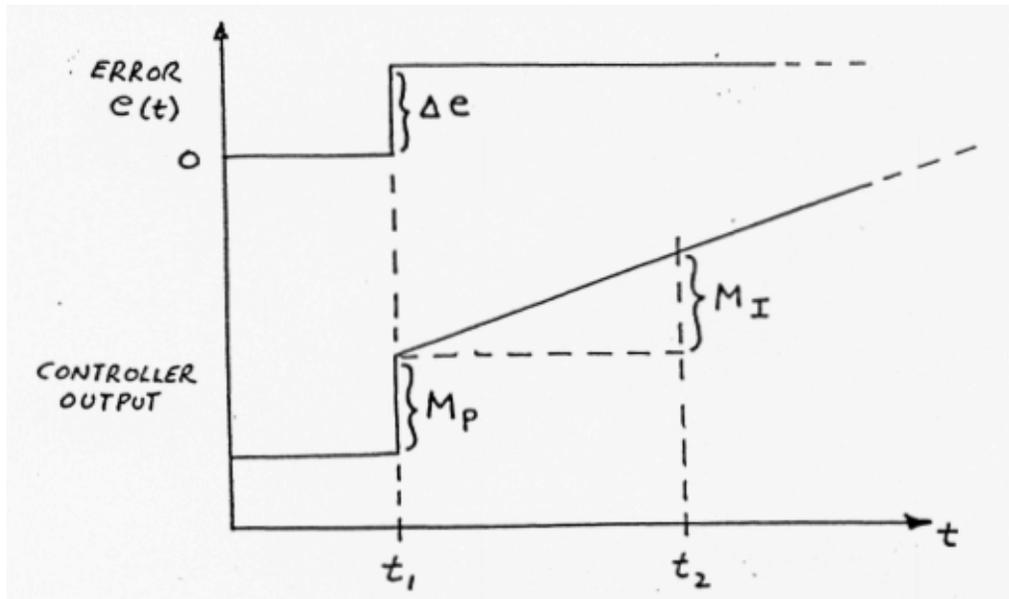


Figure 5: Integral Action Time

Then, as long as the error signal does not start to change (for example, if the feedback is disconnected from the controller), the controller output will continue to rise in a ramp-like fashion as shown. The ramp portion, given as

$$KK_I \int_{t_1}^t (\Delta e) dt = KK_I (\Delta e)(t - t_1),$$

is due to the integral part of the PI controller. Assume that at time t_2 the integral part of the controller output, M_I , is equal to the initial change in the output due to the proportional part of the controller, i.e. $M_I = M_P$. Thus, if we let $T_R = (t_2 - t_1)$,

$$M_P = KK_P(\Delta e) = M_I = KK_I(\Delta e)T_R$$

or

$$T_R = K_P/K_I$$

or

$$K_I = K_P/T_R$$

T_R is the time it takes the integral part of the controller to produce the same change in $u(t)$ in response to Δe as that produced by the proportional part of the controller in response to Δe . It is the time it takes the integral part of the controller to repeat the proportional action, and it can be thought of as having the units minutes/repeat. For a given proportional gain K_p , the larger the integral gain K_I is the steeper will be the ramp and the smaller T_R will be, i.e. one will get more repeats/minute (fewer minutes/repeat) with a larger K_I . Most commercial controllers express integral gain in units of repeats/minute or resets/minute, and they also assume time is measured in minutes, not seconds. The integral portion of the controller is often referred to as “integral action” or “reset action” or just “reset” because integral control will generally “reset” the output to the set point in the face of disturbance upsets whereas proportional action alone will not do that. Thus T_R is sometimes referred to as “reset rate” although it makes more sense to think of it in terms of repeats/minute.

