Physics Education

PAPER

Automation experiments in physics laboratories

PAPER
Phys. Educ. **53** (2018) 055009 (9pp) iopscience.org/ped

Automation experiments in physics laboratories

J E M Perea Martins

Computer Science Department, School of Sciences (FC), São Paulo State University (UNESP), 17033-360, Bauru-SP, Brazil

E-mail: perea@fc.unesp.br

Abstract
This work presents experiments to teach fundamentals of automation through a sequence of laboratory practices that naturally guide to development of an on/off control system. It focuses on the integration of technological and scientific concepts, based on an educational approach associated with a problem-solving technique.

Presentation

Automation is a technology that allows a system operation without direct human intervention, which includes a simple device switching according to specific parameters or even a complete system control to stabilize a physical phenomenon at a specific value.

This subject theory includes advanced mathematical concepts, but its basic practical principles can be easily demonstrated in classroom with only a primary students' background of electronic, which can motivate them to design different other systems for experiments automation in physics laboratories.

This work proposes this subject teaching through a problem-solving technique called *divide-and-conquer*, which models conceptually a specific problem and so divides it in small parts whose solutions are separately investigated and next integrated [1]. Docktor and Mestre [2] accentuates this approach is a realistic physics education research subject and emphasize the technological tools relevance in the physics education practices, which motivated the present work.

In this context, figure 1 shows a basic automation system model divided in four modules analyzed in the next sections. Basically, an electronic circuit process the signal from the sensing system and switches a controlled device through a power driver circuit.

The sensing system

The sensing system is physically composed by a sensor, whose output electric signal is proportional to the measured phenomenon intensity. The output signal format can be either analogue or digital, and its format influences directly the he subsequent signal processing module design. In some cases, the sensing system uses a sensor that requires some additional components to allow its effective operation.

Analogue signals are represented by a voltage value, which can assume several values into a fixed range defined by its manufacturer. Otherwise, digital signals are physically represented by only two pulses level (low or high), and therefore they require a set of pulses to represent the phenomenon value.

Physically, the real pulse level voltage can vary within a range whose limits depend on the electronic component manufacturing technology and the supply voltage. Table 1 shows the voltage ranges with a supply voltage of 5 V for popular technologies.

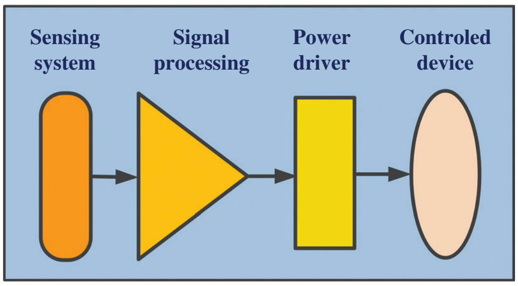

Figure 1. Automation system division.

Table 1. Voltage ranges for digital pulses.

Technology	Low pulse	High pulse
TTL	0 V…0.8 V	2.0 V…5 V
CMOS	0 V…1.6 V	3.5 V…5 V

Digital signals present a better noise immunity and usually are more stable, but this work uses an analogue sensor, which usually allows a simpler electronic circuit for their signal processing.

The processing circuit

This work uses an electronic *comparator* to compose the processing module. Figure 2 shows the comparator symbol (triangle) with two typical configurations called *inverting* and *non-inverting circuit*. Both compares the voltage from a sensor (V_s) with a fixed reference voltage (V_{ref}) and so provide an output voltage (V_o) that assumes either a high level (V_{oh}) or a low level (V_{ol}), according to the comparison result [4, 5]. There are electronic components designed exclusively as comparators, but traditional operational amplifiers can also operate as comparators.

The non-inverting circuit operation is summarized as:

- If $V_s < V_{ref}$ then $V_o = V_{ol}$
- If $V_s > V_{ref}$ then $V_o = V_{oh}$

The inverting circuit operation is summarized as:

- If $V_s < V_{ref}$ then $V_o = V_{oh}$
- If $V_s > V_{ref}$ then $V_o = V_{ol}$

The real V_{oh} and V_{ol} voltage values usually do not reach the supply voltages, and despite the comparator datasheet specifications they can vary for each new component, and therefore it should be measured with a voltmeter.

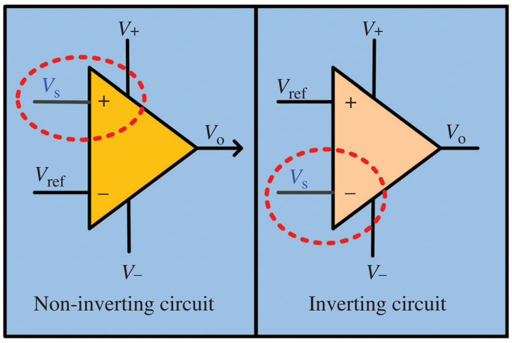

Figure 2. Comparator circuits.

