EXPERIMENT 11

Control Loops

11.1 Control Systems

Most electronic circuits involve some sort of control system. In order to drive an output device to a desired state, the inputs are filtered and combined in a defined method to drive a control signal for the device to the desired state. Within control systems, there are two types: open loop and closed loop controls. The primary difference is that closed loop systems have a feedback system whereas open loop systems do not.

11.1.1 Open Loop Control

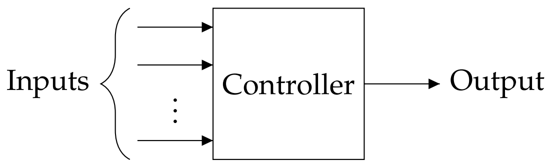

Figure 11.1: Open Loop Control System

Open loop controls, like the motor speed control from experiment 2 and regulator circuits from experiment 10, do not verify that the output is at the correct state. Instead, careful calibration of the system is needed to ensure that the output will be in the correct state when it receives the control signals. Open loop control is generally reserved for tasks that do not require adaptation to changing output conditions without user interaction.

One could argue that an operator adjusting inputs based on the output state is a form of "closed loop" control where the human is the feedback system, but we will leave that determination up to you.

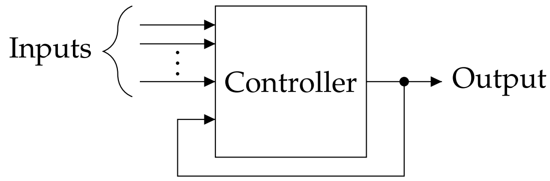

Figure 11.2: Closed Loop Control System

11.1.2 Closed Loop Control

Closed loop control measures the output of a system and feeds it back in to the input of the system. By doing this, the system can ensure that the output is in the correct state instead of relying on making assumptions about how the output will respond to the control signal. A simple example is a thermostat. It constantly measures the temperature in a room, and when the temperature is below the set point, it turns on the furnace. Without closed loop control, the thermostat would have to guess when it needed to turn on to keep the room at the correct temperature. Feedback can also enable more precise control of outputs compared to open loop. For this reason, closed loop control is widely employed in automated machinery, vehicle drive systems, and more.

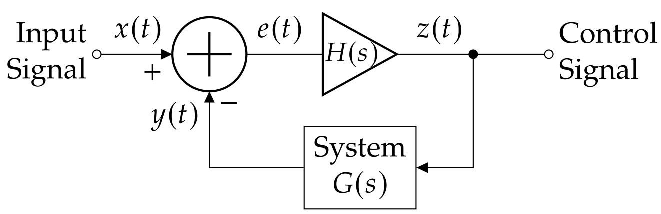

Figure 11.3: Feedback system model

In order to analyze or design a feedback system, we must first establish a model for the system. One such model is presented in figure 11.3. This system has one input $x(t)$, which is the desired state of the system. The current measured state of the system is given as $y(t)$. These two quantities are used to determine the current error, $e(t) = x(t) - y(t)$. This error signal is then passed through an amplifier with frequency response $H(s)$. The output of that system, $z(t)$, is then fed into the system we are trying to control. Ideally, this system has a well modeled or known response which we will call $G(s)$. Fortunately, feedback systems can still work if the model for $G(s)$ is not well defined.(1)

In effect, this system will adjust $z(t)$ until the error is minimized. Any changes to the system will change the value of $y(t)$, so the loop amplifier will detect increased error and

(1) If the system's behavior is not well defined, it is very important to test that your control loop operates safely! In safety critical systems, it is very important to have a good model for the system you are controlling so you can verify it will always operate safely.

adjust $z(t)$ as needed to compensate for the change in the system. Similarly, a change is the desired state $x(t)$ will cause the error to increase in magnitude and require a change in the control signal. The complete response of the control signal to an input is given in equation (11.1)

$$\frac{Z(s)}{X(s)} = \frac{H(s)}{1 + G(s)H(s)} \tag{11.1}$$

If we consider the case where $H(s)$ is large in magnitude, then the transfer function $Z(s)/X(s) \approx 1/G(s)$. That is, the system will drive Z to be whatever it needs to be to exactly undo the system $G(s)$ and minimize the error. In fact, in simple feedback systems, we only need to have $H(s)$ have a large linear gain to achieve effective closed loop control.(2) You actually have been utilizing this fact throughout all of the operational amplifier (op amp) experiments. The simplest to analyze in this regard is the non inverting amplifier shown in figure 11.4. In this circuit, $G(s)$ represents the resistive feedback network, and the feedback circuit drives the error $e(t) = v^+ - v^-$ to zero. This process of driving the input error to zero with negative feedback is the basis of virtual short circuit analysis.

