Quanser NI-ELVIS Trainer (QNET) Series:

QNET Experiment #06: HVAC Proportional-Integral (PI) Temperature Control

Heating, Ventilation, and Air Conditioning Trainer (HVACT)

Student Manual

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1. Laboratory Objectives

The objective of this experiment is to design a temperature closed-loop controller that meets required specifications. The system should track and/or regulate the desired chamber temperature with minimum peak time and overshoot.

A pre-requisite to this laboratory is to have successfully completed the system identification experiment described in Reference [3]. This laboratory is consistent with the system nomenclature used in Reference [3].

2. References

[1] *NI-ELVIS User Manual.*
[2] *QNET-HVACT User Manual.*
[3] *QNET Experiment #05: HVAC System Identification.*

3. Pre-Lab Assignments

This section must be performed before you go to the laboratory session.

3.1. Pre-Lab Assignment #1: Open-Loop Transfer Function

In a first approach and in the present laboratory, the HVACT system is assumed to be a Single-Input-Single-Output (SISO) plant. This is motivated by the fact that both heating and blowing processes have first-order transfer functions, G_h and G_b respectively, with similar system parameters.

While the controlled output is always the chamber temperature T_c, the controlled input is either the heater or the blower voltage (but not both simultaneously) depending on whether the chamber needs to heated up or cooled down. Such a switching mechanism results in a "decoupling" between the the two inputs. The remaining HVAC input voltage is "disabled" and set to zero.

Therefore, the HVAC open-loop chamber transfer function, $G_c(s)$, from input voltage to chamber temperature difference can be defined such as:

$$G_c(s) = \left(\frac{\Delta T_c(s)}{V_c(s)} = \frac{K_{ss\_c}}{\tau_c s + 1} \right) \quad [1]$$

where the model variables are defined in Table 1, below.

Symbol	***Description***	***Unit***
V_c	Chamber Command Voltage	V
K_{ss_c}	Chamber Open-Loop Steady-State Gain	ºC/V
τ_c	Chamber Open-Loop Time Constant	s
s	Laplace Operator	rad/s

Table 1 HVAC SISO Model Nomenclature

As described in Reference [3], it is reminded that the temperature difference, ΔT_c, is the difference between the actual chamber temperature, T_c, and the assumed-constant ambient temperature, T_a.

The first-order transfer function parameters of Equation [1] can be calculated as the average values of the model identified in Reference [3]. This is shown below:

$$K_{ss\_c} = \frac{1}{2} K_{ss\_h} + \frac{1}{2} K_{ss\_b} \quad \text{and} \quad \tau_c = \frac{1}{2} \tau_h + \frac{1}{2} \tau_b \quad [2]$$

1. From the system estimates obtained in Reference [3], obtain a numerical expression for the chamber open-loop steady-state gain K_{ss_c} and time constant τ_c, as defined in Equation [2].

2. What is the type of the system? What can you infer about the resulting steady-state error?

3.2. Pre-Lab Assignment #2: Closed-Loop Transfer Function

The purpose of the laboratory is to design a controller that allows us to command the chamber temperature to a desired level with no steady-state error. Therefore, a Proportional-plus-Integral (PI) control scheme is first chosen. This results in a temperature closed-loop diagram similar to the one illustrated in Figure 1, below.