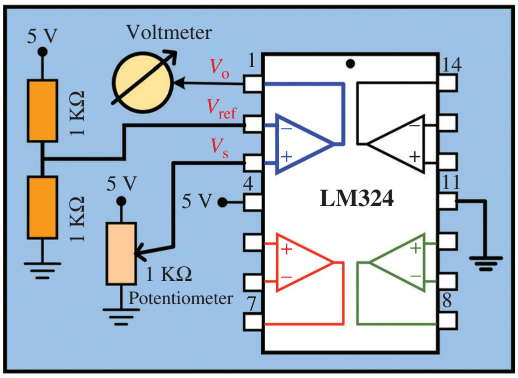

Figure 3. Experiment for V_o measurement with the LM324.

Figure 3 shows the symbolic structure of an experiment to verify V_o from a LM324 chip that has four internal operational amplifiers and in this work, was powered with 5 V (V_+) and 0 V (V_-). V_{ref} was fixed at 2.5 V, while V_s was variable and adjusted with a potentiometer from 0 V to 5 V. For the LM324 used in this work, the measured V_{oh} was 3.8 V and V_{ol} was 0 V.

Temperature alarm

Figure 4 shows the temperature alarm schematic with a non-inverting comparator that turns on a LED when the ambient temperature represented by V_s is greater than a referential temperature value (V_{ref}).

The LM35 is an integrated temperature sensor with a linear analogue output signal (V_s) with a *sensitivity* of 10 mV °C^{-1}. For example, for an ambient temperature of 25.3 °C, the sensor output is 253 mV (0.253 V). Figure 5 shows the LM35 requires only a power source and its operation can be demonstrated in classroom with a single voltmeter.

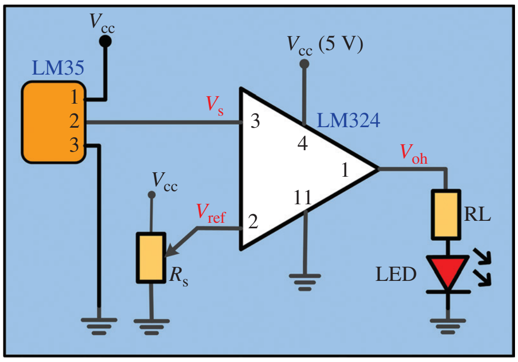

Figure 4. Temperature alarm schematic.

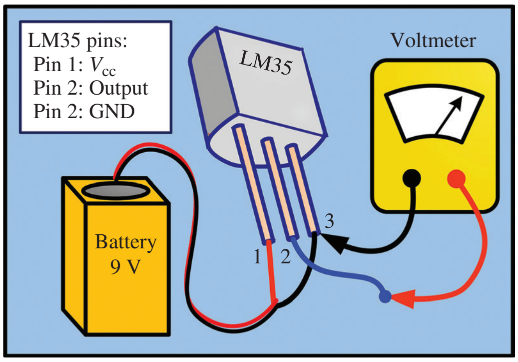

Figure 5. LM35 pins and test.

The phenomenon value that is fixed as a reference is generically called *setpoint* (SP), and therefore V_{ref} must be proportional to the SP and is fixed through a 1 kΩ potentiometer (R_s). For example, for a SP of 27.0 °C, then V_{ref} must be fixed at 0.270 V, in the present case.

The resistor RL controls the LED and is computed as:

$$\mathrm{RL} = \frac{V_{oh} \ - \mathrm{VL}}{\mathrm{IL}}. \quad (1)$$

Where VL is the drop voltage on the LED, usually at 2.0 V, and IL is its current usually fixed between 15mA and 20 mA. With V_{oh} at 3.8 V, it can be computed as:

$$\mathrm{RL} = \frac{3.8\,\mathrm{V} - 2\,\mathrm{V}}{15\,\mathrm{mA}} = 120\,\Omega.$$

The figure 4 circuit can also be designed with an inverter comparator that turns on the LED when the ambient temperature is smaller than the SP. Both alarms can be tested in laboratory by heating the sensor with the approximation of a heater or even covering with the fingers, or by cooling it with the contact of an aluminium cup with ice.

Light intensity alarm

Figure 6 shows a light intensity alarm schematic that turns on the LED when the light intensity measured with a LDR is higher than the SP.

Figure 7 shows a LDR (*light dependent resistor*), whose resistance value depends on the incident light intensity.

