# A Versatile Experiment in Electrical Engineering Technology

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## Abstract

An experiment used to implement multi-electrical course knowledge is described. The experiment is an automatic control system in nature with ties to electronics, digital system and computer hardware and software. The idea is to design and build a simple temperature control system, to maintain the temperature inside an enclosed box within a specific user selected range. The plant in this case is the box heated by a light bulb. To monitor the temperature, an LM335 transducer or equivalent is used. The actuator used is a relay switch to control the lamp circuit. Finally, the controller can be analog or digital. It could be a simple operational amplifier comparator or a computer. To emphasize the electronics knowledge, the controller can be built using a window comparator interfaced with a NOR latch for memory. The use of the operational amplifier-latch combination teaches the student how to interface analog and digital parts. A transistor circuit is used to provide the current necessary to energize the relay switch. To provide the circuit with DC power, the students have to design and build a DC power supply. If the emphasis is on computer hardware and software instead of electronics, the controller can be a digital one provided by a personnel computer. The student has to design and build an interface circuit to enable the computer to read the voltage from the LM335 and send a signal to energize the relay. The interface circuit includes an ADC0804 analog to digital converter, a 4N28 Opto-Isolator and the PC parallel port. A computer program using C and Assembly languages is written to control the temperature. The designs presented in this paper can be a part of any senior electronics, automatic control, digital systems design, or capstone courses.

## Introduction

A good experiment in engineering technology is one with a lot of practical implications. Through it, a student can see the theorems and laws come to life, which makes the subject matter more interesting. The experiment should be easily understood and closely related to material covered in the lecture. The experiment should be the bridge that connects abstract class material to reality. It should be universal in the sense that it brings together and makes use of different material learned in diverse subject matters.

In automatic control [1], students learn about basic control system components such as the controller, the actuator, the process and the sensor and how they interact together to make a control system. In electronics [2], students learn about transistor amplifiers and switches. They also learn about power supplies and regulators. In digital systems [3], students learn about computer hardware and interface. In programming courses [4], students learn assembly and C programming. In the technology program, each of these courses is associated with a lab in which students can test and then validate the theory learned in lectures. The experiment presented in this paper utilizes the knowledge from all of these different courses and could be used in any one of the advanced course labs.

In general, a control system can be designed to maintain a system variable to within a specific range. Even though, in this paper, the chosen system variable is temperature, the proposed experiment can be easily adapted to work with other control variables such as level, pressure, humidity and flow. This would only involve changing the sensor to measure the new variable and hardware modifications to implement the new control action.

This experiment encourages both self-confidence and skill-development. Since students are dealing with a measurable variable, they can actually see the result of their work. It is a simple experiment, easy to design, build and troubleshoot. Students are very involved through out all of these stages. When they are finished, there is a feeling of real achievement. This experiment is actually implemented in an automatic control system course I teach and has proved to be a very successful learning experience. Many students have commented on their involvement and achievement and the knowledge and experience they gained by completing this project.

It is each student's responsibility to acquire the different system parts through local dealers or the Internet. This requirement will help to familiarize the student with the cost of building such a system as well as the need to be cost effective. It also gives him or her more responsibility in researching the compatibility of different components and necessitates the reading of data sheets not just connecting parts.

This experiment is not designed to be a mind-bending, cutting-edge project. Rather, it is a simple yet effective way of getting the material across to the students. In designing this experiment the objective was generality not efficiency. The idea is to combine the knowledge from as many courses as possible and use as many devices as possible. It is important to note, that this project could be achieved using a much smaller, more advanced circuit. Therefore, the issue of efficiency and advancement could be the subject of an in-depth class discussion as well as being the focus of an extra-credit assignment following completion of the experiment

## Analog Temperature Control System

Depending on the time allocated to this experiment, students are required to build or design and build a temperature control system capable of maintaining the temperature inside a box within a specific range. As in the case of any control system, the main components are the process, the sensor, the controller and the actuator. Students are to select, design and build each of these components based on the required specifications. They then assemble the components together to form the entire system as shown in Figure 1. The project can be completed in the following steps:

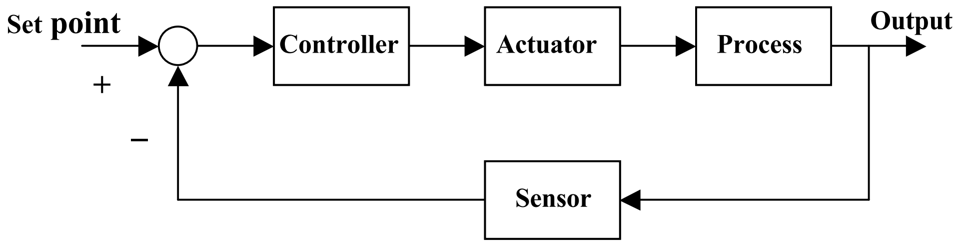


Figure 1. Closed Loop Control System

**The Process**

Since the objective is to control the temperature inside a box, the first step would be to build the box. To prevent interface from outside temperature, the box can be built with an insulating board such as Styrofoam. With the thermocouple wires inserted inside the box, a thermometer can be used to monitor the temperature. If the box is to be used as an incubator and there is a need to see what is going on inside, it could be built using Plexiglas, which is light and durable. In this case, a cheaper thermometer can be placed inside the box to monitor the temperature. The heat inside the box is provided by a 100W light bulb powered by a 110 V ac source. The light bulb can provide a smooth transition in heating cycles in the low thermal capacitance box. The ac circuit is controlled by a relay switch which is turned on or off by the controller.

**The Sensor**

The second step to building this project is to select a suitable temperature sensor. Since the rest of the control system is based on voltage readings, and to ensure compatibility, the output of the selected sensor must be voltage proportional to the temperature being measured. One such sensor a student might use but is not limited to, is the LM335 temperature sensor. The LM335 is a precision, easily calibrated, integrated circuit temperature sensor with an operating range of $-40^{o}$C to $100^{o}$C. The low impedance and linear output makes interfacing to a control circuit simple. The sensor comes in a TO-92 package and provides an output voltage directly proportional to the absolute temperature at the rate of +10mV/$^{o}$K. The output is calibrated with an external potentiometer to provide a 2.98 V output at $25^{o}$C [5]. When calibrated at $25^{o}$C, the LM335 has an error of less than $1^{o}$C over a $100^{o}$C range. Extension wires can be soldered to the LM335 leads to remotely sense the temperature inside the box. The leads are short enough not to affect the calibrated reading of 10mV/$^{o}$K at the circuit board. The output of the LM335 is already in a suitable form to be processed by the controller circuit. Therefore, no further signal conditioning of any kind is required.

**The Controller**

The next step would be to compare the actual temperature to a preset one. The actual temperature is represented by the voltage output of the sensor while a voltage divider circuit simulates the preset temperature. An operational amplifier comparator circuit usually does the comparison. Students often make the mistake of trying to use only one comparator to compare to only one set temperature. This will produce chattering caused by the relay switching on and off due to temperature oscillating above and below the set point. The students will learn that although they cannot control temperature to one preset value, they can do it within a preset range. Basically, give the controller a neutral zone in which there is no switching. Switch on or off below or above the range. This can be achieved by using an operational amplifier switching circuit with hysteresis [6].

A more elaborate approach might be to use the combination of a window comparator and a NOR latch. The window comparator is to provide the range and the latch is to provide the memory to differentiate between switching at either end of the temperature range. The heat is to stay on until reaching the upper set point and then remaining off until reaching the lower set point. Basically, the NOR latch is used to create the neutral zone between the set points. This latch is implemented using two 7402 NOR gates. The truth table for the NOR latch is given in Table 1. The comparison action itself is implemented using two LM741 operational amplifiers. The varying voltage from the LM335 temperature sensor is connected to the inverting pin of one Op-Amp and the non-inverting pin of the other Op-Amp. The non-inverting pin of the first Op-Amp is connected to a voltage divider circuit setting up the lower limit and the inverting pin of the second Op-Amp is connected to another voltage divider circuit setting up the upper limit. This is all shown in Figure 2.