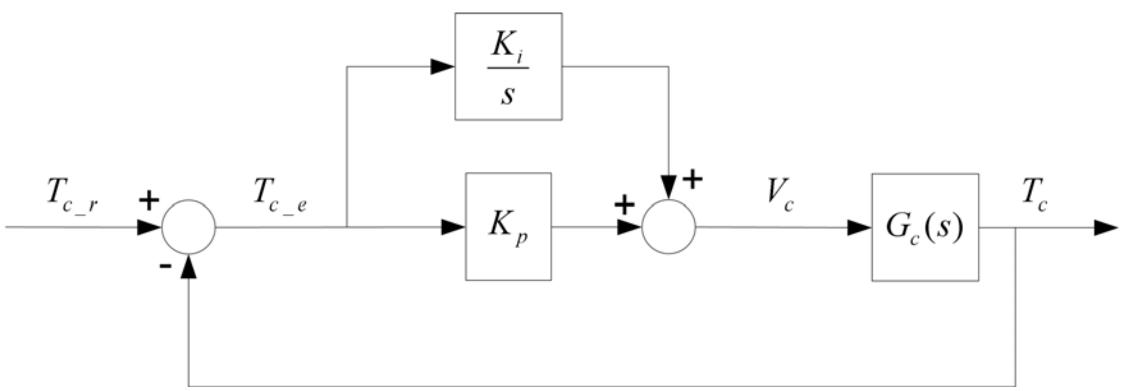

Figure 1 Temperature PI Control Loop

The PI control law implemented in the block diagram of Figure 1 can be formulated as follows:

$$V_c(t) = K_p\, T_{c\_e}(t) + K_i \int T_{c\_e}(t)\, dt \qquad [3]$$

where the temperature error, T_{c_e}, can be expressed as shown underneath:

$$T_{c\_e}(t) = (\Delta\, T_{c\_r}(t) - \Delta\, T_c(t) = T_{c\_r}(t) - T_c(t)) \qquad [4]$$

The corresponding control loop gains and variables are enumerated in Table 2, below.

Symbol	***Description***	***Unit***
K_p	Proportional Gain	V/ºC
K_i	Integral Gain	V/s/ºC
T_{c_r}	Reference Chamber Temperature (i.e. Setpoint)	ºC
T_{c_e}	Chamber Temperature Error	ºC

Table 2 PI Control Loop Nomenclature

The sign of the command voltage V_c, as calculated in Equation [3], can then be used to implement the switching strategy between the plant two possible inputs, that is to say V_h and V_b. Specifically, the sign of V_c determines whether the chamber needs to heated up (i.e. V_h is controlled by the PI loop and V_b is set to zero) or cooled down (i.e. V_h is set to zero and V_b is controlled by the PI loop). Such a switching strategy is formulated by Equation [5] below:

$$V_h(t) = \begin{cases} V_c(t) & 0 \le V_c(t) \\ 0 & V_c(t) < 0 \end{cases} \quad \text{and} \quad V_b(t) = \begin{cases} 0 & 0 \le V_c(t) \\ |V_c(t)| & V_c(t) < 0 \end{cases} \qquad [5]$$

1. The resulting closed-loop transfer function, $T_{CL}(s)$, of the PI control system is defined in the Laplace domain as follows:

   $$T_{CL}(s) = \frac{T_c(s)}{T_{c\_r}(s)} \qquad [6]$$

   Using the control block diagram [1] and/or Equation [3], derive the expression of $T_{CL}(s)$ as a function of the system parameters (K_{ss_c} and τ_c) and the PI controller gains (K_p and K_i).

2. $T_{CL}(s)$ should be a second-order system whose denominator can be expressed under the following standard form:

$$s^2 + 2\,\zeta\,\omega_n\,s + \omega_n^{\,2} \qquad [7]$$

where s is the Laplace operator, ζ the damping ratio, and ω_n the undamped natural frequency.

Derive expressions for the proportional and integral gains, K_p and K_i, as functions of the system parameters, the damping ratio ζ, and natural frequency ω_n.

3. For such quadratic systems, it is reminded from classic control theory that the response peak time, t_p, can be expressed as:

$$t_p = \frac{\pi}{\omega_n \sqrt{1-\zeta^2}} \qquad [8]$$

Likewise the response Percent Overshoot (PO) can be formulated as:

$$PO = 100\, e^{\left(-\frac{\pi\,\zeta}{\sqrt{1-\zeta^2}}\right)} \qquad [9]$$

Derive expressions for the proportional and integral gains, K_p and K_i, as functions of the system parameters, the damping ratio ζ, and the time to first peak, t_p.

