ME 530.241: Electronics and Instrumentation

Design Project: Safeguarding Vaccine Shipments

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Introduction

Over the past year, safe shipping and handling of vaccines has become incredibly relevant. They must be stored at low temperatures; thus, the people receiving the order must know whether the temperature of the vaccines ever rose above the allowable temperature during shipment.

The goal of this project was to design and prototype a circuit that allows a user to check whether a certain temperature threshold has been reached. Although the driving application for this project was safe vaccine shipping, the product can be applied to anything with a temperature threshold--for example, raw meat storage, or tracking conditions inside a greenhouse.

Device Description and Function

The device takes temperature measurements continuously. When the temperature exceeds some given threshold value, the system should trigger. When the status button is pressed while the system is triggered, an LED will light up--alerting the user that the temperature threshold has been crossed. The circuit also includes a reset button: when pressed, it will no longer remember whether the threshold has been crossed.

Internal Operation

- A voltage regulator steps down the +9V battery, providing a constant +5V as power to the circuit. A regulator was chosen over a voltage divider because it protects circuit components from sudden voltage surges (although these are not anticipated, because the power input is a standard 9V battery).
    - Although the LM78L linear regulator we used would generally be used with capacitors for decoupling, we did not include them because we're not expecting significant noise from the 9V battery.
- A TMP36 temperature sensor takes +5V as input and outputs a voltage that changes with temperature. At 25° C, V_{out} = 750 mV, and it changes with a scale factor of 10 mV per degree Celsius.
- A potentiometer allows the user to change the voltage sent to the positive input terminal of the op-amp, which lets them control the threshold temperature. It acts as a voltage divider, so changing the position of the wiper changes the voltage that the op-amp receives.

- Next in the circuit is an op-amp in open-loop mode, acting as a comparator. It compares the potentiometer output to the T36 output: if $V_{T36} < V_{pot}$, then the op-amp saturates high and provides an output voltage of +5V. When $V_{T36} > V_{pot}$, then it saturates low and provides an output voltage of +0V.
- The comparator output voltage is connected to the trigger of a 555 timer. When the trigger drops to 0V, the timer sends +5V to the output.
    - Connected to the timer's reset leg is a reset pushbutton. When pressed, the pushbutton connects the timer's reset leg to ground, and the output voltage is reset to 0V.
- The 555 timer's output connects to a green LED that indicates whether the temperature limit has been exceeded. In order to preserve the battery and LED life, we have a pushbutton in between the timer's output and the LED so that the LED only turns on while the button is being pressed. When the temperature limit has been exceeded, the LED will turn on while the button is being pressed. If the temperature limit has not been reached, the LED will remain off because it will receive no voltage from the timer's output. To keep from blowing out the LED, it is connected in series with a resistor.

