EXPERIMENT 6
CLOSED-LOOP TEMPERATURE CONTROL
OF AN ELECTRICAL HEATER

Introduction:
The main objective in this experiment is to:

- Learn the basics of Open-Loop and Closed-Loop temperature control.
- Observe the effects of each controller (P-Controller, I-Controller, D-Controller), on the dynamic behavior of the system, separately.
- Learn the basics of PID (Proportional, Integral, Derivative) controllers and a tuning method for finding the values of the controller constants.

Equipments:

<table>
<thead>
<tr>
<th>Table 1. List of Equipments</th>
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<tbody>
<tr>
<td>726 86</td>
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<tr>
<td>734 02</td>
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<tr>
<td>734 12</td>
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<tr>
<td>734 13</td>
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<td>734 061</td>
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<td>Metra Hit 25S</td>
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General Information:

Open and Closed Loop Control of Systems:

Each system has at least one input and one output. The systems output is called the process variable and this process variable (PV) can be changed to a desired value by setting the input signal to a specific value. Figure 1 shows the system block diagram and the equation representing its input to its output is given below.

Equation defining the system output ($Y(s)$: process variable) to the input signal ($X(s)$: input signal) is called the transfer function.
If the system output is controlled, by an operator changing the input signal manually, to have a desired value then; the system is said to be controlled in **Open-Loop**.

![Closed-Loop controlled System](image)

Figure 2. Closed-Loop controlled System

Figure 2 shows a system controlled in Closed-Loop form. A sensor is used to sample the output signal; this sample is subtracted from a reference value giving an error ($E(s)$). The reference value set to be proportional to desired output value. The system is automatically controlled by a controller according to the error signal. Once the error is set zero the system output ($Y(s)$) has reached its desired value ($Y_{ref}(s)$).

**Proportional - Integral - Derivative (PID) Controller:**

In previous classes** you have designed a closed-loop system using proportional ($P$) controllers. You have experimented and investigated that the P-controller can reduce the effects of disturbances and maintain an automatic control for a system. You have also seen that there was an unwanted nonzero steady-state error. You also figured out that trying to reduce the steady state error by increasing the gain of the P-controller would affect the settling time of the system in a bad manner.

In this work you will see that these problems (Steady-State Error and Settling Time) can solve by adding integral controller (I-controller) and a derivative controller (D-controller).

The PID controller has a transfer equation as shown below:

$$C(s) = k_p + \frac{k_i}{s} + k_d \cdot s = k_p \left[ 1 + \frac{1}{T_i s} + T_D \cdot s \right]$$

(2)

$k_p$:

This is main term defining the gain of the controller, also known as the gain of the P-controller.

$$\frac{k_i}{s} \text{ or } \frac{1}{T_i s}$$
The second term in equation defines the I-controllers. This controller includes a term proportional to the integral of the error \(E(s)\) signal. By doing this it is possible to eliminate steady-state error.

\(k_D s\) or \(T_D s\):

The third term in equation defines the D-controller. Addition of this term in to the controller stage provides an improvement in the dynamic response of the output. This controller can reduce the maximum overshoot and settling time of the output.

Sophisticated methods are available to develop a controller that will meet the steady-state and transients specifications for both tracking the input references and rejecting disturbances. These methods require that the designer has either a dynamic model of the system or a detailed frequency response over a substantial range of frequencies. Both of these can be very difficult to obtain for some systems. This problem engineers to develop some sophisticated methods in the identification of the system model. These methods lead to finding the necessary coefficients for a PID controller \((k_p, T_i, T_D)\). A general name for finding these parameters using some special techniques is called Tuning.

**Ziegler-Nichols PID Tuning Method:**

J. G. Ziegler and N. B. Nicholas (1942, 1943) recognized that the step response of a large number of systems exhibit an output curve as shown in Figure 3. This S-shape curve is characteristic for many systems and can be generated by running the system in open-loop configuration for a constant input.