3.3. Pre-Lab Assignment #3: Controller Design

1. Additionally to exhibiting no steady-state error to a step input, the temperature closed-loop response is desired to achieve the following design specifications in terms of peak time, t_p, and damping ratio, ζ:

   $$t_p = 20.0\ [s] \quad \text{and} \quad \zeta = 0.56 \qquad [10]$$

   Calculate the proportional and integral gains, K_p and K_i, required to satisfy the design requirements stated in Equation [10].

2. What is the desired Percent Overshoot (PO)?

3. Finally the designed PI control loop will operate around the following operating temperature level, T_{c_op}:

$$T_{c\_op} = 32.0\ [degC] \tag{11}$$

If the chamber temperature setpoint variation, ΔT_{c_r}, is a square wave of 2-degree-Celsius amplitude around T_{c_op}, to what values do you expect the temperature to overshoot to?

3.4. Pre-Lab Assignment #4: Final Controller Design

The temperature Proportional-plus-Integral (PI) control scheme previously developed and illustrated in Figure 1, above, is improved in this section to better suit the characteristics of each of the heating and cooling processes, both composing the HVAC system. Therefore although based on the same standard PI loop, two slightly different control schemes are designed hereafter in order to better accommodate the physical particularities of each process.

As previously defined in Equation [5], it is reminded that the switching logic between the heating and cooling control loops is still determined by the sign of V_c.

3.4.1. Heating Control Loop

For a more effective heating control loop, the basic PI scheme shown in Figure 1, above, is complemented with a feed-forward action, an offset voltage, and an integrator anti-windup element, as illustrated by the block diagram shown in Figure 2, below.

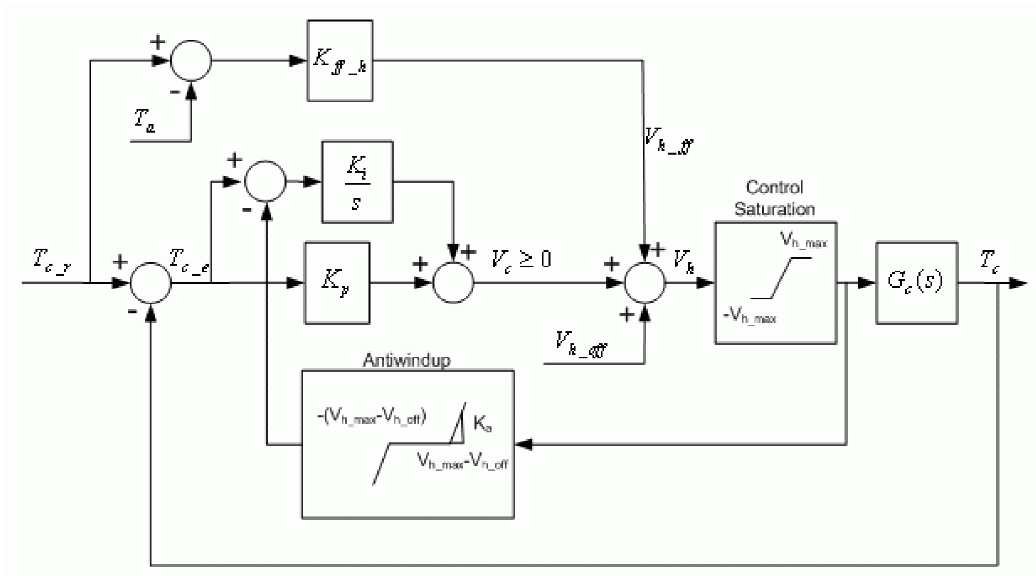

Figure 2 Heating Control Loop: Active Iff $V_c \geq 0$

It is reminded that the heating control loop effectively commands the heater input voltage, V_h, and is only active if and only if V_c is positive. The basic chamber command voltage V_c is calculated accordingly to the PI control law formulated in Equation [3]. Also during the heating process, the blower input voltage remains constant and set to zero, as expressed below:

$$V_b(t) = 0 \qquad [12]$$

where t is the continuous time.