Figure 8 shows the LDR relation between incident light intensity and resistance value,

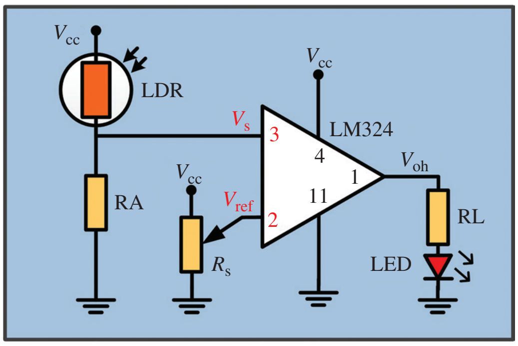

Figure 6. Light intensity alarm schematic.

which is nonlinear and usually presents typical extreme values in the range of few MΩ and dozens of Klx.

The figure 6 LDR is connected in series with a resistor to compose a *voltage divider circuit* that divide the source voltage (V_{cc}) according to the Ohm's law and provide an output voltage (V_s) proportional to the resistances, and therefore the V_s variation is a function of the light intensity, computed as:

$$V_s = \frac{V_{cc}}{(R_a + \mathrm{RLDR})} R_a. \quad (2)$$

Where, RLDR is the LDR resistance.

V_{ref} is adjusted with the potentiometer (R_s) and the circuit can be easily tested lighting the LDR with a flashlight or shading it with the hand.

Twilight alarm

This work proposes a system design that operates similarly to commercial devices that automatically switches a bulb at the twilight, turning it on

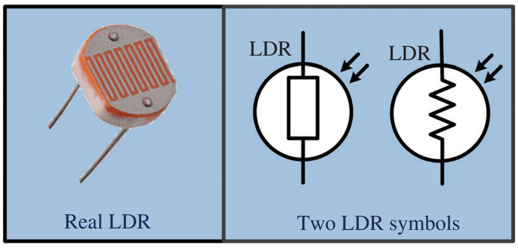

Figure 7. LDR and symbols.

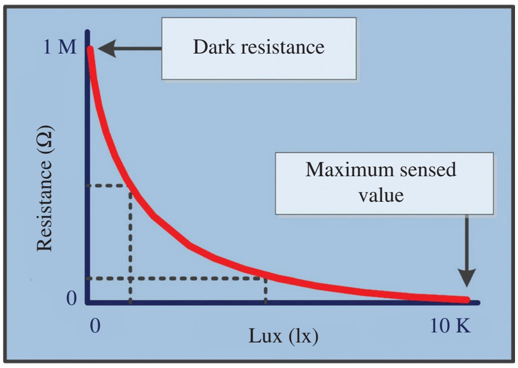

Figure 8. LDR resistance variation.

at the sunset and turning it off at the sunrise. It uses the figure 6 circuit, but it requires the definition of a V_{ref} proportional to the light intensity (SP) at the twilight.

Figure 9 exemplifies the called *civil twilight* that is the first of three-twilight stage and occurs when the geometric sun centre angle relative to the horizon is between 0° and 6°. Usual outdoor activities in this period do not yet require artificial light in clear days and the higher light intensity is between 410 and 585 lux and the lower is between 2.0 and 3.5 lux [3].

In this work, the SP was fixed at 70 lux that is typical for commercial automatic lighting devices, and therefore the LDR resistance at 70 lux must be measured. Figure 10 shows an experiment where the LDR is positioned next to a lux meter and both under a bulb. The light intensity on the LDR is adjusted by varying the bulb height or shading the LDR with an intermediate barrier, and when it reaches 70 lux the LDR resistance is measured. The LDR sensitivity depends on the incident light wavelength and usually it presents a peak at about 550 nm, and therefore the selected bulb must provide a spectral range with a satisfactory intensity at this wavelength. Table 2 shows

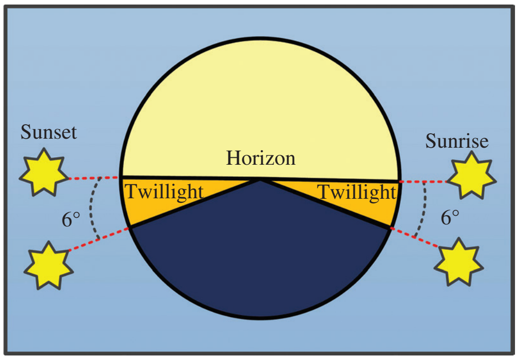

Figure 9. The sun civil twilight angles.

