Lab 6: Exploring the Servomotor Controller Circuit

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1. Purpose:

The purpose of this lab is to examine the circuit that controls the servomotor. The goal is to mathematically characterize this system in terms of its electrical input and mechanical output. The information gained about the servo circuit will be useful when the circuit is connected to and driven by the receiver in the lab project. There are eight servomotor controller boards in the lab. Please treat them with care.

Equipment:

- Agilent 54600B Oscilloscope or Agilent 54622A Deep Memory Oscilloscope (Replacement model: Agilent DSO5012A Oscilloscope or Agilent DSO6012A Oscilloscope)
- Agilent E3631A DC Power Supply
- Agilent E3611A DC Power Supply

2. Servomotor

A servomotor (servo) is an electromechanical device in which an electrical input determines the position of the armature of a motor. Servos are used extensively in robotics and radio-controlled cars, airplanes, and boats.

You will be using an Airtronics 94102 Precision Heavy-Duty Standard Servo. The position of the armature (See Figure 1) is determined by the **duty cycle** of a periodic rectangular pulse train. The **duty cycle** of a rectangular pulse train is expressed in %: It is the ratio of the pulse duration to the pulse period times 100% (See Figure 2 for examples.)
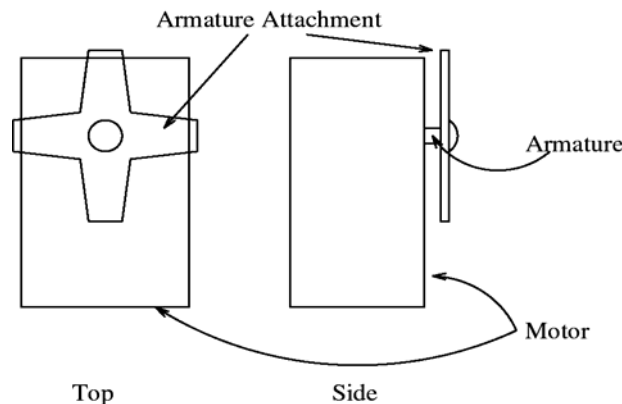

Figure 1: Illustration of Servomotor Identifying the Armature

The receiver sub-circuit of the lab project outputs a DC voltage. Therefore it is necessary to convert the DC voltage produced by the receiver into a rectangular pulse train whose **duty cycle** is determined by the DC level. In this lab exercise you will investigate how the servo controller circuit accomplishes this conversion from a DC voltage level to a rectangular pulse train with a specific **duty cycle**.

3. Components of the Servomotor Controller Circuit

The servo controller circuit consists of several op-amps and Transistor-Transistor Logic (TTL) components. Its purpose is to convert a DC voltage into a rectangular pulse train whose **duty cycle** is determined by the DC level. The servo responds to variations in the **duty cycle** of a 50 Hz rectangular pulse train. The controller circuit is designed to produce a 50 Hz rectangular pulse train with a **duty cycle** determined by the DC voltage level at its input. The path of the signal through the circuit is shown in the block diagram of Figure 3. A summary of each component is provided in the following section.
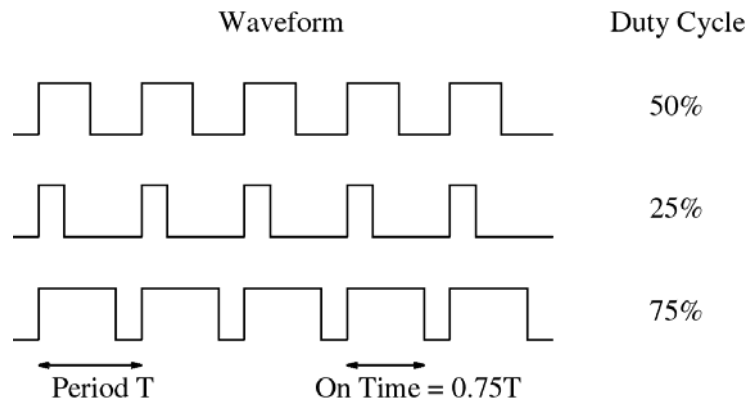

Figure 2: Examples of Duty Cycle Calculation

3.1 555 Timer

The 555 Timer is a TTL digital logic circuit that is used in the controller circuit to produce a periodic square wave signal. The period and duty cycle of the square wave signal are determined by the resistors and capacitors connected to the timer. A square wave with a 50% duty cycle is desired. In order to obtain exactly a 50% duty cycle from the 555 Timer, two resistors of identical value are required. Since it is impractical to obtain two resistors of identical value, two resistors close in value are used to generate a square wave with a duty cycle close to 50%, and then a JK flip flop is used to create a square wave with a duty cycle of exactly 50%. The frequency of the square wave produced by the JK flip flop is 1/2 the frequency of the output of the 555 timer, as you will see in the next section.