The complete control law for heating, as depicted by the block diagram of Figure 2 above, can be expressed as:

$$V_h(t) = V_c(t) + V_{h\_ff}(t) + V_{h\_off} \qquad [13]$$

where V_{h_off} is the heater offset voltage and V_{h_ff} is the heater feed-forward voltage as defined by:

$$V_{h\_ff}(t) = K_{ff\_h}\,(T_{c\_r}(t) - T_a) \qquad [14]$$

with T_a the ambient temperature outside of the chamber, T_{c_r} the desired chamber temperature, and K_{ff_h} the heater feed-forward gain.

Feed-forward action is necessary to bring and maintain the chamber temperature to the desired level. It compensates for the standard air cooling in the chamber due to natural heat dissipation. The PI control system compensates for small variations (e.g. disturbances) from that operating point.

1. Using the definition of the heater steady-state gain K_{ss_h}, characterize the heater voltage feed-forward gain K_{ff_h}, as defined in Equation [14].
   Hint:
   It is reminded that in the steady-state V_{h_ff} is the voltage required to maintain T_c at the desired level T_{c_r}.

2. From the parameters of the heating transfer function $G_h(s)$ estimated in Reference [3], calculate the numerical value of K_{ff_h}?

The heater constant offset voltage, V_{h_off}, is included in Equation [13] in order to compensate for the halogen lamp deadband. The actuator behaviour, resulting from such a deadband compensation will be more linear around small input voltages. V_{h_off} has been estimated in Reference [3] as the upper limit of the heating actuator deadzone.

The anti-windup element in the feedback loop stops the integral action when the actuator saturates to prevent large overshoots in the response. The HVAC heater saturates at V_{h_max}. When this limit is reached, the surplus voltage is multiplied by the gain K_a and the result is removed from the integrator input. The anti-windup element is implemented using a deadzone nonlinearity with a slope of K_a, as shown in Figure 2.

3.4.2. Blowing Control Loop

Likewise for a more effective blowing control loop, the basic PI scheme shown in Figure 1, above, is complemented with a constant offset voltage used for actuator deadband compensation and an anti-windup scheme. The resulting control scheme is illustrated by the block diagram shown in Figure 3, below.

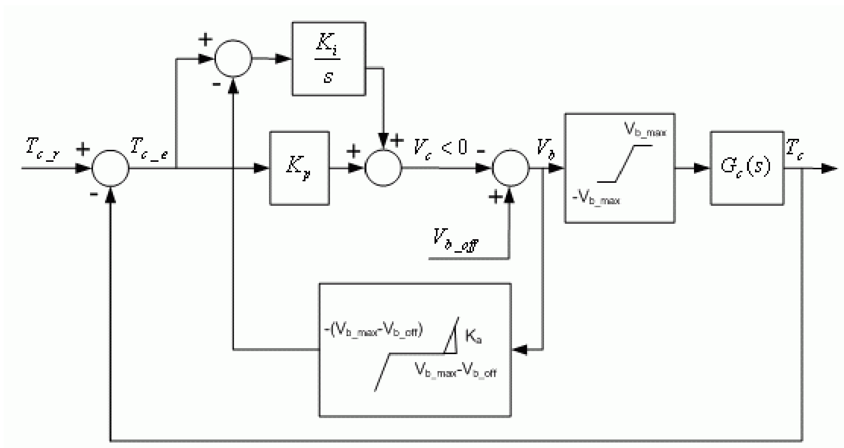

Figure 3 Blowing Control Loop: Active Iff $V_c < 0$

It is reminded that the blowing (or cooling) control loop effectively commands the blower input voltage, V_b, and is only active if and only if V_c is negative. The basic chamber command voltage V_c is calculated accordingly to the PI control law formulated in Equation [3]. Also during the cooling process, the heater input voltage remains constant and set to zero, as expressed below:

$$V_h(t) = 0 \tag{15}$$

where t is the continuous time.