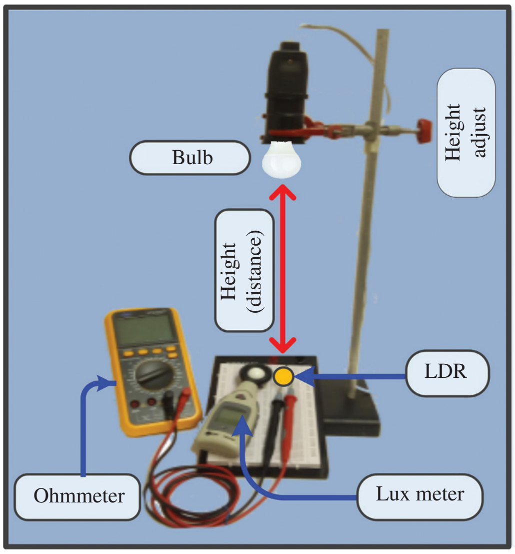

Figure 10. LDR resistance measurement.

the measured resistance of the LDR used in this work under different light sources.

Figure 11 shows a voltage divider design whose resistor Ra is connected in series to a potentiometer (trimpot) to allow accurate V_s adjust. When the sum of both equals RLDR, V_s becomes $V_{cc}/2$ according to equation (1), and therefore, in this case V_{ref} must be set to 2.5 V.

This work proposes the twilight alarm design as an efficient way to integrate technological and scientific concepts.

The driver power circuit

The comparator output signal can switch a LED, but it hasn't power enough to switches directly high-power devices such as bulbs, motors, or

Table 2. Light sources and the LDR resistance.

Light source	LDR resistance at 70 lx
Sun	4.1 kΩ
Fluorescent bulb	3.8 KΩ
LED bulb	4.5 KΩ
Incandescent bulb	2.4 KΩ

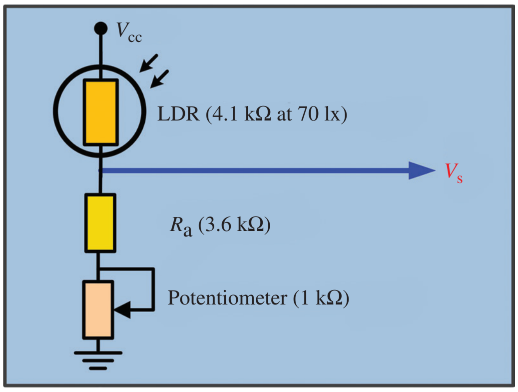

Figure 11. LDR voltage divider.

heaters, and therefore it requires a driver power circuit that allows the switching of a high-power device based on a low power input signal. Figure 12 shows its schematics.

The relay voltage (V_{dc}) causes a current flow (I_{rc}) through its coil, which naturally generates an electromagnet field that closes automatically an internal electro-mechanical contact that turns on an external high-power device (D_v). Note that, the relay has electrical operational limits and the external device power value cannot be greater than the maximum relay output switching power.

In fact, I_{rc} is usually great for a typical comparator circuit, and therefore the driver circuits use a transistor to connect it and the relay. Figure 13 exemplifies that a transistor base voltage value (V_b) can determines the transistor operation as an open key (cut-off state) as a closed key (saturated state) in relation to the collector-emitter connection. It means, a smaller current in the transistor base (I_b) can control a larger current flow between the transistor collector and emitter (I_c) [4, 5].

The relation between I_c and I_b depend on a transistor parameter called gain (*hfe*) and is expressed as:

$$I_b = I_c/hfe. \tag{3}$$

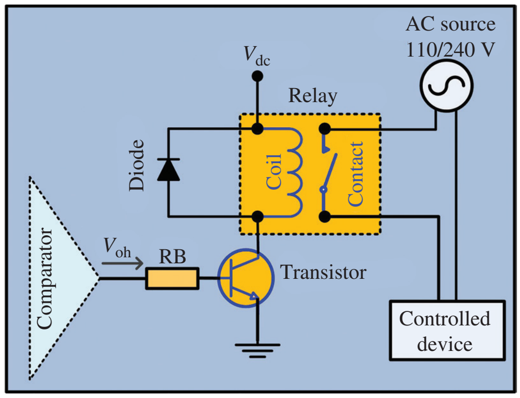

Figure 12. The driver power circuit.

In the figure 13, I_c is computed as:

$$I_c = (V_{dc} - V_{ce})/R_c. \tag{4}$$

Where: V_{dc} (*relay coil voltage*) is the voltage required for the coil electromagnet field generation.

V_{ce} is voltage drop that occurs at the collector-emitter transistor junctions, which is usually 0.2 V.