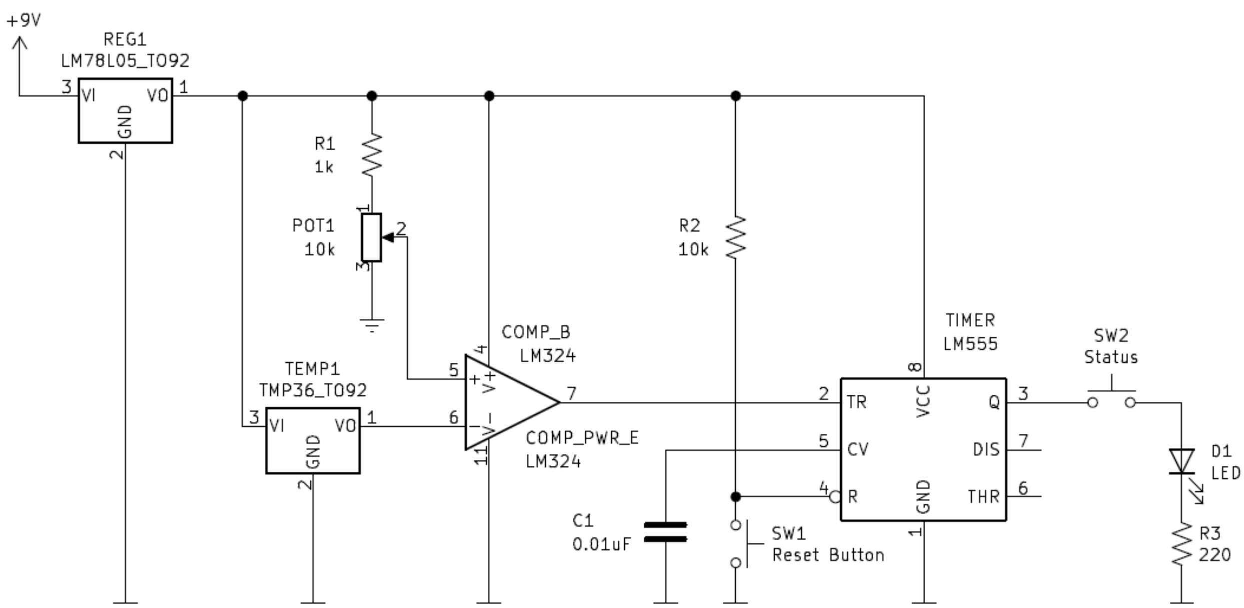

Fig. 1. Schematic of temperature threshold circuit.

Circuit Analysis

Potentiometer calculations:

To control the temperature threshold, we used the 10 kΩ potentiometer found in our kit. At first, we just used the potentiometer and did not connect it to any other resistors. To know how far to turn the potentiometer, we calculated the percent that it needed to be turned in order to reach a certain temperature using these equations:

$$V_{OUT} = V_{IN}\left[\frac{R_2}{R_1+R_2}\right]$$

We were able to express R_1 and R_2 in terms of the total resistance, R

$$R_1 = (1 - \%)R$$

$$R_2 = \%R$$

where % is the percentage that the knob is turned.

Plugging this in, we get

$$\frac{V_{OUT}}{V_{IN}} = \frac{\%R}{(1-\%)R+\%R} = \frac{\%}{1-\%+\%}$$

$$\% = \frac{V_{OUT}}{V_{IN}}$$

We then realized that with that configuration, the potentiometer was very sensitive, and all temperature values that we would be able to test in our apartments fell in a very small range on the potentiometer, from about 10-15%. In order to make the potentiometer easier to use, we connected two 10 kΩ resistors in series to the input of the potentiometer so that the 25°C would be at the midpoint of the potentiometer. We then redid our calculations to find the percentage the knob should be turned for each temperature value. We used MATLAB to calculate the needed potentiometer position given the desired temperature T. The MATLAB code can be found here: https://drive.google.com/file/d/1l5tltZksudbCyLmUtJ0f-7mrpWOz_oKs/view?usp=sharing.

- V_{IN} = 5V from voltage regulator
- V_{OUT} = 0.75 + 0.01(T - 25) V
  - We obtained this equation for the necessary output voltage from the specs of the temperature sensor.
- Using the voltage divider equation, we calculated the potentiometer knob position:

$$V_{OUT} = V_{IN}\left[\frac{R_2}{(R_1+Q)+R_2}\right]$$

where Q is the 20 kΩ resistance in series with R_1.

We were able to express R_1 and R_2 in terms of the total resistance, R

$$R_1 = (1 - \%)R$$

$$R_2 = \%R$$

where % is the percentage that the knob is turned.

Plugging this in, we get

$$\frac{V_{OUT}}{V_{IN}} = \frac{\%R}{(1-\%)R+Q+\%R}$$

$$\frac{V_{OUT}}{V_{IN}}(R - \%R + Q + \%R) = \%R$$

$$\% = \frac{V_{OUT}}{RV_{IN}}(R + Q)$$

LED Calculations:
In order to not blow out our LED, we had to calculate the appropriate resistor to use with it. We used a green LED, which has a forward voltage of approximately 2V. The desired current for an LED is approximately 20mA (which we found from the LED's datasheet), and the LED received 5V from the 555 Timer output.

$$R_{LED} = \frac{V_s - V_{LED}}{I_{LED}} = \frac{5V - 2V}{0.02\ A} = 150\Omega$$

Since we did not have a 150Ω resistor in our kit, we used the 220Ω resistor that we also used for our LEDs in the RS Latch lab.