The complete control law for blowing, as depicted by the block diagram of Figure 3 above, can be expressed as:

$$V_b(t) = |V_c(t)| + V_{b\_off} \tag{16}$$

where | | represents the absolute value function and V_{b_off} is the blower offset voltage. Since V_c is negative during blowing, the absolute value is required to send a positive command voltage to the blower (i.e. fan).

The blower constant offset voltage, V_{b_off}, is included in Equation [16] in order to compensate for the fan deadband. V_{b_off} has been estimated in Reference [3] as the upper limit of the fan deadzone.

The blower saturates at V_{b_max}. Similarly to the heating control loop, the integrator is "turned off" when V_{b_max} is reached to prevent large overshoots that can result from the integrator charging up too much. The same deadzone nonlinearity slope K_a is used.

3.4.3. Final Temperature Control Laws

To summarize and reformulate the previous design considerations, the two actuator input voltages are completely defined below by Equations [17] and [18].

Using Equations [13] and [15], the heater input voltage is calculated as defined below:

$$V_h(t) = \begin{cases} V_c(t) + V_{h\_ff}(t) + V_{h\_off} & 0 \le V_c(t) \\ 0 & V_c(t) < 0 \end{cases} \tag{17}$$

Likewise using Equations [14] and [16], the blower input voltage is determined as follows:

$$V_b(t) = \begin{cases} 0 & 0 \le V_c(t) \\ |V_c(t)| + V_{b\_off} & V_c(t) < 0 \end{cases} \tag{18}$$

4. In-Lab Session

4.1. System Hardware Configuration

This in-lab session is performed using the NI-ELVIS system equipped with a QNET-HVACT board and the Quanser Virtual Instrument (VI) controller file *QNET_HVAC_Lab_06_PI_Control.vi*. Please refer to Reference [2] for the setup and wiring information required to carry out the present control laboratory. Reference [2] also provides the specifications and a description of the main components composing your system.

Before beginning the lab session, ensure the system is configured as follows:

QNET HVACT module is connected to the ELVIS.
ELVIS Communication Switch is set to BYPASS.
DC power supply is connected to the QNET HVAC Trainer module.

The 4 LEDs +B, +15V, -15V, +5V on the QNET module should be ON.

4.2. Experimental Procedure

Please follow the steps described below:

Step 1. Read through Section 4.1 and go through the setup guide in Reference [2].

Step 2. Open the VI controller file *QNET_HVAC_Lab_06_PI_Control.vi*. You should obtain a front panel similar to the one shown in Figure 4, below. The default sampling rate for the implemented digital controller is 250 Hz. However, you can adjust it to your system's computing power. Please refer to Reference [2] for a complete system's description. The chamber temperature, directly sensed by the thermistor, is plotted on a chart (in red) as well as displayed in a Numeric Indicator located in the *Chamber Temperature* front panel box. The values are in degrees Celsius.