3.2 J-K Flip Flop

The output of the timer is sent to the J-K flip flop. The J-K flip flop is also a TTL digital logic circuit. A J-K flip flop may be used to perform many different functions. In this circuit the J-K flip flop is being used as a frequency divider. The frequency of the output signal is related to the input frequency by Equation 1.

$$f_{out} = \frac{f_{in}}{2} \qquad\qquad (1)$$

The J-K flip flop requires the input signal to complete one full cycle in order for its output to change states from 0V to 5V or from 5V to 0V. Therefore, it takes 2 periods of the input signal to produce one period at the output of the flip flop.

3.3   Comparator 1: Used as a Level Shifter

A comparator circuit, in general, contains a threshold (reference) voltage to which another signal is compared. If the signal is greater than the reference voltage, the output voltage of the comparator is $+V_{cc}$. If the signal is less than the reference voltage, the output voltage of the comparator is $-V_{cc}$.

In the controller circuit the comparator (comparator 1) is used to shift the **Levels** of the square wave from 0V and 5V to -5V and +5V.

The output of the J-K flip flop is a voltage square wave with **Levels** of 0V and 5V. This square wave is the input to the comparator. The comparator circuit utilizes one of the 741 op-amps on the LM324 Quad Op-Amp chip shown in Figure 6,7. The purpose of the comparator in this circuit is to shift the voltage **Levels** of the square wave produced by the flip flop to the power supply **Levels** ($+V_{cc} = 5V, -V_{cc} = -5V$) of the op-amp. This change in amplitude creates a square wave signal that is symmetric around ground (ideally) but does not affect the shape or frequency of the square wave input signal. Hence, the output of the comparator is also a square wave, but its voltage **Levels** have been shifted from 0V and 5V to -5V and +5V.
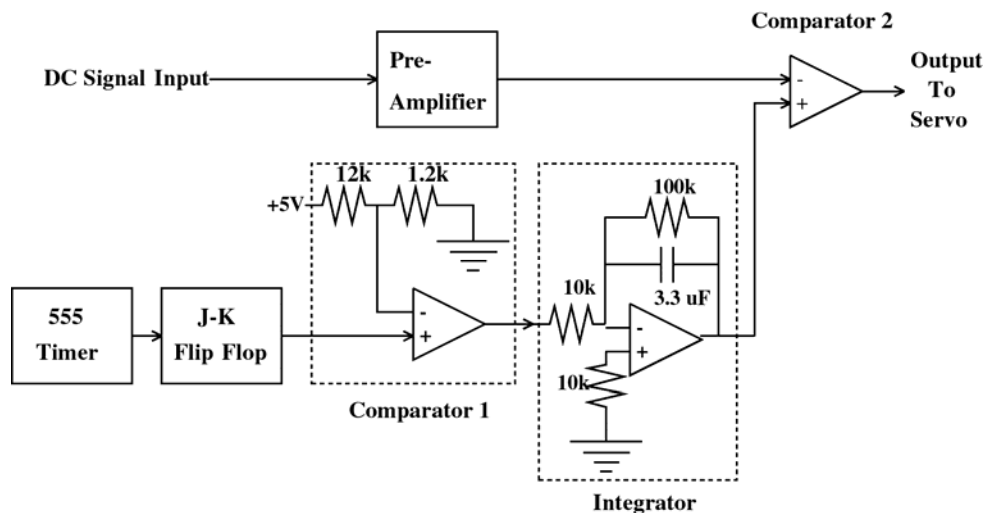