Prototype

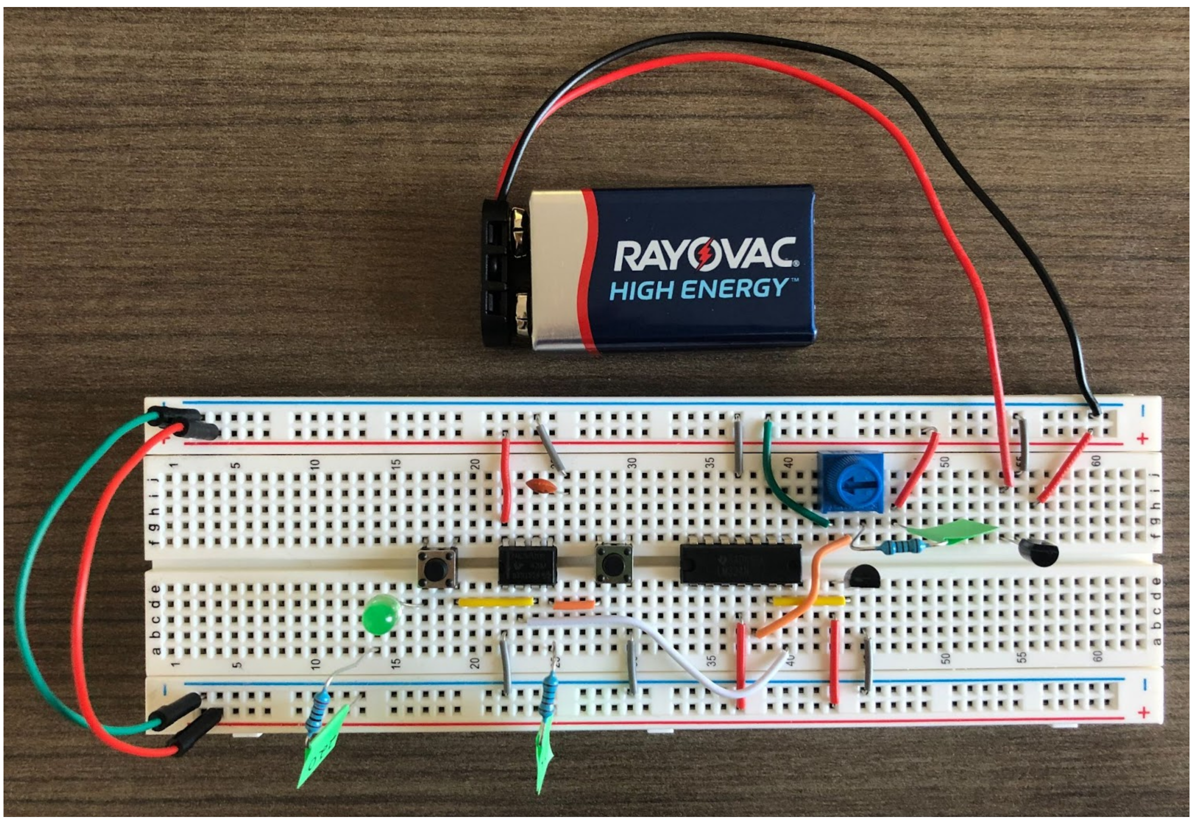

Fig 2. Photo of circuit as built on breadboard.

The exact circuit from Fig. 1 was constructed on a standard breadboard. A 9V battery provides power to the linear regulator, which sends +5V to the breadboard's power rails. From left to right, we have: the status button, an NE555P timer chip, the reset button, an LM324 op-amp chip, the TMP-36 temperature sensor, and the LM78L linear voltage regulator.

Response of System

To visualize the behavior of the circuit, we measured the response at several points of interest with an Espotek Labrador oscilloscope. For all of the following plots, the baseline was at room temperature, and a hair dryer was used to raise the temperature past the threshold.