| **A** | **B** | **C** |
|---|---|---|
| Low | High | High |
| Low | Low | Low |
| High | Low | Low |

Table 1. Truth Table for NOR latch

The Op-Amp is an analog device, whereas the NOR gate is a digital device. For the circuit to work properly, students must understand how to interface the two together. Digital devices work with two voltage levels: a low level (0-0.8V) and a high level (2.4V-5V). Therefore, the output of the Op-Amp comparator must satisfy these levels. With this in mind, the LM741 DC supplies must be adjusted to produce an output within these levels. The positive DC supply is set to 5 V and the negative DC supply is set to –1V. With these settings, the upper and lower saturated outputs of the LM741 are 4V and 0V which are compatible with the high and low levels of the NOR gate. To avoid using two power supplies, a single ended operational amplifier such as the LM358 can be used instead of the LM741.

The outputs of the window comparator are then connected to the inputs of the NOR latch. When the output C of the latch is high, the heat must be turned on and when C is low, the heat must be turned off.

**The Actuator**

Whether the heat is turned on or off inside the box, is a reflection of the voltage level at the output of the latch. When the output is high the heat is on and when the output is low the heat is off. This can be implemented using a relay. The relay interfaces the DC output of the latch to the ac lamp circuit. The relay is a magnetic switch, which is normally open. The ac source is connected to the light bulb through the switch in the relay. When the output of the latch goes high, the relay is activated, closing the switch, turning the light bulb on, and heating the box. When the output of the latch is low, the relay is deactivated, opening the switch and turning the bulb off. One complication here, is that the output current of the NOR gate is less than what is needed to activate the relay. To amplify the current, a 2N3904 transistor is used. The relay coil is connected at the collector of the transistor, while the base is connected at the output of the latch. When the output of the latch is high, the transistor is turned on, which activates the relay and that turns the heat on. Students must design the input resistance of the transistor based on the relay current requirements.