Figure 3: Servomotor Controller Circuit Block Diagram
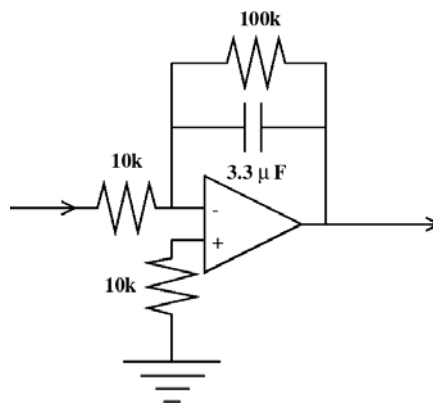
3.4 Integrator

Figure 4: Approximate Integrator Circuit

The square wave signal with **Levels** +5V produced by the comparator is the input signal to the (approx) integrator. The (approx) integrator utilizes one of the 741 op-amps on the LM324 Quad Op-Amp chip. The circuit, called an integrating amplifier or integrator, is shown in Figure 4. The output voltage of the integrator is, ideally, the accumulated area of the input voltage (accumulated as a function of time) multiplied by a constant. This ideal integral relationship is given by Equation 2. The integral relationship between the input and output voltages arises as the result of the derivative relationship between voltage across and current through a capacitor. Given that the square wave signal with **Levels** ±5V produced by the comparator is the input signal to the integrator, try to figure out what the waveform will look like at the output of the integration.

$$V_{out} = \int AV_{in}\, dt \qquad\qquad (2)$$

3.5 Comparator 2

The final stage of the servo controller circuit is a comparator (Comparator 2 in Figure 3). The integrator output is compared to the (amplified) DC signal. This comparator circuit utilizes the second 741 op-amp on the LM324 Quad Op-Amp chip shown in Figure 6,7. Whenever the integrator signal amplitude is greater than the DC input, the output of the comparator is high (+Vcc). Whenever it is less than the DC input, the output of the comparator is low (0 V). This operation is shown for an arbitrary signal in Figure 5. Consider the time-varying periodic signal as **compared** to the DC threshold level. When the threshold is set to level 1, the time-varying signal exceeds the threshold only for a relatively short duration near its peak. During this time, the output signal from the comparator is a rectangular pulse train with a **duty cycle** as shown in Figure 5. If the threshold is reduced to level 2, the time-varying signal exceeds the threshold for a longer duration and the **duty cycle** is increased.
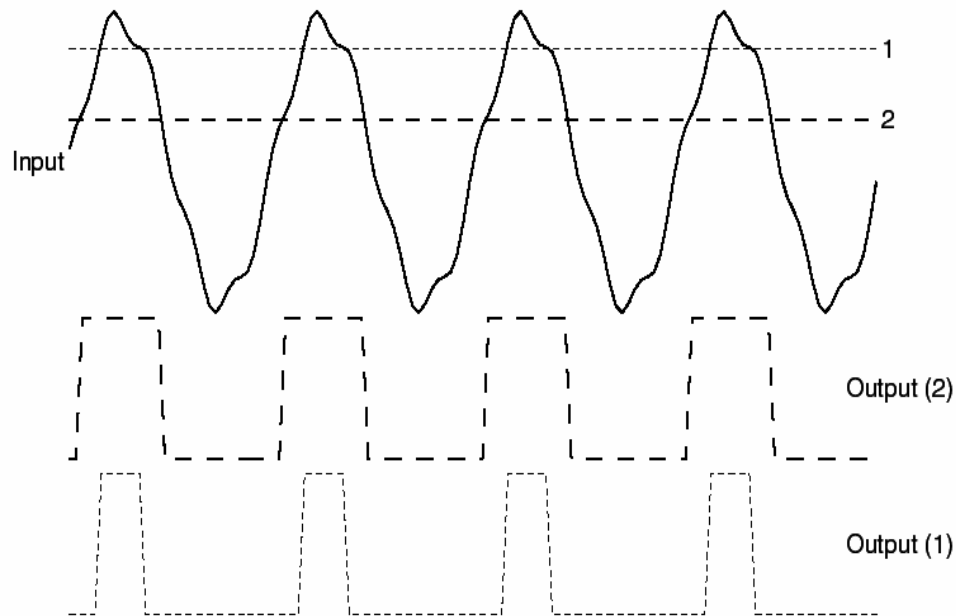

Figure 5: Comparator output

It should now be apparent that raising the DC signal voltage, or threshold level, will decrease the **duty cycle** of the comparator's output and lowering the DC signal voltage will increase the **duty cycle** of the output.