R_c (*relay coil resistance*) is the relay coil resistance, which can also be measured with an ohmmeter.

The resistor RB is computed as:

$$\mathrm{RB} = (V_{in} - V_{be})/I_b. \tag{5}$$

Where V_{be} is the base and emitter voltage that cause a saturated state and usually is at about 0.7 V.

In this work, V_{dc} was 5 V and R_c was 70Ω, which generates a I_c of 68.5 mA. The transistor was a general-purpose model BC238B, whose theoretical *hfe* can vary between 180 and 460. The measured comparator V_{oh} was 3.8 V, but it was mathematically decreased to 3.5 V to ensure a safety margin.

For a transistor gain of 180, RB is computed as:

$$\mathrm{IB} = 68.5\,\mathrm{mA}/180 = 0.38\,\mathrm{mA}$$
$$\mathrm{RB} = (3.5 - 0.7)/0.38\,\mathrm{mA} \cong 7,5\,\mathrm{k}\Omega.$$

In this case, any voltage between 3.5 V and 5.0 V causes the transistor saturation, and therefore it should work well with V_{oh} at 3.8 V. If the transistor had a gain of 400, then the V_{in} would be:

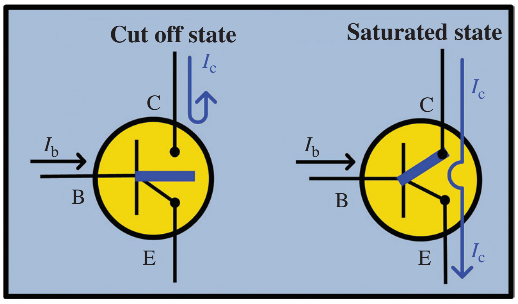

Figure 13. Transistor operation as switch.

$$\text{IB} = 68.5\,\text{mA}/460 = 0.15\,\text{mA}$$
$$7.5\,\text{K}\Omega = (V_{\text{in}} - 0.7\,\text{V})/\,0.15\,\text{mA}$$
$$V_{\text{in}} = 1.8\,\text{V}.$$

In this case, V_{in} must be 1.8 V or higher, and therefore the RB of 7.5 K ensures an effective operation for any possible BC238B gain.

Figure 12 schematics has a diode (*suppression diode*) protects the circuit when V_{in} is turned off and the energy remained in the coil can move the electrons again, which consequently can generate a harmful high voltage peak, which is common with inductive loads as motors. A diode such as the 1N4001 or similar, shuts the electrons flow in a loop with the coin, which decreases the voltage peak and consequently protects the circuit.

Figure 14 shows the real power driver circuit mounted in this work and exemplifies its connections.

The complete system

Figure 15 shows the schematic of a complete automation system, which fellows exactly the figure 1 modules and proves that the design of a basic automation system based on the divide-and-conquer technique is feasible and can encourage technological studies associated with physics concepts.

In this work, this system was used to control the ambient temperature. When the temperature is smaller than the SP, the circuit turns on a heater and it increases. When it reaches the SP, the circuit turns off the heater and the ambient temperature decrease, and the process repeats itself continuously. It composes a basic control technique called *on-off control* that is not the more

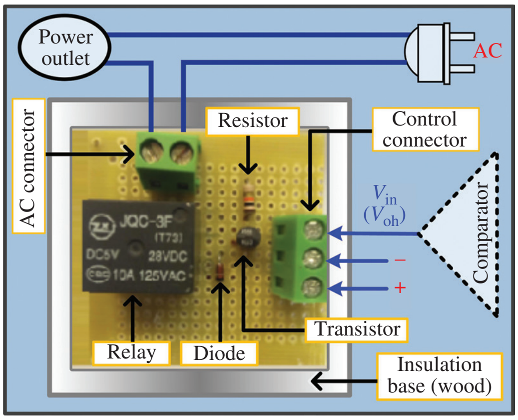

Figure 14. Mounted driver circuit.

accurate technique, but is easy to understand and simple to implement.

Figure 16 shows the theoretical expected phenomenon variation for the on-off control, which is a sinusoidal curve about the SP straight line. It fellows this trend due to the natural phenomenon inertia, and presents an initial peak called *overshoot* and so stabilizes in a stage called *Hunting* where its variation is limited into a range called *error band* (E_b).

Figure 17 shows the experiment structure, which included an additional data logger to record the ambient temperature variation to allow its later analysis. In the absence of a commercial data logger, a practical alternative is the data acquisition system called Easy-DAQ, whose software is free of charge and the hardware is based on an inexpensive Arduino board [6]. It was originally designed with a waterproof sensor that can be directly replaced by a simple LM35 for the present experiment. The simplest alternative is to measure the control system sensor voltage (V_s) with a voltmeter and note its peaks, which is less accurate but can prove the oscillatory temperature behaviour into a range.