(2) Proportional only control has several drawbacks including a constant error in the output of the system and can behave undesirably to large changes in the control signal or system state, but it still works well enough for very simple systems.

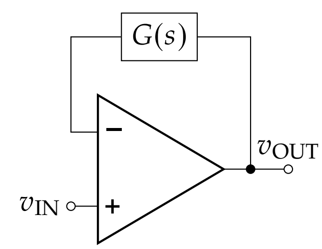

Figure 11.4: Closed loop feedback op amp circuit

11.1.3 The proportional-integral-derivative (PID) controller

The most ubiquitous controller system used in feedback systems is the PID controller. In this system, the feedback function $H(s)$ consists of three portions: a proportional term, an integral term, and a derivative term. Mathematically, the transfer function is given in equation (11.2). The three gain terms K_p, K_i, and K_d set the amount of each type of feedback is included in the control loop.

$$H(s) = K_p + \frac{1}{s}K_i + sK_d \tag{11.2}$$

By adjusting the gain parameters(3), the feedback loop can be tuned to a wide variety of systems. Of the parameters, the proportional gain K_p simply adjusts the input to the system based on a constant proportion of the error. The integral term integrates the error, which allows for eliminating the offset that occurs at the output of a proportional only system. In systems that need to quickly respond to changes, the derivative term adds to the output only while the error is changing. All together, the PID control system allows for carefully tuning the response of a system so that it performs as desired.

(3) For some PID systems, K_i or K_d can be set to 0, making it a PI or PD controller

11.2 Analog control circuits

Several simple op amp circuits can be used to implement a feedback controller. The simplest control loop circuit can be built with a single op amp. Using the circuit in figure 11.4, the negative terminal is connected to the measured output of a system, the positive terminal is connected to a control voltage, and the output is what is connected to the input of the system, which could be any electrically controllable device. Unfortunately, this simple system is not effective in many applications as the gain is actually too large which can lead to nonlinear behavior. Small amounts of error will cause the inputs to the electrically controllable device to swing wildly and overshoot the targeted value.

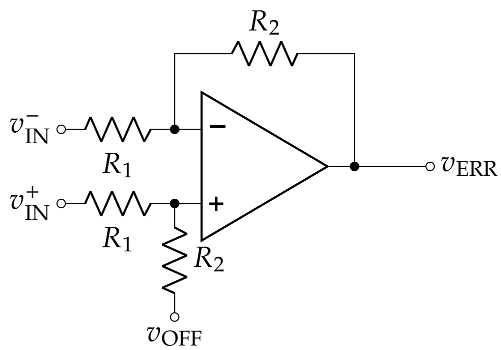

Figure 11.5: Single sided error amplifier

The input impedance of the circuit in figure 11.5 is equal to R_2. If a high impedance input is needed, an instrumentation amplifier circuit may used as the error amplifier.

In order to drive the input of the PID controller, we need to create an error amplifier. This circuit needs to find the difference between the desired state and current state. A simple one op amp solution is shown in figure 11.5. The behavior of this circuit can be found by using superposition with the three inputs.

$$v_{ERR} = \frac{R_2}{R_1}\left(v_{IN}^+ - v_{IN}^-\right) + v_{OFF} \tag{11.3}$$

The offset voltage, v_{OFF}, is used to allow for operation with a single sided supply. It ensures that the output and input voltages to the op amp stay within the acceptable values.

Next, we need a circuit that can implement the transfer function in equation (11.2). There are many ways to build integrators, differentiators, and amplifiers that can be used in a PID controller. In this experment, we will focus on the PI controller[4]. The PI controller can be built using a single op amp, as shown in figure 11.6.

[4] The derivative component adds a level of complexity beyond the scope of thise experiment, but will be covered in any thorough course on controls.