PI Controller Tuning Method

The term “tuning” in this context means the process of choosing the two PI controller gains K_p and K_I so that the closed loop system has a “good” transient response. Over the years a number of tuning procedures have evolved, each emphasizing a slightly different criteria for judging what is meant by “good” transient response, and each specifying a different method for going about determining controller gains which yield that “good response. The methods can be grouped under two major headings: open loop methods and closed loop methods. However, they all lead to controller gains which produce about the same closed loop response characteristics. A good reference on the various open loop methods is, J.A. Miller, A.M. Lopez, C.L. Smith and P.N. Murrill, “A Comparison of Controller Tuning Techniques,” Control Engineering, December 1968, pp. 72-75. The method to be used in this experiment is a closed loop method in which the controller gains are obtained while the controller is actually controlling the process (as compared to open loop methods in which the open loop step response is used to determine the controller gains). A good reference on closed loop methods is, An Introduction to Process Dynamics and Control, by Thomas W. Weber, John Wiley and Sons, Inc., 1973. The closed loop method we will use here is called the Ultimate Sensitivity Method.

The tuning procedure is as follows. The process is run closed loop with just proportional control. The proportional controller gain is increased until the process **just** begins to maintain a steady oscillation. If we let $K_{p,max}$ be the proportional gain which just produces oscillation, and P_u be the period of the oscillation (in minutes), then the proportional and integral gains to be used with a PI controller on this process are given by

$$K_p = 0.35(K_{p,max})$$

and

$$K_I = 0.6(K_p/P_u)$$

PROCEDURE

Part I—Familiarization With the Controller and Liquid Level System

The purpose of this first part of the experiment is to familiarize you with the controller and the liquid level system.

1. From the foregoing discussion and diagrams you should be able to identify the liquid level system (tanks, piping, flow meter, etc.) as well as the patch panel and controller. Hook up the control loop using the proper jacks on the patch panel. Use the SLC controller, analog input #1, and analog output #1. Connect an ammeter into the loop so that the measured level (transmitter output current) can be read. Also connect both channels of the strip-chart recorder to the analog #1 measurement jacks, and the green chassis ground lead on the recorder input to the green ground jack on the patch panel: since analog input #1 is measured level, this connection allows you to record measured level. When you feel confident about your hook-up, call the instructor over and explain the complete system to her.
2. **Under the instructor's supervision**, turn on the air supply and the controller panel power. Then put the controller in manual and open the control valve manually.
3. Since the controller will be used in the automatic mode, it is worthwhile setting up initial gains at this point. Set the controller proportional gain to 15, the integral gain to 60, the derivative gain to zero (derivative mode is not used here), and the conversion factor to 1.0.
4. Set the set point to 30 and put the controller in "auto" (the control valve should open). Turn on the pump: water should begin to flow into the tank and the controller should bring the level to 30 and maintain it there.
5. After the level has settled out, make step changes in the level set point from 30 to 40, 40 to 50, 50 to 40, and 40 to 30. To make a step change in level set point, proceed as follows. First, it is assumed that the controller is in auto and the level is steady at the desired level. Then put the controller in manual. The controller is designed so that when it is put in manual the current out of it will be held constant at the value that existed just before it went to manual. Therefore, going to manual should not cause a change in the control valve or the flow rate or the level (as long as no disturbance occurs in the system). The level set point can now be changed to the new set point. Since the controller is in manual, the set point is being ignored by the controller; hence this change will have no effect on the controller output. However, if the controller is now returned to auto, the controller will see this new set point as a step change from the old one--and it will control to this new set point. For this operation to be effective however, you must do the manual/set-point-change/auto sequence **FAST**. Ask your instructor to show you how to operate the strip chart recorder. Then record the level step responses indicated above. **Note that these are closed loop step responses**. Choose a chart speed so that each response is not stretched out or squeezed up too much, and choose a voltage scale so that each response uses almost the full scale.