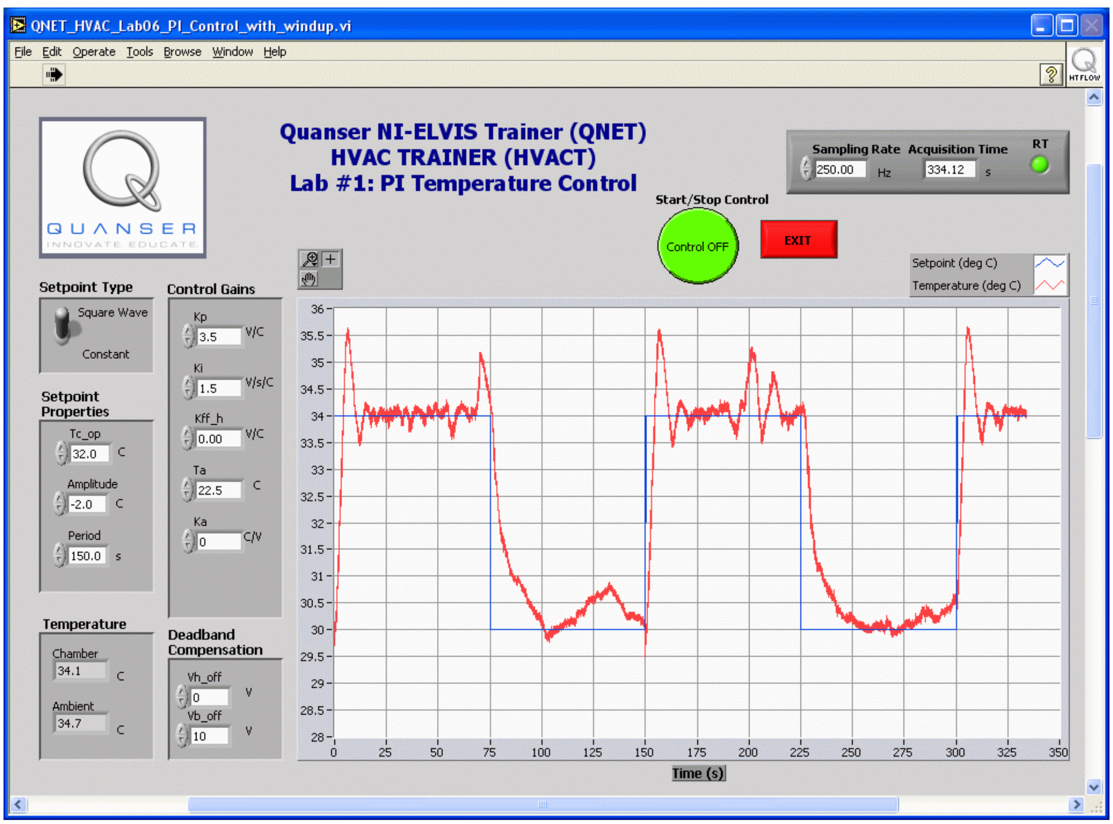

Figure 4 Front Panel Used for the QNET-HVACT Temperature Control Laboratory

Step 3. The vertical toggle switch in the *Setpoint Type* box allows you to choose between a *Square Wave* or a *Constant* type of reference temperature, T_{c_r}. Ensure that it is set to the *Square Wave* position. The temperature setpoint is also plotted on the front panel chart (in blue). Use the Numeric Controls of the *Setpoint Properties* box to set the chamber operating temperature, T_{c_op}, to 32 °C (as expressed in Equation [11]), the square wave *Amplitude* to -2 °C, and *Period* to 150 seconds. Specifically the setpoint properties parameters are expressed in Table 3, below.

Signal Type	T_{c_op} [°C]	Amplitude [°C]	Period [s]
Square Wave	32.0	-2.0	150.0

Table 3 Temperature Setpoint Parameters

Step 4. When you first open the *QNET_HVAC_Lab_06_PI_Control.vi* controller file, the default controller gains are not yet tuned. An example of "untuned" controller parameters is provided in Table 4, below.

K_p [V/°C]	K_i [V/s/°C]	K_{ff_h} [V/°C]	T_a [°C]	Ka [°C/V]	V_{h_off} [V]	V_{b_off} [V]
3.50	1.50	0.00	22.5	0.0	0.0	0.0

Table 4 "Untuned" Controller Parameters

Run the LabVIEW VI (Ctrl+R) to start the controller. Ensure the initially green START push button is pressed and shown as a red STOP button to activate the controller. This button can be used to pause the controller execution. With the control action active, the chamber temperature should now go up and down to roughly track the desired square wave setpoint. You should obtain an "untuned" temperature response similar to the one depicted in Figure 4, above. After a few periods, you can stop the VI by pressing the red EXIT button on the front panel.