Figure 18 shows the real experiment elements used in this work to control the ambient temperature.

In this work, figure 19 exemplifies the heater was placed in a box without one of the side walls. It is not an essential procedure, but the box size is more proportional to the heater size and it can generate a temperature variation easier to be analyzed.

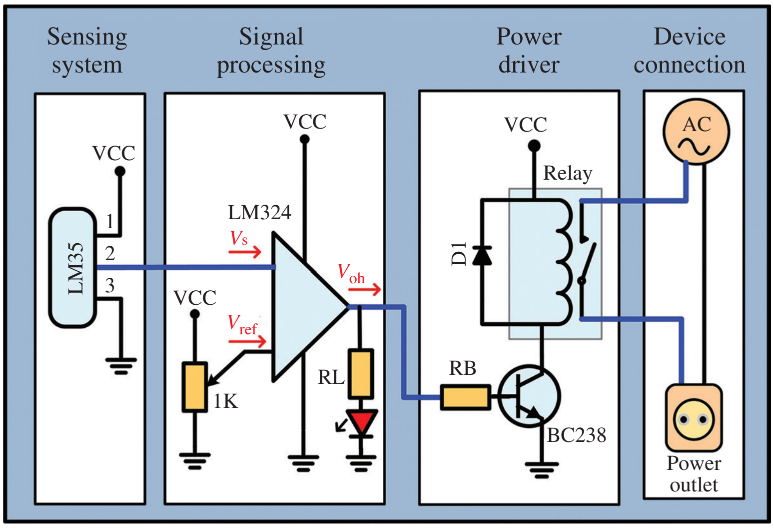

Figure 15. Complete automation system circuit.

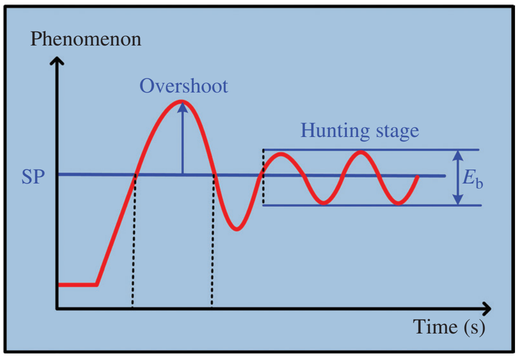

Figure 16. Typical on-off control response.

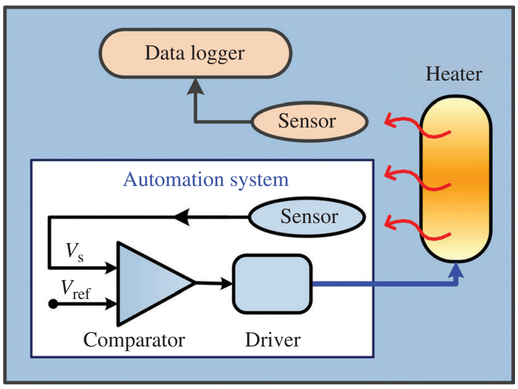

Figure 17. Experiment structure.

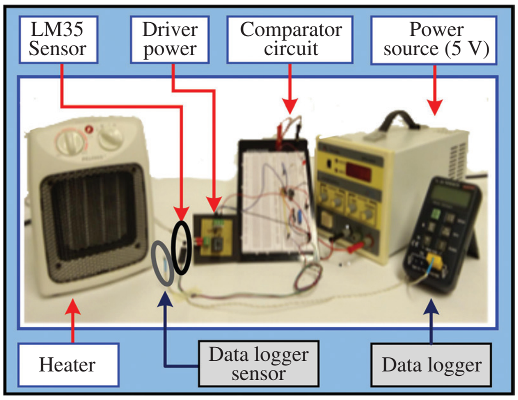

Figure 18. Real experiment elements.

Figure 20 shows the real experiment curve for this work experiment. The initial ambient temperature was 26.5 °C and the V_{ref} was fixed at 0.55 V to provide a SP of 55.0 °C. It fellows the sinusoidal curve where the overshoot reached 59.3 °C and the E_b varied from 52.0 °C to 58.3 °C with a mean value of 55.54 °C. It proves the experiment is feasible and allows satisfactory results for educational purposes.

Note that, the overshoot, E_b, and heating and cooling periods can vary for each experiment according to several factors, such as sensor location in relation to the heater, room size, heater power, and air flow.