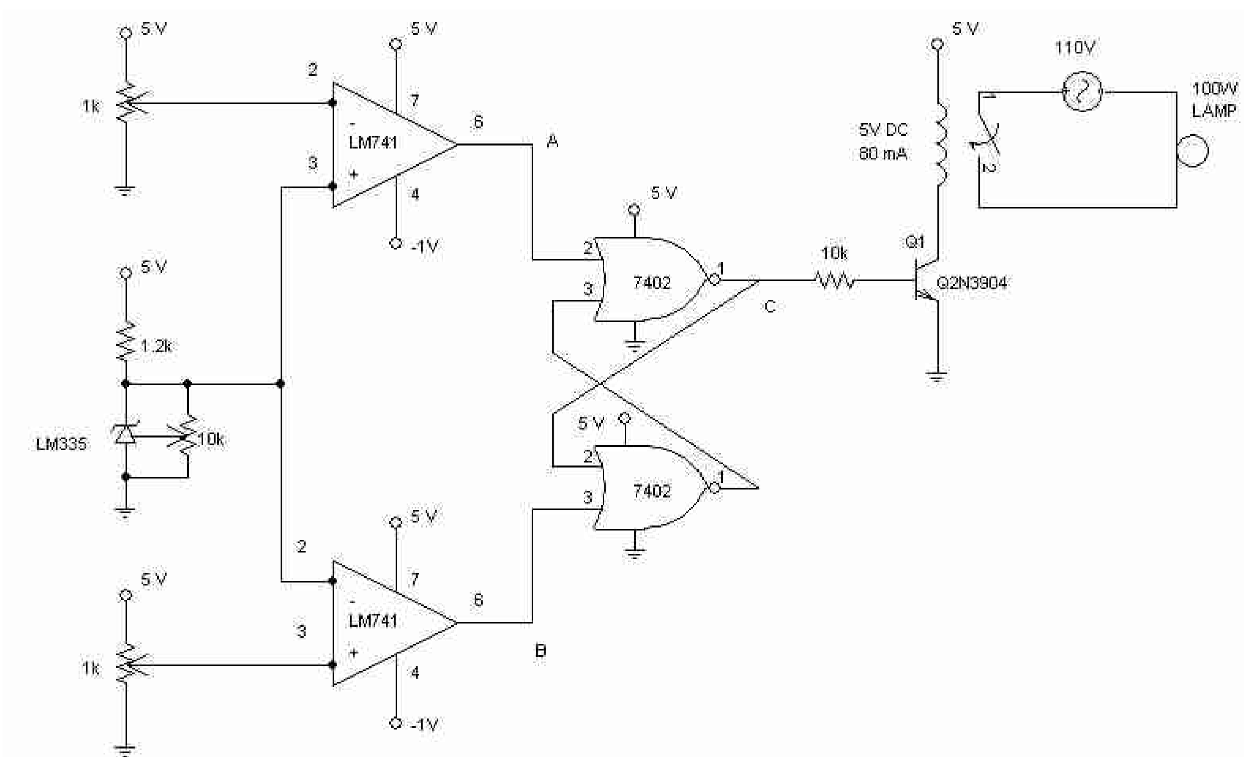


Figure 2. Analog Temperature Control System

**Case Study**

As an example, assume that the temperature inside the box is to be maintained between 85°F and 90°F. Based on the fact that the LM335 temperature sensor is calibrated to produce 2.98V at 25°C and that the voltage changes at the rate of 10mV/°K, the selected temperature range is equivalent to a voltage range of 3.02V and 3.06V. These voltage set points are obtained from the 5V source using two 1kΩ potentiometers. This is shown in Figure 2. The potentiometers can be easily adjusted to change the set points as needed.

To start with, assume that the temperature inside the box is 60°F. The output A of the top Op-Amp in Figure 2 is close to 0V, while the output B of the bottom Op-Amp is close to 4V. This is equivalent to latch inputs of low (0V) and high (4V), which will produce an output C of high (5V). A high input at the base of the transistor will turn it on allowing current to flow through the relay coil, closing the switch and turning the light bulb on.

As long as the bulb is on, the temperature inside the box will continue to rise. When the temperature is within the specified range, the outputs of amplifiers A and B are 0V and 0V respectively. The latch inputs are both low, which will result in no change in, the output and the heat will stay on.

As soon as the temperature rises above the upper range limit of 90°F, the voltage at A is 4 V and the voltage at B is 0V. This will result in latch inputs of High and low and an output of low. Applying 0V at the base of the transistor turns it off, resulting in no current flowing through the relay coil. This will open the relay switch and turn the bulb off. Temperature will drop until reaching the lower range limit and the cycle is repeated maintaining temperature within the specified range.

**Power Supply**

For the temperature control system to be self-supportive, a DC power supply is needed to provide the positive and negative biasing voltages required by the different devices in the system. Students are required to design and build ± 5V DC source starting with the 110V, 60Hz ac source. There are four main stages in converting ac power to dc.

*The Transformer*: The first stage in a power supply circuit is the transformer. The basic function of the transformer is to step down the voltage close to the desired level. This will minimize the current and therefore the power dissipation in the circuit. A 12.6V center tap transformer can be used in the design of the ± 5V supply for this experiment.

*The Rectifier:* The purpose of the rectifier is to convert the ac signal at the output of the transformer to a pulsating DC signal. The full wave bridge rectifier can be used in the design and is implemented using four 1N4001 diodes.

*The Capacitor-Filter:* The function of the filter is to reduce the changes in the output of the rectifier through the charging and discharging of the capacitor. Basically, the filter changes the domes into ripples. The amplitude of the ripples is a function of the capacitor used. The capacitor can be selected using the following formula:

$$C_F = \frac{I_L * T}{Vr}$$

Where $I_L$ is load current, T is period of the signal at the output of the rectifier and Vr is the peak-to-peak value of the ripples. If the load current is assumed to be 200 mA, the frequency of the output of the full wave rectifier is 120Hz and the maximum ripples are selected by the following formula:

$$Vr = Vopk - Vrect - V_{REG} - V_{DC}$$
$$Vr = 17.8 - 1.4 - 3 - 5$$
$$Vr = 8.4\ V$$

Where Vopk is the peak voltage at the output of the transformer, Vrect is the voltage drop across the bridge rectifier, $V_{REG}$ is the overhead voltage of the regulator and $V_{DC}$ is the output DC voltage. Then the capacitor value is calculated to be $C_F = 200\ \mu F$.