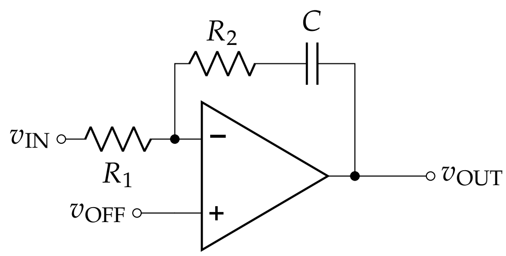

Figure 11.6: PI controller circuit

The response of the circuit can be found by analyzing it in the laplace domain and using superposition.

$$
\begin{aligned}
v_{OUT} &= -\frac{Z_C + R_2}{R_1} v_{IN} + \left(1 + \frac{Z_C + R_2}{R_1}\right) v_{OFF} \\
v_{OUT} &= -\frac{Z_C + R_2}{R_1} (v_{OFF} - v_{IN}) + v_{OFF} \\
v_{OUT} &= \frac{1}{sR_1C} (v_{OFF} - v_{IN}) + \frac{R_2}{R_1} (v_{OFF} - v_{IN}) + v_{OFF} \qquad (11.4)
\end{aligned}
$$

By comparing equation (11.4) with equation (11.2) while $v_{OFF} = 0$, we see that $K_p = \frac{R_2}{R_1}$ and $K_i = \frac{1}{R_1 C}$. This circuit implements a PI controller for a system with a DC offset of v_{OFF}, which is useful for single supply systems. Conveniently, the error amplifier in figure 11.5 adds this offset to the error signal for us.

11.2.1 Pulse width modulation (PWM) Modulator

In experiment 2, we built a PWM modulator to convert an analog control voltage to a PWM signal to efficiently drive the motor. In this experiment, we will use a similar PWM modulator circuit to control the PWM signal driving the buck switching regulator built in experiment 10.

11.3 Prelab

Task 11.3.1: Prelab Questions

1. In your own words, *describe* the difference between open loop and closed loop control.
2. *Plot* the Magnitude and Phase response of $\frac{v_{OUT}}{v_{IN}}$ for the circuit in figure 11.6 given:
   a) $R_1 = 1\,\text{k}\Omega$, $R_2 = 33\,\text{k}\Omega$, and $C = 10\,\text{nF}$
   b) $R_1 = 1\,\text{k}\Omega$, $R_2 = 2.2\,\text{k}\Omega$, and $C = 10\,\text{nF}$

Use a log-log plot for the magnitude response and a semilog plot for the phase response.

3. *Calculate* K_p and K_i for both of these configurations.
4. *Pick* R_1 and R_2 for the error amplifier design in task 11.4.2. Make sure to pick values available in your kit.