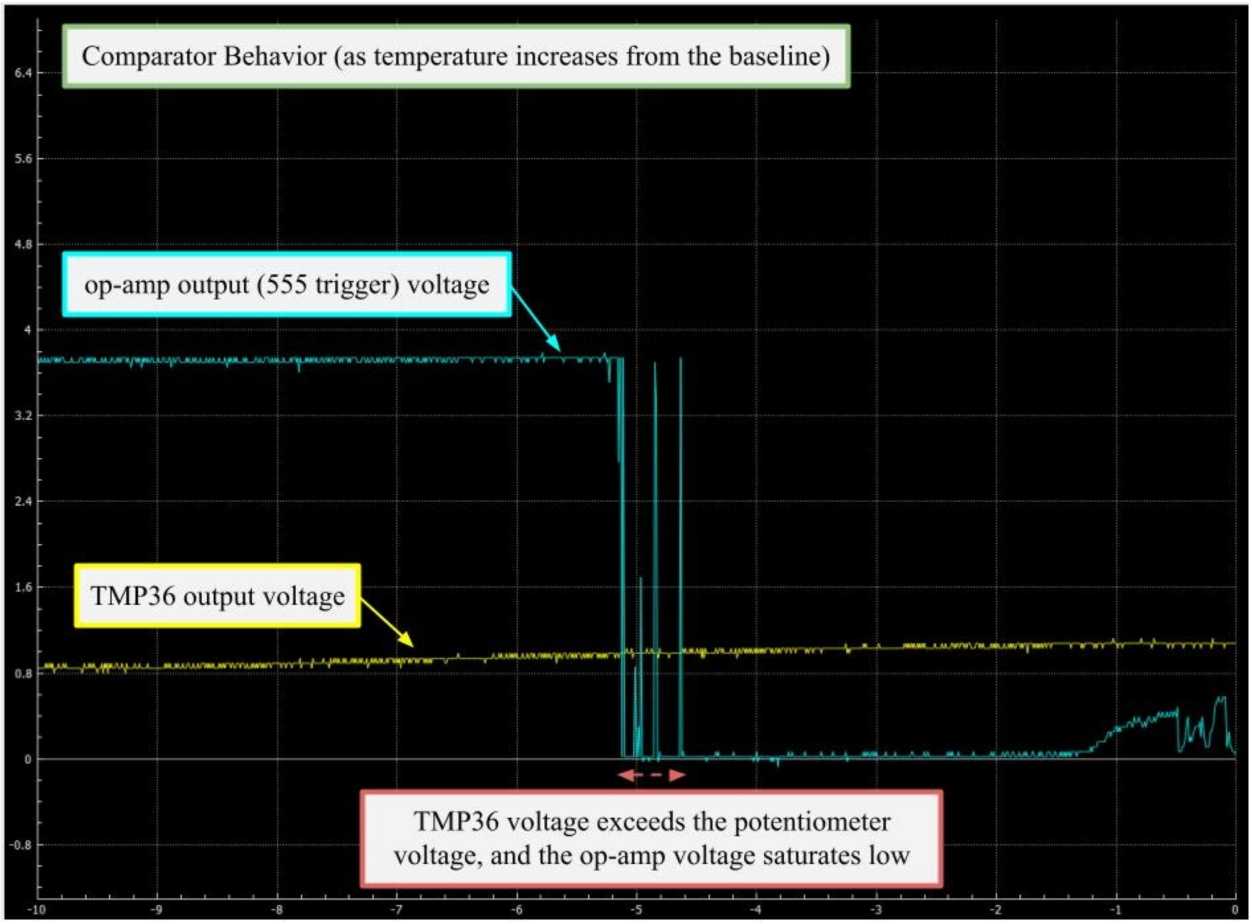

Fig. 3. Oscilloscope plot visualizing the behavior of the comparator.