4. Experimental Procedure

There are two different versions of the servo controller board. You must first determine which servo controller board you have at your lab station. The main difference between the two versions is the DC power supply for the op-amps and TTL logic chips. The controller shown in Figure 6 shows the controller which utilizes two 9V batteries and Figure 7 shows the controller which utilizes an external split DC source for its on-board logic. Depending on which board you have at your lab station, follow the procedure below. Both controller boards will require the use of the Agilent E3631A Triple Output DC power supply in addition to the Agilent E3611A power supply that you have used in previous experiments.

As its name suggests, the Agilent E3631A Triple Output DC power supply is capable of producing three independent DC levels *simultaneously*. The first output of the Agilent E3631A can provide up to 6V and 5A. The second output can provide up to 25V and 1A, and the third output can provide up to -25V and -1A. The second and third outputs share the same common (ground) terminal. This makes the Agilent E3631A ideal for situations that require the use of $\pm V_{cc}$ such as an op-amp circuit. When the Agilent E3631A is turned on, the display will read "OUTPUT OFF." To use the power supply, first press the "Output On/Off" button. To set the voltages, first press the button that corresponds to the output that you wish to set (+6V, +25V, or -25V). Then turn the dial to set the voltage. Note that the two arrow buttons beneath the dial can be used to change which digit is being adjusted by the dial.

For both types of controller boards:

*****WARNING*****

Do not unscrew the banana jacks. Unscrewing the banana jacks can result in the disconnection of wires on the bottom of the boards.

You will use the Agilent E3611A power supply as the DC input signal and the 6V output of the Agilent E3631A power supply as the servomotor power source (+5V). Before connecting the Agilent E3611A, be sure to adjust the voltage to 0V. Notice that the DC input signal and the servomotor power source share the same ground node on the controller board. This means that you must connect the negative terminals on the Agilent E3611A and the 6V output of the Agilent 3631A. It is important to use the Agilent E3631A as the servomotor power source because the Agilent E3611A **cannot provide enough current**. The DC input signal is the control signal, determining the angular displacement of the servomotor armature, and is therefore a low current signal. In fact, an ideal control signal input would not require any current at all. On the other hand, the servomotor power source provides the power that physically moves the servomotor armature. This requires a relatively larger amount of current. After connecting both power supplies, set the 6V output on the Agilent 3631A power supply to provide 5V.

If your controller utilizes an external DC power supply for logic circuit power:

Your controller board requires two additional power inputs to provide the split $\pm5V$ for the logic circuit. For these you will use the $\pm25V$ outputs of the Agilent E3631A power supply. To do this, simply connect the +25V terminal on the power supply to the +5V terminal on the controller board, the -25V terminal to the -5V terminal, and the "COM" terminal to the "ground" terminal. Set the two voltage outputs on the Agilent E3631A to $\pm5V$.

The remaining sections apply to both controller versions:

The digital oscilloscope will be used to examine the signals present at the output of each stage in the controller circuit.

1. Adjust the Agilent E3611A power supply to ≈ +1 V

2. Flip the toggle switch on the servo controller board and observe that the red light emitting diode (LED)is illuminated. There is a 100 kΩ Clarostat potentiometer mounted near the top of the board that will need to be adjusted to calibrate your servo board. Your TA will explain the calibration procedure you are to follow.
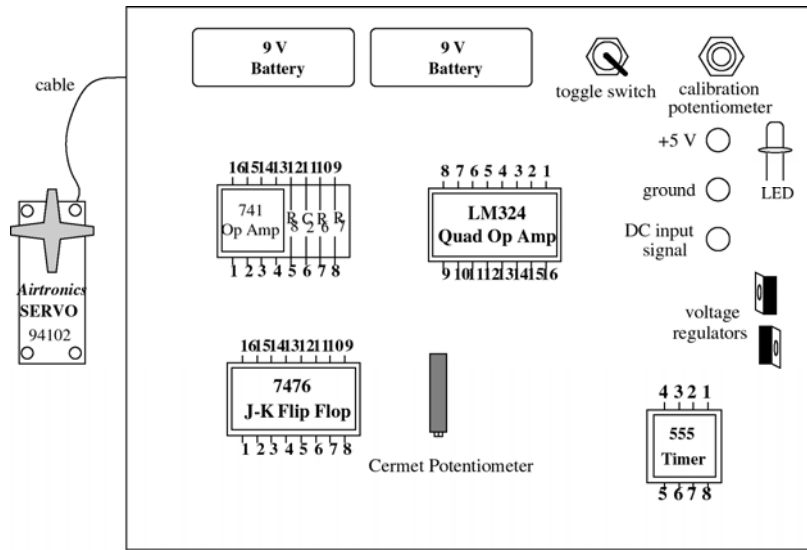