Besides the heater control, the figure 15 comparator can be designed as a non-inverter circuit and the header replaced by an air cooler that is turned on when the ambient temperature is greater than the SP. It is a fun experiment in sweltering summer days.

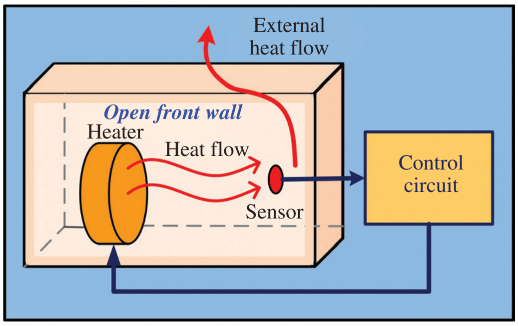

Figure 19. Experiment in a box.

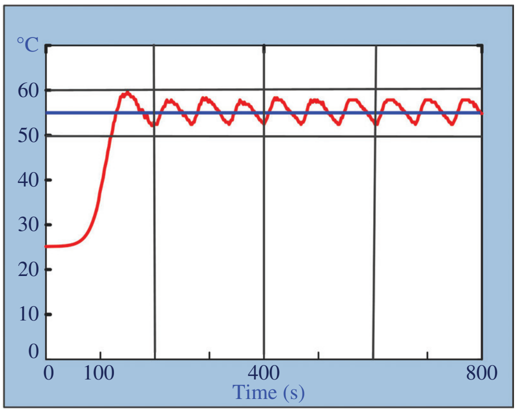

Figure 20. The real temperature variation.

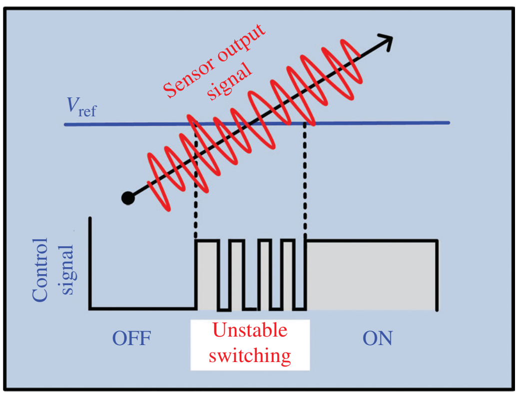

Figure 21. The unstable switching.

Additional considerations

There are two practical problems that may occur in some specific cases:

1. The sensor output signal can oscillate significantly due to its precision degree, which causes an undesirable unstable switching period, as shown in figure 21.

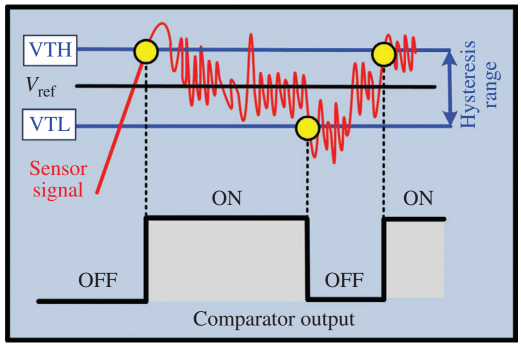

Figure 22. Hysteresis control.

2. There are phenomena whose controlled magnitude can vary quickly about the SP and it causes a successive switching

Both problems can generate an extremely intensive switching that can damage the system. In fact, each system has a tolerance degree and these problems relevance becomes relative only for specific cases.

These problems can be attenuated with a comparator circuit designed with *hysteresis*. Figure 22 show it creates a voltage range celled *hysteresis range* and limited by VTL and VTH, where the sensor signal oscillation does not influence the comparator output, and therefore avoids intensive switching.

Figure 23 shows comparator schematics with hysteresis, which require only two additional resistors (R1 and R2) to define the hysteresis range.

The parameters for a non-inverter hysteresis comparator are:

$$\mathrm{VTH} = \frac{(\mathrm{R1} + \mathrm{R2}) * V_{\mathrm{ref}} - (\mathrm{R1} * \mathrm{V}_{\mathbf{oL}})}{\mathrm{R2}} \quad (6)$$

$$\mathrm{VTL} = \frac{(\mathrm{R1} + \mathrm{R2}) * V_{\mathrm{ref}} - (\mathrm{R1} * \mathrm{V}_{\mathbf{oh}})}{\mathrm{R2}} \quad (7)$$

$$\frac{\mathrm{R2}}{\mathrm{R1}} = \frac{(V_{\mathrm{oh}} - V_{\mathrm{oL}})}{(\mathrm{VTH} - \mathrm{VTL})}. \quad (8)$$