Step 5. Using the Numeric Controls of the *Controller Gains* box, you should enter the system controller gains, namely K_p, K_i and K_{ff_h}, that you have calculated in the pre-lab section. Also enter the ambient temperature (T_a, in °C) present outside of the HVAC chamber. Set the value of K_a to 0.0 °C/V, which effectively turns off the integral anti-windup element in the feedback system. Finally the deadband compensation parameters, V_{h_off} and V_{b_off}, should also be properly set to the values that you estimated in Reference [3]. Do so by using the Numeric Controls of the *Deadband Compensation* box on the front panel. Summarize your final tuned controller parameters by filling up Table 5 as shown below.

K_p [V/°C]	**K_i [V/s/°C]**	**K_{ff_h} [V/°C]**	**T_a [°C]**	**Ka [°C/V]**	**V_{h_off} [V]**	**V_{b_off} [V]**

Table 5 Tuned Controller Parameters

Step 6. Start the controller by running the LabVIEW VI (Ctrl+R) in order to try your calculated gains on the actual system. The software applies square wave temperature setpoints to the closed-loop control system and plots both setpoint and actual chamber temperature over a 350-second time range. Observe the way the system switches between the two actuators (i.e. lamp and fan) in order for the chamber temperature to track the desired square wave setpoint around the operating level T_{c_op}.

Step 7. Let the system run until you have plotted on the chart the temperature response to 2 heating steps and to 2 cooling steps (at least the overshoot and peak time part of it).

Step 8. Make a screen capture of the obtained step response plot and join a printout to your report.

Step 9. Does the closed-loop system track the desired square wave setpoint accurately? Is there any steady-state error? Comment on the symmetry (or lack of) of the temperature response between heating and blowing steps. Explain.

Step 10. Set the value of K_a to 0.2 °C/V, which corresponds to slope of the integral anti-windup deadzone to 0.2 °C/V, and keep the same values for the other control parameters entered in Table 5. Start the controller by running the LabVIEW VI (Ctrl+R) in order to try your calculated gains on the actual system using the anti-windup element. Observe the effects on the response of having an anti-windup element. Then, adjust K_a to improve the response and enter the tuned parameter in Table 5, above.

Step 11. Let the system run until you have plotted on the chart the temperature response to 2 heating steps and to 2 cooling steps (at least the overshoot and peak time part of it).

Step 12. Make a screen capture of the obtained step response plot and join a printout to your report.

Step 13. You should now measure and determine your system performance from the actual response plot, as displayed on the VI Front Panel. Do so by using the Graph Palette located on top of the Chart top left corner. Fill up Table 6 as shown below. You should have plotted two iterations of both step types, i.e. heating and blowing. First measure the corresponding Percent Overshoot, PO, and peak time, t_p, for all 4 step responses as specified in Table 6. T_{c_peak} is the overshoot value. Then take the average of PO and t_p over the 2 iterations of each step type. Finally, combine and average the results of both step types. What are your final values for PO and t_p?

Step Type	***Iteration #***	***T_{c_peak}* [ºC]**	***PO* [%]**	***t_p* [s]**
Heating	1			
	2			
	Average:	X		
Blowing	1			
	2			
	Average:	X		
Average Values:		X		

Table 6 Step Response Actual Performance

Step 14. Do the measured Percent Overshoot and peak time meet the required specifications? Explain your observations.

Step 15. If the design requirements defined by Equation [10] are still not satisfied, you should manually fine tune the controller parameters of Table 5 until the response performance improves to the desired level. Include in your laboratory report your final tuning parameters, experimental plots and results, as well as the measured system performance criteria satisfying the specifications.

Step 16. Once all your experimental results are obtained, shut off the PROTOTYPING POWER BOARD switch and the SYSTEM POWER switch at the back of the ELVIS unit. Unplug the module AC cord. Then, stop the VI by pressing the red EXIT button.