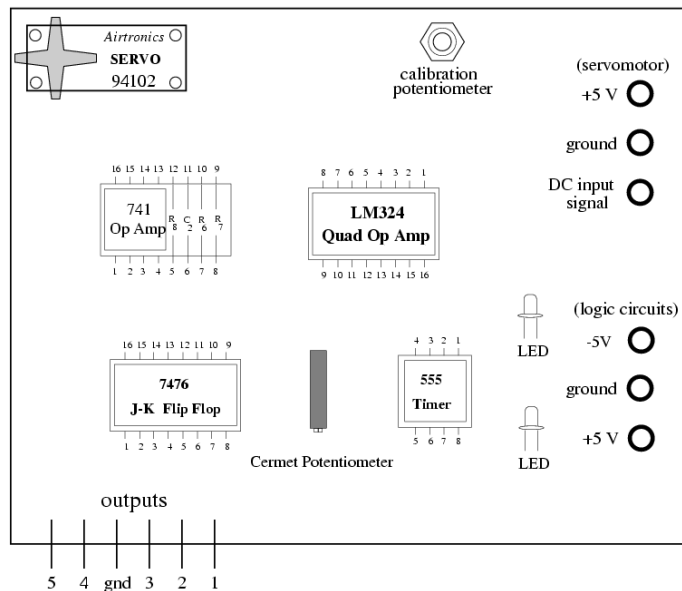**Figure 6: Servo Circuit Layout (9V battery version)**

Figure 7: Servo Circuit Layout (all external DC power supply version)

4.1 Black Box: Input and Output

To begin our investigation we will treat the servo controller as if it were a black box, where all we can observe is the electrical input (DC voltage) and mechanical output (position of the rotor).

- Vary the input voltage (DC Signal) between 0 and 10 volts, and observe the behavior of the servo's rotor. Estimate the full range of the rotor's motion in degrees. Using the fully clockwise position as $\theta = 0$, record voltages and angles for several positions.

- Connect the ammeter between the the output of the E3631A power supply and the **servomotor** +5V input. Vary the input voltage (DC Signal) between 0 and 10 volts and observe the amount of current drawn from the (unmounted) power supply. Can you draw any conclusions about the consumption of power by the servomotor?

4.2 Signal Analysis

We will now examine the output of each stage in the controller circuit. The goal is to describe the waveforms as precisely as possible. To do this we will measure two quantities, peak-to-peak voltage and frequency, of each signal. Connect the ground lead of the scope's probe to the controller ground.

1. Connect the scope probe to lead **1**. This is the output of the **555 Timer**. Measure the peak-to-peak voltage and frequency of the signal. Obtain a hard copy of the scope trace from the printer.

2. Connect the probe to lead **2**. This is the output of the **J-K flip flop**. Measure the peak-to-peak voltage and frequency of the signal. Obtain a hard copy of the scope trace from the printer.

3. Connect the probe to lead **3**. This is the output of the **Level Shifting Comparator** (comparator 1). Measure the peak-to-peak voltage and frequency of the signal. Obtain a hard copy of the scope trace from the printer.

4. Connect the probe to lead **4**, the output of the **integrator**. Measure the peak-to-peak voltage and frequency of the signal. Obtain a hard copy of the scope trace from the printer.

5. Connect the probe to lead **5**, the output of **comparator 2**. Measure the peak-to-peak voltage and frequency of the signal. Obtain a hard copy of the scope trace from the printer. Measure the duty-cycle of the signal. Now vary the DC Signal voltage and observe the changes in the duty-cycle. Record the duty-cycle and rotor position for several **DC** input voltages.

5. PSpice (to be done outside of lab)

Use PSpice to simulate the integrator circuit of Figure 4 using the op-amp model with the 741 parameters (see Figure 8). Use the same resistor and capacitor values as are shown in Figure 4. Create an input voltage in PSpice identical to the integrator input voltage as measured on the servo controller board in Section 4.2 part 3. In addition to simulating the integrator circuit

using PSpice, Solve for the output voltage of the integrator analytically (you may use an ideal op-amp in the your analytical solution). Include the PSpice output, plots, and your analytical solution in your lab report.