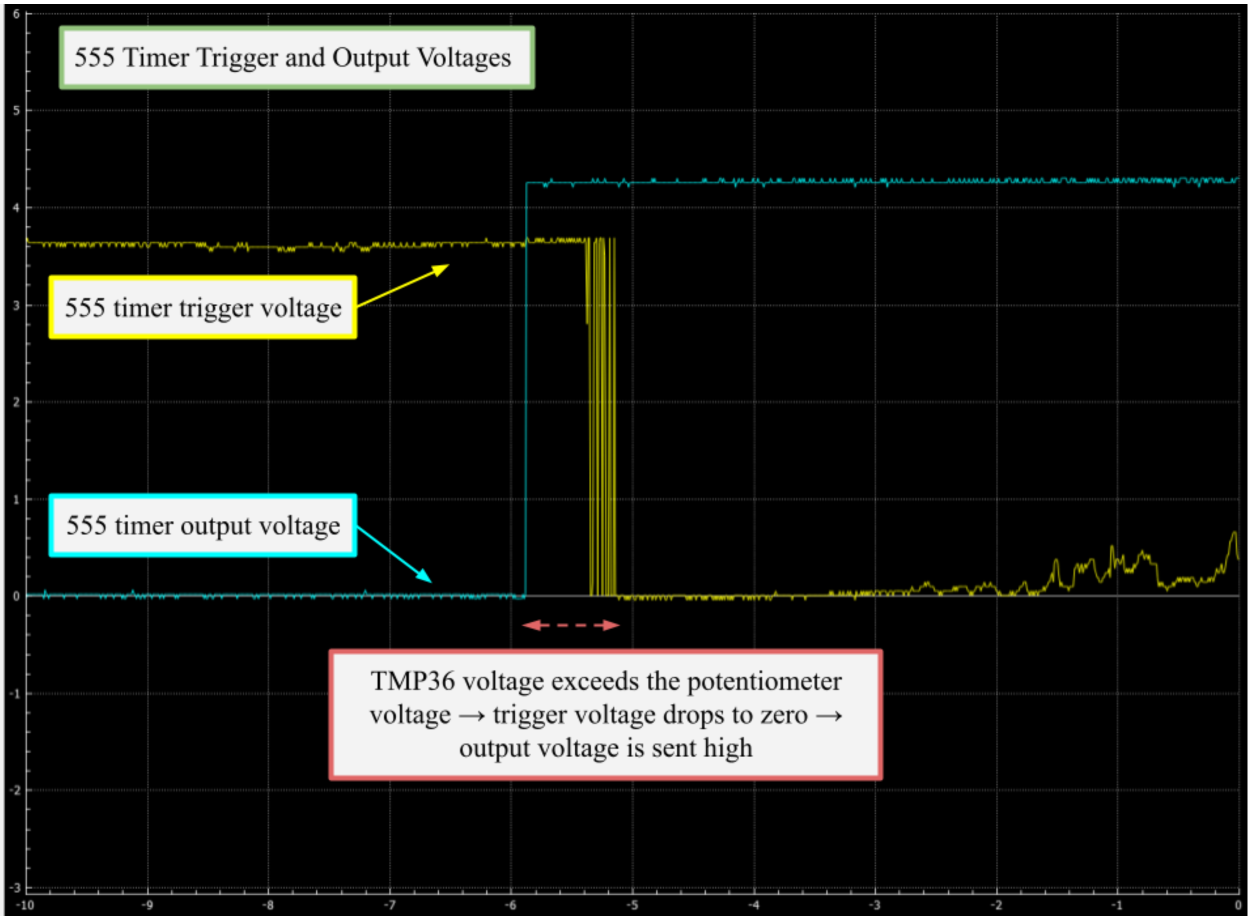

Fig. 4. Oscilloscope plot showing how the 555 timer output is sent high when the trigger goes low.