*The Regulator:* Now that the sinusoidal ac signal has been reduced to ripples around the DC value, the last stage of the power supply circuit is the voltage regulator. The function of the regulator is to produce a constant output regardless of changes in the input or the load. Basically, eliminate the ripples. For the purpose of the experiment, two IC regulators can be used, the 7805 to provide a +5 V and the 7905 to provide a –5V.

The complete power supply circuit is given in Figure 3. The capacitor C1=1µF is added to improve the transient response.

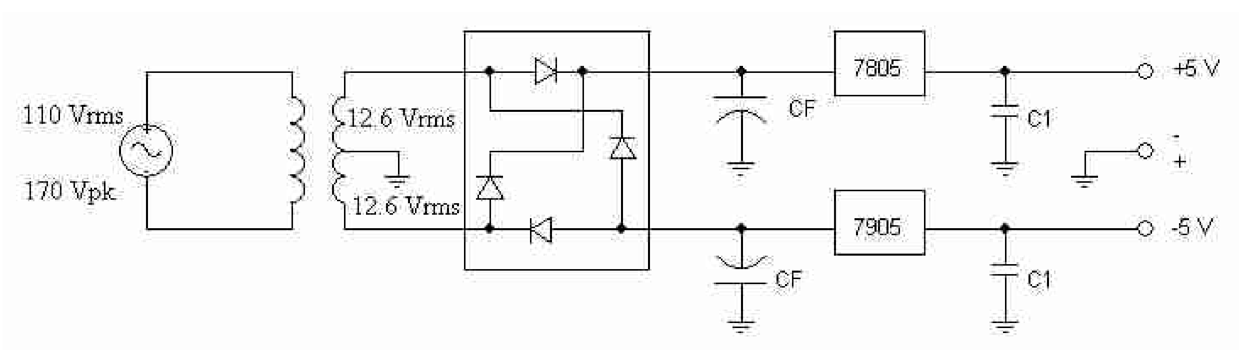


Figure 3. Power Supply Circuit

**Digital Temperature Control System**

To enhance the student's knowledge of computer hardware and software, the controller in the temperature control system can be a digital one. A personal computer can be used to control the temperature to within the specific range. The student has to interface the output of the LM335 temperature sensor to the PC and then interface the PC to the actuator. Since the LM335 is an analog device and the PC is a digital device, this experiment provides the student with the experience of interfacing analog and digital devices. An ADC0804 analog to digital converter is used to interface the LM335 to t he PC. The ADC0804 resolution is set to 10mV/step. Temperature is read by the LM335, digitized by the ADC0804 and then read to the PC through the parallel port. A program can be written using C and assembly languages to read in the values, perform the calculations, compare to the preset temperature range limits and then send out the signal to turn the light on or off. The parallel port is used to send the control signal to the 5V relay, which is used to control the light bulb ac circuit. A 4N28 opto-coupler is used to isolate the relay from the PC and pull-up the voltage in case a higher voltage relay is used. The complete digital temperature control system configuration is given in figure 4.