The parameters for an inverter hysteresis comparator are:

$$\mathrm{VTH} = \frac{\mathrm{R2} * V_{\mathrm{ref}} + \mathrm{R1} * V_{\mathrm{oh}}}{\mathrm{R1} + \mathrm{R2}} \quad (9)$$

$$\mathrm{VTL} = \frac{\mathrm{R2} * V_{\mathrm{ref}} + \mathrm{R1} * V_{\mathrm{oL}}}{\mathrm{R1} + \mathrm{R2}} \quad (10)$$

$$\frac{\mathrm{R2}}{\mathrm{R1}} = \frac{(V_{\mathrm{oh}} - V_{\mathrm{oL}})}{(\mathrm{VTH} - \mathrm{VTL})} - 1. \quad (11)$$

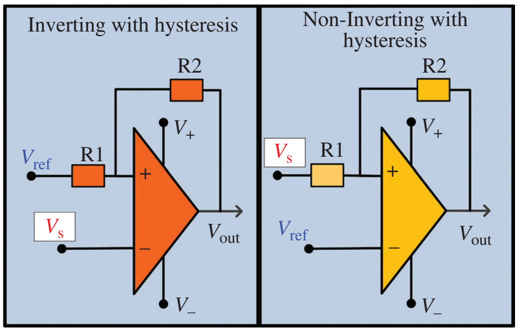

Figure 23. Comparators with hysteresis.

Table 3. Values for design.

Parameter	Value
V_{oh}	5 V
V_{ol}	0 V
V_{ref}	0.25 V
VTL	0.24 V
VTH	0.26 V

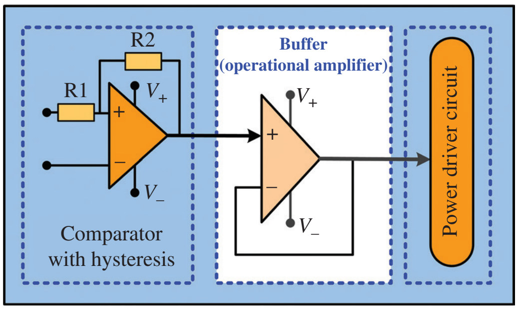

Figure 24. The buffer circuit.

For example, table 3 shows the parameters for a non-inverting hysteresis comparator design, where V_{ref}, VTL and VTH were fixed by the designer.

According to equation (11), the resistors relation is:

$$\frac{R2}{R1} = \frac{(5-0)}{(0.26-0.24)} = 250.$$

The resistors must be chosen with R2 two hundred and fifty times greater than R1, and then equations (9) and (10) are processed to verify the real hysteresis range.

The driver circuit can represent a load for the comparator output, which can influence the hysteresis precision. Figure 24 shows an additional operational amplifier called *buffer*, designed between the comparator and the driver to eliminate this problem due to its high input impedance [5].

Despite these considerations relevance, it is important to emphasize the present work did not used neither hysteresis circuit nor buffer to achieve the results shown in figure 20.

Conclusion

This work presented experiments to switch electronic devices according to a physical phenomenon measurement and proved that a basic control system can be taught with the divide-and-conquer technique. It also demonstrated that sensing and automation experiments compose an interesting way to integrate physical and technological concepts.

ORCID iDs

J E M Perea Martins https://orcid.org/0000-0003-1056-497X

Received 3 May 2018, in final form 12 June 2018
Accepted for publication 14 June 2018
https://doi.org/10.1088/1361-6552/aaccd8

References

[1] Wang Y and Chiew V 2010 On the cognitive process of human problem solving *Cogn. Syst. Res.* **11** 81–92
[2] Docktor J L and Mestre J P 2014 Synthesis of discipline-based education research in physics *Phys. Rev. Spec. Top.-Phys. Educ. Res.* **10** 0201191
[3] Considine G D 2002 *Van Nostrand's Scientific Encyclopedia* 9th edn vol 1 (New York: Wiley) p 320
[4] Malvino A and Bates D 2015 *Electronic Principles* 8th edn (New York: McGraw-Hill)
[5] Eggleston D L 2011 *Basic Electronics for Scientists and Engineers* (Cambridge: Cambridge University Press)
[6] Perea Martins J E M 2017 A data acquisition system for water heating and cooling experiments *Phys. Educ.* **52** 015019

João E M Perea Martins is a professor in the Computer Science Department at the Sao Paulo State University (UNESP), in Brazil. He received his bachelor degree in Computer Science from UNESP and his master and PhD degrees in Physics from the University of São Paulo (USP), in Brazil. Currently, his research interest areas include electronic instrumentation, microcontrollers, computer simulation, environmental systems, and physics education.