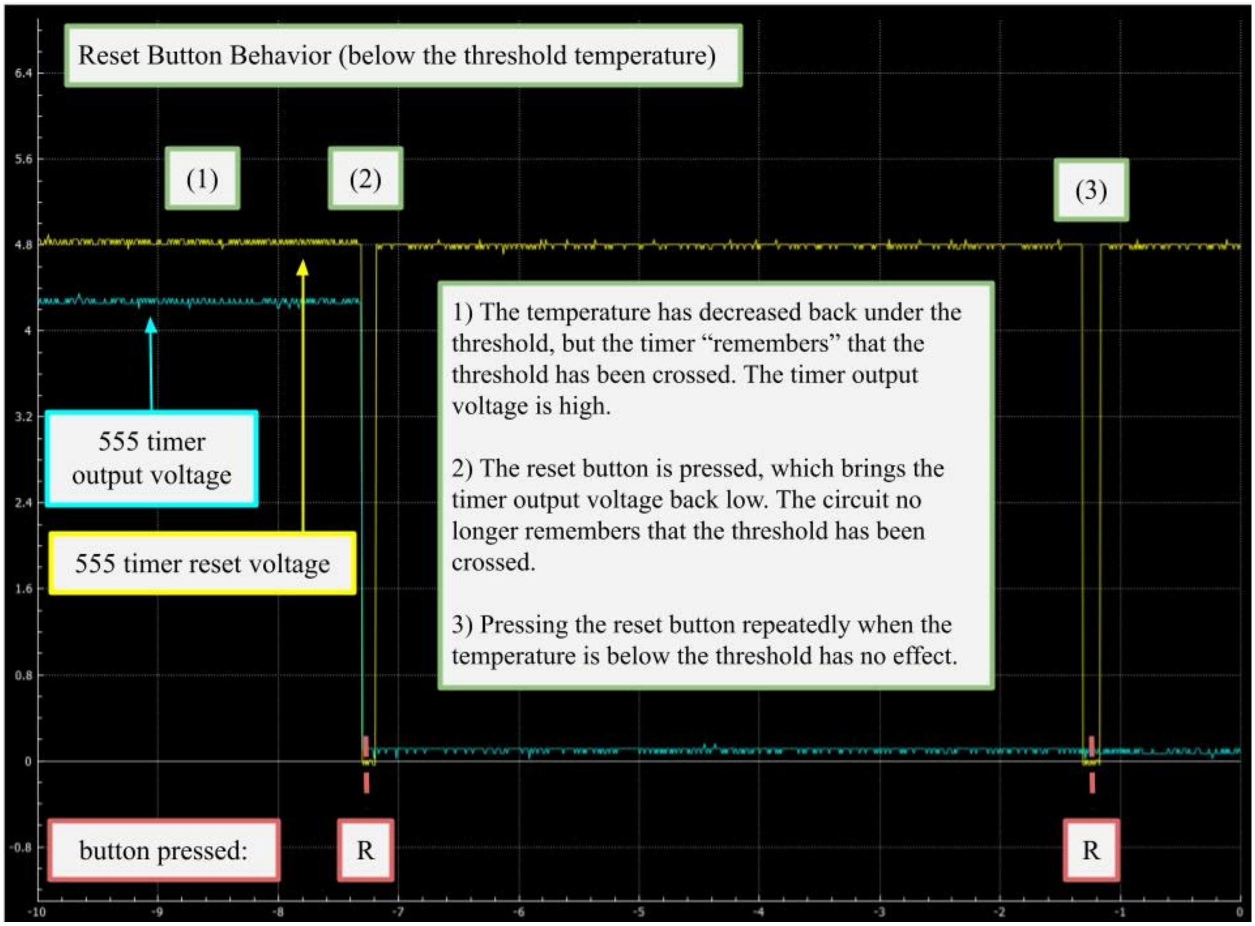

Fig. 5. Oscilloscope plot showing how if the threshold has been crossed, pressing the reset button at temperatures below the threshold will "wipe" the memory of the timer.

Conclusion

Our circuit went through a variety of revisions during this design process. Originally we were using an RS latch to save the state, and we had it in the same configuration we used in the lab. We then realized that we could edit our circuit so that we only used one side of the latch. This eliminated many of the overlapping wires, which were hard to follow, especially in TinkerCAD. After we learned about the 555 Timer in class, we changed out our latch for a timer, which further simplified our circuit. Unlike the latch, the timer turns on when it experiences 0V, so we had to change our inputs to the timer. We switched the + and - on the op-amp so that it would turn off when the temperature sensor's voltage exceeded the input voltage, which triggered the timer. We also changed the reset button so that it connected to ground instead of 5V.

We also went through various revisions to our resistor/potentiometer configuration, some of which were mentioned in the analysis. As we worked on the circuit, we updated that part of the circuit to make it easier for the user to use. Adding the additional resistors in series with the potentiometer allowed the knob to be set at a more reasonable level, which makes it both easier and more intuitive for the user.

In conclusion, our design is both functional and user friendly. It can perform all of the necessary operations, and it is simple to use. It saves energy by having the status LED connected to a button, and it is small and portable. This device would be useful anywhere one needed to monitor the threshold temperature of a space.

Video: https://www.youtube.com/watch?v=DSID2qOr8os