DISCUSSION QUESTIONS

1. Mount the strip chart recordings of the level responses. Follow the mounting instructions given in the procedures for the laboratory. Make sure time is moving to the right. Clearly label each recording (time scale, ordinate, controller gains, level, date, etc.).
2. Draw a complete block diagram of the system showing the controller, the tank, the valve, and the sensor. Give each block a name, and **label all arrows (signals) with three things: a name, symbol, and units.** Is this a unity feedback system? **Why or why not?**
3. Derive a transfer function $G_p(s)$ for the tank part of the controlled system. The input is the inflow $q_{IN}(t)$ or $Q_{IN}(s)$ and the process output or controlled output is the level $l(t)$ or $L(s)$. Assume the outflow $q_o(t)$ is proportional to the level $l(t)$, i.e. $q_o(t) = c_o l(t)$ where c_o is some constant. To derive the transfer function $G_p(s)$, first derive the differential equation governing the relationship between level $l(t)$ and inflow $q_{IN}(t)$, and then LaPlace transform it to get $G_p(s)$. When deriving the differential equation, **BE SURE YOU USE CONSISTENT UNITS FOR FLOW RATE, LEVEL (MARKS), VOLUME, TIME, ETC.**
4. What is the PI controller transfer function $G_c(s)$. You should be able to determine not only its general form, but also the values of all the coefficients of “s”.
5. What is the system type, and what should the steady state error be? **Explain.**
6. Draw a root locus for the system. Does it predict the observed responses? Did you observe overshoot? Does your root locus predict overshoot? **Explain.**

Part II—Calibration of the Level Sensor

The objective of this part of the experiment is to calibrate the level sensor or, as it is called in practice, the level transmitter (it is called a transmitter because it transmits back to the controller a current signal proportional to level). The transmitter will be calibrated by filling the tank, then emptying it manually in steps of 10 marks, and reading the transmitter output current at each level step.

- (a) **Under the instructor’s supervision,** fill the tank to just above the 100 mark. This is done most easily (and safely) by putting control in manual, opening the control valve all the way, and closing the manual valve at the tank output. The tank will fill rapidly. When it has reached a level above the 100 mark, **turn the pump off by throwing the pump switch!** Do not attempt to stop the inflow by closing the control valve-it is too slow and the tank may overflow.
- (b) Using the manual valve at the tank outlet, drop the level from 100 to zero in steps of 10 marks. At each step (level), record transmitter output current (ma). Then determine the calibration constant for the transmitter by obtaining the slope of the straight line fit to the data set. The final constant should be in (ma/mark).

DISCUSSION QUESTIONS

1. Draw the calibration curve for the transmitter. Label each axis with the variable's **name and units**.

Part III—Tuning the Controller

The purpose of this part of the experiment is to tune the PI controller. The gains used in Part I just allowed the system to be operated closed loop in a satisfactory manner; the gains obtained below represent proper tuning of the controller (to the process) and should result in an improved transient response. The procedure used in this part to select the gains is a procedure frequently used in an industrial setting.

1. Set the controller gains to the values used in Part I, and bring the system to steady state with the level set point at 30. Then reduce the integral gain to zero so that only proportional control is being used.
2. Increase the proportional gain, make a small change in the level set point (magnitude of about 5.0) and see if the closed loop system oscillates. Continue increasing the proportional gain until the oscillation doesn't die out and a steady oscillation is just obtained. Once the oscillation is achieved, record the oscillating level on the strip chart recorder; make sure you can accurately read the period of the oscillation. Record 5 or 10 cycles of the oscillation. Also record the proportional gain.
3. Calculate the PI gain settings using the expressions given in the Introduction to the experiment, set the controller to these gains and to a set point of 30. Then record step changes from 30 to 40, 40 to 50, 50 to 40 and 40 to 30.
4. Now change both gains (using intuition) by various amounts to see if you can get responses which are better than the "tuned" responses.

DISCUSSION QUESTIONS

1. Mount the strip chart recordings of the level responses. Follow the mounting instructions given in the procedures for the laboratory. Make sure time is moving to the right. Clearly label each recording (time scale, ordinate, controller gains, level, date, etc.).
2. Calculate the time it takes each level change response for this part of the experiment to reach steady state. Now do the same for the level change responses in Part I. **Make a table** with both sets of response times. **Discuss the differences**. Has tuning the controller improved the speed of response of the closed loop system? By what percentages has it been improved for the different cases.
3. In tuning the controller you made the process oscillate with just a proportional controller. Consider a unity feedback closed loop system with your $G_p(s)$ (derived in Part I) as the process (or controlled system) transfer function, and with a proportional-only controller. **Show** that theory does not predict this oscillation as the proportional gain is increased. Then **explain** how the oscillation could have occurred.
4. Discuss what happened when you tried to improve on the tuned gains yourself.