11.4 Tasks

Task 11.4.1: Buck regulator with PWM modulator control

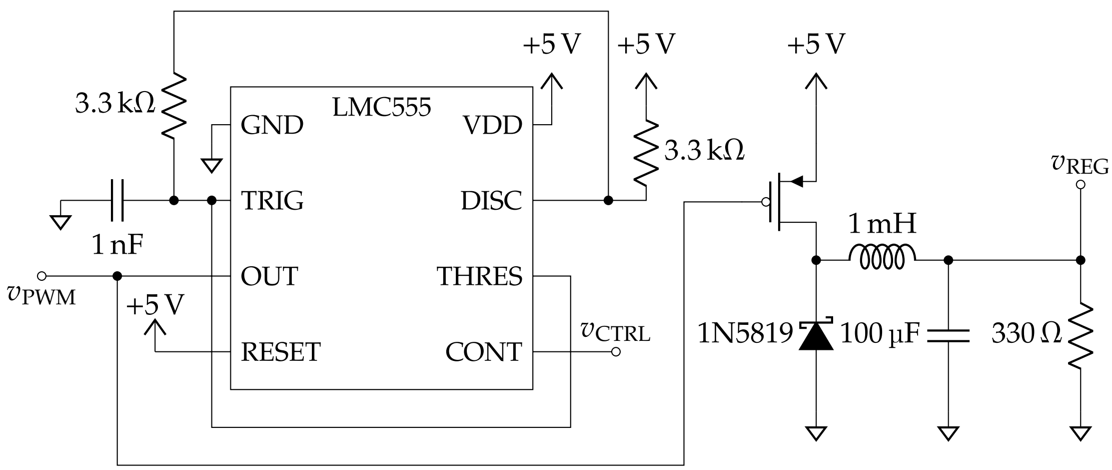

Figure 11.7: PWM Modulation Circuit

1. *Construct* the circuit in figure 11.7
2. *Connect* v_{CTRL} to the function generator and configure the function generator to output DC.
3. *Measure* and *Plot* the relationship between v_{CTRL}, the duty cycle of v_{PWM}, and v_{REG}.
4. What control voltage and duty cycle is needed for a 2.5 V output?
5. *Change* the supply voltage from 5 V to 4 V then *adjust* the control voltage until v_{REG} = 2.5 V. *Record* the control voltage and PWM duty cycle at this point and *compare* these values with the answer from step 4.
6. Is this method of controlling the regulated output voltage open loop or closed loop?

Task 11.4.2: Error amplifier

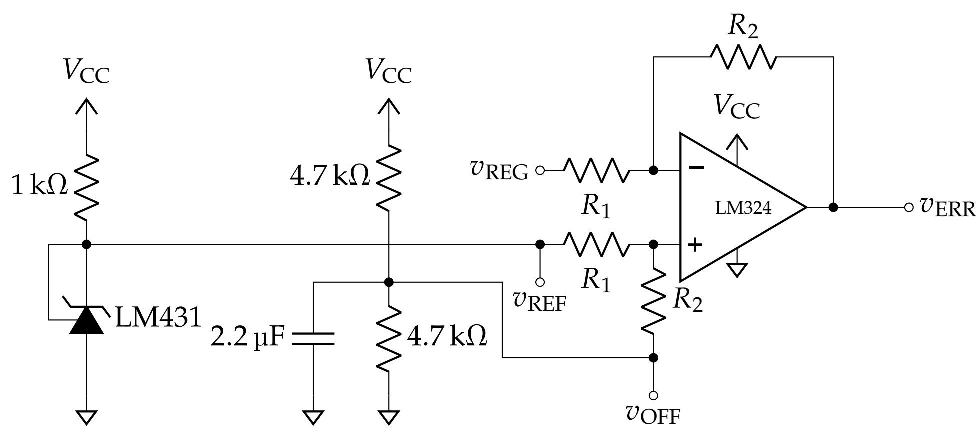

Figure 11.8: PWM Modulation Circuit

In this task, we will design and build an error amplifier that will measure how far from our target voltage of 2.5 V the output of the regulator is. Because this is a single supply design, we must supply an offset voltage to stay within the common mode input and output range of the op amp.

1. Pick R_1 and R_2 in figure 11.8 in order to make $v_{ERR} = v_{REF} - v_{REG} + v_{OFF}$. Choose values greater than $20\,k\Omega$.
2. *Construct* the circuit in figure 11.8 with $V_{CC} = 5\,V$.
3. *Connect* v_{REG} to the function generator in DC mode.
4. *Sweep* the function generator from 1 V to 4 V and record v_{ERR} at each step.
5. *Set* $V_{CC} = 4\,V$ then *repeat* step 4.
6. Does the circuit implement the desired error measurement equation? What is the output voltage when the error is zero for each case?

Task 11.4.3: Closed loop buck controller

1. *Construct* the circuit in figure 11.9. Make sure to close the feedback loop by connecting both v_{CTRL} points together.
2. *Set* V_{CC} to 5 V and measure the average value of v_{CTRL} and v_{REG}.
3. *Sweep* V_{CC} from 4 V to 5 V. *Record* v_{REG} and v_{CTRL} at each step.
4. *Capture* an oscilloscope screenshot showing v_{REG} and v_{CTRL} during the power up sequence. That is, turn off V_{CC}, set the oscilloscope to single trigger mode, then turn on $V_{CC} = 5\,V$.

5. *Replace* R_L with a 150 Ω resistor. What happens to v_{REG} and v_{CTRL}?

6. Is this control system able to effectively and automatically regulate v_{REG} over a variety of conditions? What is the relationship between V_{CC} and the control voltage? What is the relationship between R_L and the control voltage?