![Figure 3. S-Shape Curve at Output for a Step Input](image)

This S-shape curve can be approximated into 1st order system with a time delay of \(L\) shown in Equation 3:

\[
H(s) = \frac{Y(s)}{X(s)} = \frac{K e^{-sL}}{T s + 1}
\]  

\(3\)
In this method, controller first put in manual mode where the output is set to 20%. The controller is allowed to operate at this percentage of output until the process reached a steady-state temperature – allowing to temperature to line up. If the variation is plotted with respect to time, this means that the graph will show a constant line. This can be seen in Figure 4 as a straight line before the 10% variation is introduced.

The next step in the process is to increase the output by 10% and record the variation with respect to time at the temperature output using an A/D converter and a computer where typical variation is illustrated in Figure 4.

Next step would be the determination of process gain $K_p$ which is the amount of change in the process variable ($\Delta PV$) divided by the amount of percentage change to the output signal from 0-100% ($\Delta Output$).

$$K_p = \frac{\Delta PV}{\Delta Output}$$  \hspace{1cm} (4)

Using Table 2, it is possible to tune the PID controller just by looking at the curve in Figure 4. Please note that these values are first estimates for the controller. You will then play with these parameters to obtain the desired characteristics. The effect of changing PID parameters separately on the response of system is summarized in Table 3.

### Table 2. Ziegler-Nicholas PID Tuning

<table>
<thead>
<tr>
<th>Controller Type</th>
<th>P-controller</th>
<th>I-controller</th>
<th>D-Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P$</td>
<td>$\frac{TC}{K_p \cdot DT}$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$PI$</td>
<td>$0.9 \cdot \frac{TC}{K_p \cdot DT}$</td>
<td>$3 \cdot DT$</td>
<td>-</td>
</tr>
<tr>
<td>$PID$</td>
<td>$1.2 \cdot \frac{TC}{K_p \cdot DT}$</td>
<td>$2 \cdot DT$</td>
<td>$0.5 \cdot DT$</td>
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</tbody>
</table>
Table 3. The effect of changing PID parameters on the system response.

<table>
<thead>
<tr>
<th>Effect of independent P, I, and D tuning on closed-loop response.</th>
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<tbody>
<tr>
<td>For example, while ( K_I ) and ( K_D ) are fixed, increasing ( K_P ) alone can decrease rise time, increase overshoot, slightly increase settling time, decrease the steady-state error, and decrease stability margins.</td>
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<tr>
<th>Procedure of Experiment:</th>
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1. **Open-loop operation: Determination of heater characteristics**

**Circuit Set-up:**

Assemble the circuit shown in Figure 5.

- Make sure that the PID controller is OFF, i.e., \( V_{ref} \) is directly connected to power amplifier.
- Set \( V_{ref} \) to zero volts and apply power to your circuit. You should see zero volts across heater (lamp). No light will be emitted from lamp. Write down the voltage at the output of the sensor (voltmeter \( V_{temp} \)) and room temperature (\( T_{amb} \)) at this condition. Fill in values in Table 4.
- Set the fan adjustment knob to minimum value, i.e., equals to 1 and make sure that mechanical louver is closed, i.e., in position 0.
- You should also connect reference voltage \( V_{ref} \) and sensor output voltage \( V_{temp} \) to the Channel A and B analog inputs of the Cassy A/D converter, respectively.
- Turn-on the computer and start Cassy program. Click on the left top circle in box named LD 524 016 of Figure 5a to activate that channel and set its parameters according to Figure 5b. Repeat procedure for other channel.
- Click on the **Display Measuring Parameters** button. Set sampling interval to 0.5 sec and total number of samples to maximum value.
- Make sure that the switch on reference voltage regulator is in position to zero volts. Adjust \( V_{ref} \) to 10V – this will apply 20V across the lamp. Start the sampling process by pressing F9 key. You should see on computer screen 0V reference voltage and about 2.1V for the sensor output voltage. 0.5 minutes after you start sampling throw the switch on reference voltage generator to 10V. On the computer screen you will see a step change in reference voltage.
- Lamp will be emitting high intensity light at this moment.
- Test time for this part should be long enough to obtain a nearly constant heater temperature (no large changes in temperature). When temperature levels out to a steady state value (near straight line) you can stop sampling by pressing F9 key again. Write down in Table 4, time and reference voltage at the end of this part.
- Plot the variations of temperature in Celsius (\( T_{temp} \)) with time in your report using the sensor conversion ratio.
• Calculate the temperature span \(T_{\text{span}}\) of this process by subtracting the end temperature from the value at the beginning of test. Write value in Table 4.
• At this time cool the heater, by turning fan knob to 10 and mechanical louver in position 4. After heater is cooled down, turn them back into original values.
• Determine the reference voltage value that will operate the heater at 20% of temperature span \(T_{\text{span}}\) and repeat the above steps for this operating point. Start the sampling and look at on the oscilloscope until you see a straight line at this reference voltage level.
• At this steady temperature operating with 20% value, introduce additional 10% change into the reference voltage and record the temperature output of heater. You should obtain a curve similar to the one given in Figure 4.
• Write down the values for your system in Table 5 with reference to Figure 4.