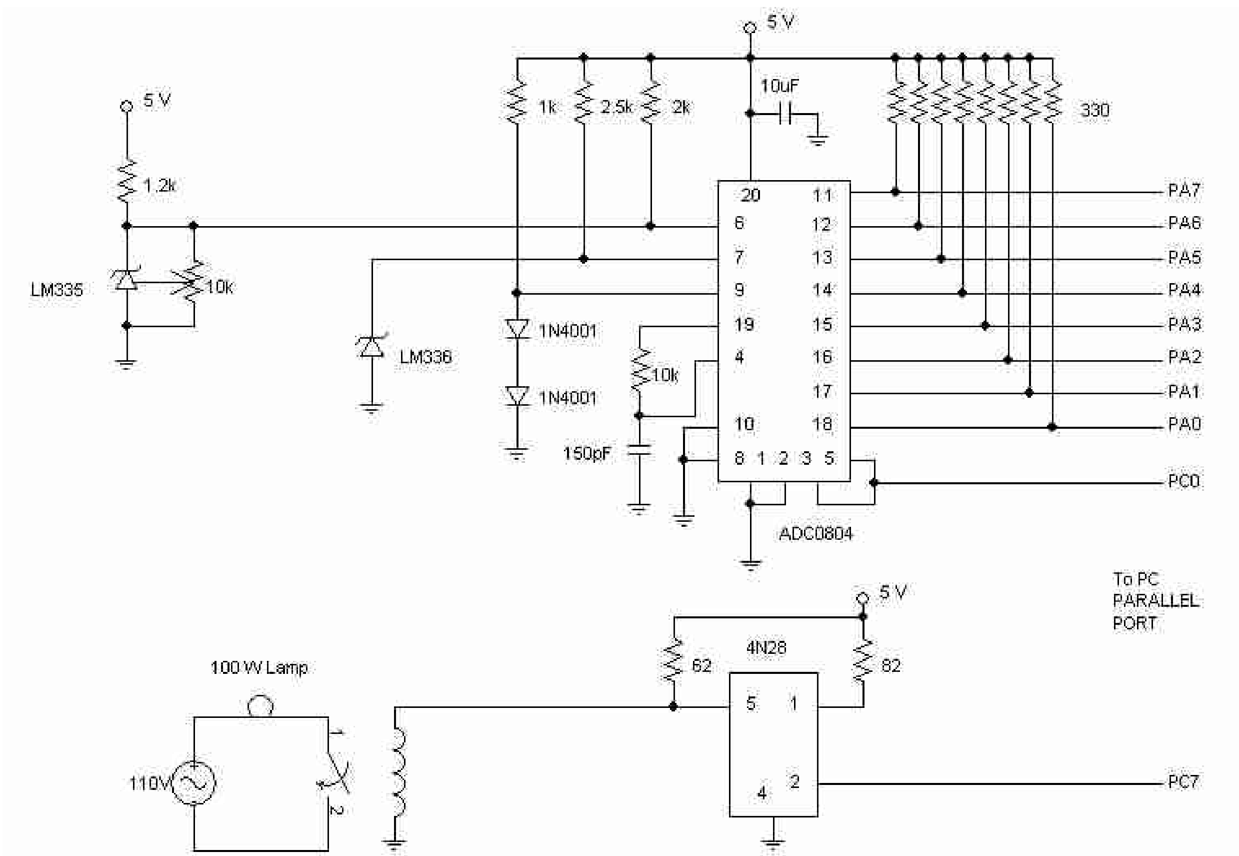


Figure 4. Digital Temperature Control System

## Conclusion

A simple experiment with a multi-course connection is described. The experiment emphasizes the knowledge learned in automatic control, electronics, digital systems and computer hardware and software. Students are required to design and build an analog or digital temperature control system. Students are also required to design and build a power supply circuit. This experiment teaches students how to interface analog and digital devices. It also teaches them the responsibility of building a complete, functioning system. They learn to use seemingly abstract information in a practical manner. This experiment was actually implemented in one of the courses and has proven to be a very successful learning and teaching experience. This experiment could be valuable as part of any senior electronics, automatic control, digital systems or capstone courses.

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## Biography


AHMAD M. FARHOUD is currently an assistant professor in the Engineering Technology Department at the University of Toledo. He received his B.S., M.S., and Ph.D. degrees in electrical engineering from the University of Toledo in 1985, 1987 and 1991 respectively. His research and teaching interests cover the areas of adaptive control of power systems, automatic control systems, Electronics, Analog and digital systems design and electric machines.