7. *Replace* the 33 kΩ resistor in the PI controller with a 2.2 kΩ resistor while still using $R_L = 150\,\Omega$. What happens to v_{CTRL} and v_{REG}? Obtain an oscilloscope screenshot showing both v_{CTRL} and v_{REG} in this configuration. Is the power supply still working correctly?

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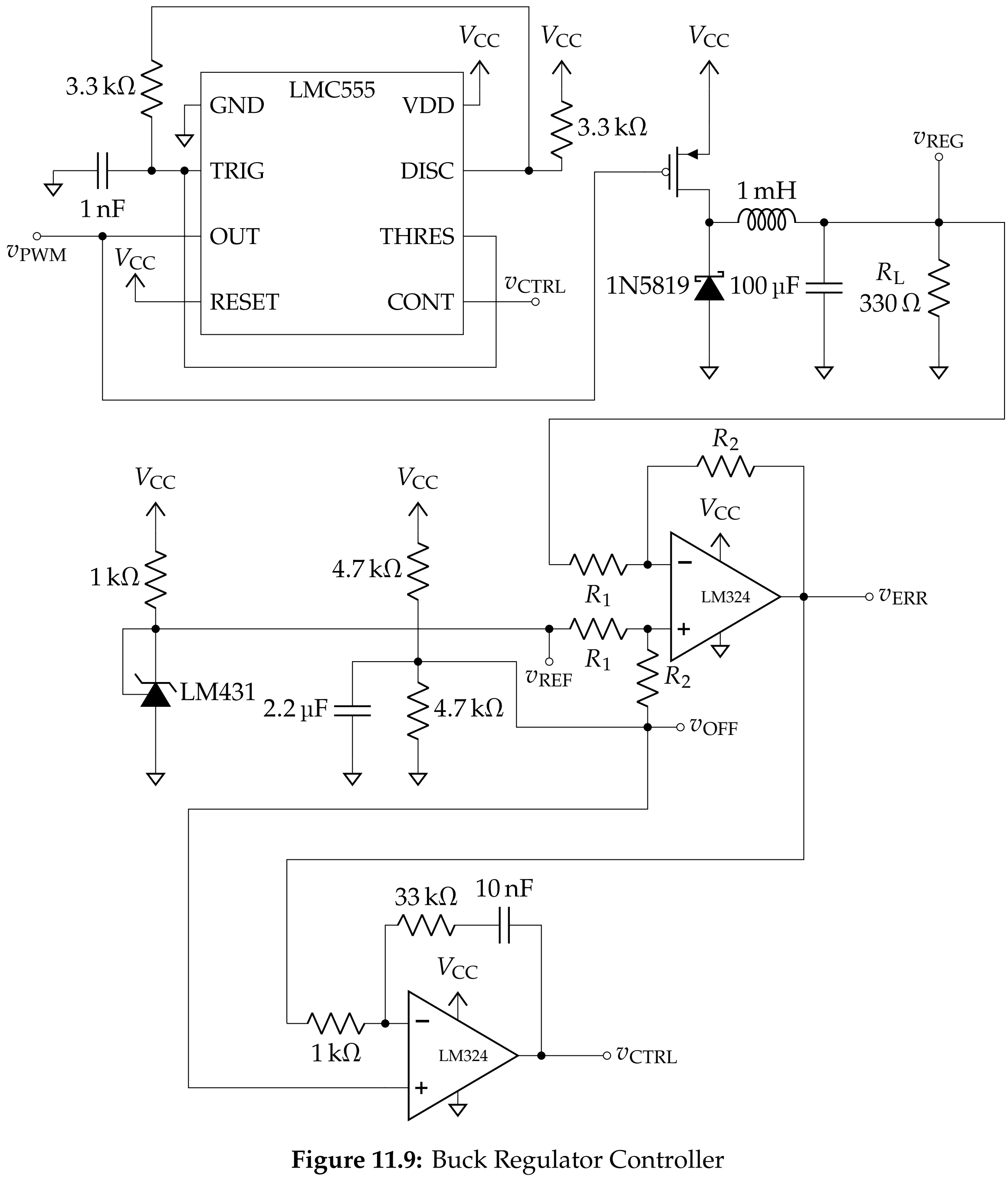

Figure 11.9: Buck Regulator Controller