![Figure 4. Temperature control of electrical heater, open-loop.](image)

![Figure 5. Cassy program channel setup.](image)

2. **Closed-loop operation of electrical heater**

**Circuit Set-up:**

Assemble the circuit shown in Figure 6.

- Using the temperature-time curve determine PID coefficients employing Ziegler-Nichols method. Write values in Table 6.
- Adjust reference voltage such that heater temperature is 60 °C.
- Connect reference voltage \(V_{\text{ref}}\) and sensor output voltage \(V_{\text{temp}}\) to the Channel A and B analog inputs of the Cassy A/D converter, respectively.
Monitor and record the step responses on the Cassy program for the closed-loop system using $P$, $PI$ and $PID$ controller, separately. Include responses of individual controllers in your report.

If necessary, fine tune these coefficients to obtain best performance and write these new values in Table 7.

Introduce some disturbances to system that operates with PID control at a steady-state point and see the response of system to these disturbances. One example of such a disturbance would be to increase the speed of cooling fan form 1 to 3. Include the response curve in your report.

![Diagram of the electrical heater setup](image.png)

**Figure 6. Temperature control of electrical heater, closed-loop.**

**Conclusion:**

The transfer function of the system you will use in the lab is as follows:

$$H(s) = \frac{K \cdot e^{-sL}}{T \cdot s + 1}$$

where,

- $K$: is the gain of the system
- $L$: delay time
- $T$: rise time

Figure 7 shows the MatLab/Simulink model of this system due to the transfer function given in Equation 5. The time delay ($T_D$) operator in the transfer function was modeled with a transport delay element with a value of 7.3 seconds, the rest was modeled with a transfer function block with $K_s$ of 5.8 and $T_r$ of 60 seconds. Since the temperature starts rising from the room temperature and it must be added to the output. The summing network output has two gain functions as you can see the upper one has a gain constant 1 where you can measure the real temperature, and the lower one has a gain of 0.1 modeling the sensor so that you can use in your feed-back circuit.
*Design and tune a *PID* controller using the Ziegler-Nicholas *PID* tuning method that has been shown to you in your Industrial Electronic course.

*You must design the closed loop system with *PID* controller using Matlab/Simulink and verify that the controller works. From results make a fine tuning which gives the minimum overshoot and minimum settling time with minimum error.*

**References:**


# EXPERIMENT 5: CLOSED-LOOP TEMPERATURE CONTROL OF AN ELECTRICAL HEATER

<table>
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## Table 4:

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>$T_{amb}$ (°C)</th>
<th>$V_{temp}$ (V)</th>
<th>$T_{span}$ (°C)</th>
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<tbody>
<tr>
<td>Start</td>
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## Table 5:

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<th>$K_p$</th>
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## Table 6: Electrical heater controller parameters, *initial values*

<table>
<thead>
<tr>
<th>Proportional (P)</th>
<th>Proportional-Integral (PI)</th>
<th>Proportional-Integral-Derivative (PID)</th>
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<tbody>
<tr>
<td>$P$</td>
<td>$I$</td>
<td>$P$ $I$ $D$</td>
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## Table 7: Electrical heater controller parameters, *values after fine tuning*

<table>
<thead>
<tr>
<th>Proportional (P)</th>
<th>Proportional-Integral (PI)</th>
<th>Proportional-Integral-Derivative (PID)</th>
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<td>$P$</td>
<td>$I$</td>
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