A KCL at the inverting node of the integrator produces a 1st order linear differential equation relating the output voltage (which happens to be the voltage across C as well) to the input voltage. To solve the problem analytically, you have to solve the differential equation (D.E.) with the proper initial conditions. The input to the integrator is a squarewave, and therefore this is a sequential switching problem. You must solve the D.E. for each interval of time in which the input voltage is constant (ie. for each half-cycle of the squarewave) using the solution to the previous interval to find the initial condition for the current interval. If you solve the problem for a few cycles, you will find that your peak-to-peak results are consistent with
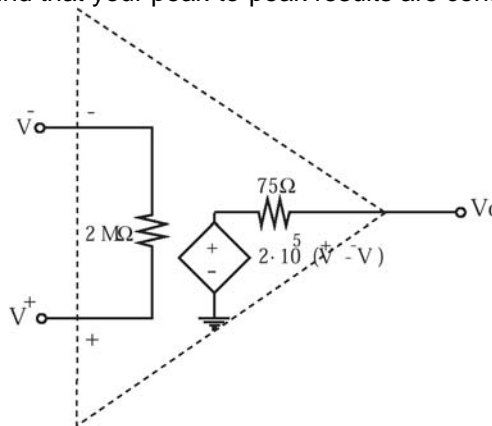

Figure 8: PSpice model for the 741 op-amp

the PSpice simulation results and lab measurements (hopefully), but that the DC value is off. In order to obtain the correct DC value, you must solve the DE for many cycles. This is a relatively difficult problem for which you will need to write a short computer program. You may use any programming language you wish. There are different degrees of solution to this problem, and partial credit will be awarded accordingly.

Note that in PSpice triangular, sawtooth, and square pulse waveforms can be created with:

$$\text{Vname } n\text{+ } n\text{- PULSE(V1 V2 TD TR TF PW PER)}$$

where V1 and V2 are the initial and pulsed voltage values respectively, TD is a time delay, TR and TF are rise and falls times, PW is the pulse width (time the voltage is at V2), and PER is the period of the pulse. There are several other source waveforms available in PSpice. These waveforms can be used for both voltage and current sources. Please refer to the PSpice tutorial in the EE61 Course-Pak and the Rashid text.

Note that the default **start time** is zero if no value is present in the .tran command line. In your simulation of the integrator circuit, you will find that it is necessary to plot the results for a time window that begins later than t=0 in order to obtain steady-state results. Try plotting voltages beginning at t=0 and you will see the necessity of plotting the voltages over a time interval that begins later than t=0. When you examine a plot of the voltage at the output of the op-amp beginning at t=0, you will observe a triangle wave superposed on an exponential. Try to explain this phenomenon.

6. Questions

Answer all of the following questions in your lab report.

1. Plot the rotor position vs. the DC input voltage. Give a mathematical expression for this relationship. Is the relationship linear?

2. Plot the rotor position as a function of the duty-cycle output of the comparator (lead **5**). Give a mathematical expression for this relationship. Is this relationship linear?

3. From the above two expressions derive a relationship between the DC input voltage and the duty-cycle of the signal output from the comparator. Is this relationship linear? Explain why the input signal to the comparator in Figure 5 would not give a linear relationship between DC input and the output signal's duty-cycle. Explain why a square wave input (instead of a triangle wave) to the comparator would not give an output signal with variable duty-cycle.

4. Analyze the integrator circuit shown in Figure 9 by relating V_{out} to V_{in} assuming an ideal op-amp. Express A in Equation 2 in terms of C and R_1.
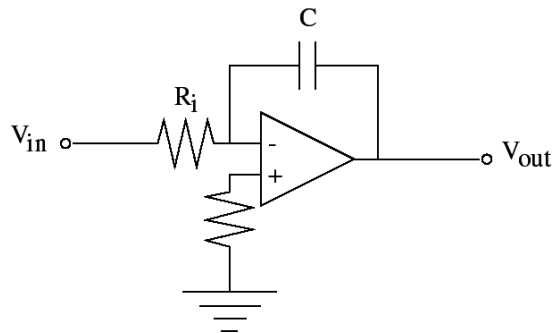

Figure 9: Integrator