Pulse-Width Modulation Theory and Circuits

A hands-on experiment to control power ratio

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INTRODUCTION

Pulse-width modulation (PWM) is a common technique to control the power level of devices. PWM can be used to control the brightness of a light-emitting diode (LED), speed of a motor, heat of a electrical heating coil and many other applications. Because PWM requires minimal analog electronic hardware and saves energy, it is applicable to many devices used on robots, especially motors. In this article, we will first discuss the reasons and theories of PWM, then proceed to build a simple, yet flexible, PWM circuit for experimentation.

Reasons for Pulse-Width Modulation

The most intuitive method to control the brightness of an LED is to control the continuous current passing through it. A variable resistor connected in series with the LED (see Figure 1) can control this current. An LED has a constant voltage drop when forward biased, and the voltage drop is usually about 1.7 V. Using Ohm's Law, the current passing through the LED is I=(Vin-1.7V)/R, where Vin is the applied voltage and R is the resistance of the variable resistor. As R is increased, the current is reduced, and the LED dims.

Since most LEDs have a maximum continuous current rating of less than 50 mA, power dissipation at the variable resistor is not a problem. However, for motors and other high-current devices, the variable resistor needs to dissipate much more energy. The power dissipation (P) of an electrical device is the product of the voltage drop across the device (V) and the current passing through the device (I). In short, Power (P) = Voltage (V) x Current (I), or P = V x I. For a modest 5 Vdc motor with a coil resistance of 10 Ω, the stall current is 5 V/10 Ω = 0.5 A. At half strength, the stall current of the motor is 50% of 0.5 A or 0.25 A. The variable resistor must have a value of 10 Ω as well. This means the voltage drop across the variable resistor is 2.5 V. The current passing through the variable resistor equal the current passing through the motor, 0.25 A. Consequently the variable resistor and the motor must *each* dissipate 2.5 V x 0.25 A = 0.625 W. While 0.625 W is not a lot of power most small printed circuit (PC) mounted variable resistors are rated for less than 0.625 W.

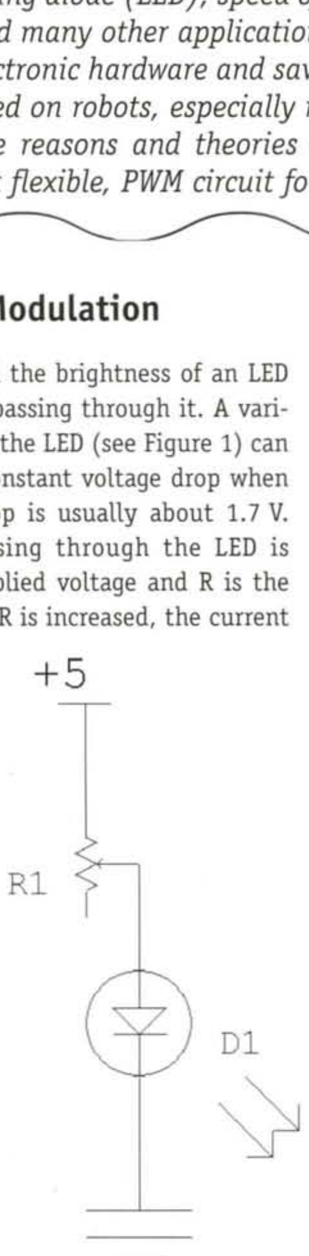

Figure 1: Variable Resistor Controlled LED

Many readers will immediately suggest the use of a power transistor to amplify the variable resistor controlled current (see Figure 2). This approach eliminates the power dissipation issue at the variable resistor. However, there is still a 2.5 V voltage drop across the collector and the emitter of the transistor, and thus there is still 0.625 W to dissipate at the transistor.

While the 0.625 W dissipated at the motor is mostly in the form of heat, the motor is developing torque (i.e. doing work) due to the current passing through the coil. However, the 0.625 W dissipated by the transistor or variable resistor is lost entirely as heat with no work performed. How can we stop this waste of 0.625 W of power?

Before discussing the obvious answer, let's consider the other drawback of using a variable resistor (regardless of using a transistor in conjunction). While a human can turn the knob and easily control a variable resistor, a computer cannot control a variable resistor as easily. There are electronic variable resistors that a computer can control, but they are extra components and impose costs, both in dollars and complexity (reliability).

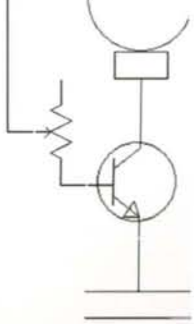

Figure 2: Transistor controlled 5V motor

Pulse-width Modulation not only addresses the wasted power issue, but it also eliminates the need of a variable resistor. In other words, PWM saves power while enabling convenient computer control. Some may argue that PWM is only convenient for computer-based control. As we will demonstrate later, it is quite inexpensive and easy to build a PWM circuit for non-computer-based and hands-on experimentation.

Pulse-Width Modulation Concepts

The most fundamental concept of PWM is "duty cycle." Consider a gas furnace without gas pressure control. If only 50% of the full output is needed, the furnace can be switched on and off periodically. For a large building, switching the furnace on and off every 15 minutes is hardly noticeable because of the large "momentum" (heat capacity). The furnace outputs an average of 50% of its full output by operating at a 50% duty cycle. In our previous example, the on time is 15 minutes, and the period is 30 minutes (sum of 15 minutes of on time and 15 minutes of off time). Consequently, the duty cycle is 15/30 = 50%.

This concept of "duty cycle" can be extended to control the brightness of an LED and the strength of a motor. For an LED with a maximum continuous current of 20 mA, we can generate the same effects as a 10 mA continuous current by pulsing the LED at a 50% duty cycle with a 20 mA current. Obviously, if the LED is switched every second, the effect is blinking, not dimming. However, if the circuit switches the LED 50 times per second, the human eye can no longer perceive the blinking. Instead, the human eye sees a dimly lit LED. The same principle applies to motors. When pulsed every second, the motor is jerky. However, as the pulse frequency increases to about 100 Hz (100 pulses per second), the motor behaves as if the continuous current is reduced.

Thus, the frequency and duty cycle characterize a PWM signal. The frequency indicates the number of potential interruptions of continuous power in a given time frame ('potential' in that a 100% duty cycle PWM waveform has no interruptions), and duty cycle indicates the proportion of time that the signal is in an on state.

Simple Circuit to Generate a PWM Signal

As mentioned earlier, some readers may argue that a variable resistor is easier to experiment with than a circuit to generate PWM. In this section, we will present a simple circuit that the reader can assemble quickly and inexpensively. The supplies required for this project should cost less than $10 US, and the circuit is useful in many applications.

The core of the PWM circuit is two 555 integrated circuits (ICs). For those who are not familiar with the 555 IC, it is an IC designed for timing operations. For discussion purposes, we treat the timers as separate entities. The 555 IC can be configured for monostable (one-shot) or astable (oscillator) applications. In this application, one 555 IC (call it timer A) is configured for astable operation and the other (call it timer M) is configured for monostable operation. Timer A generates the beginning of pulses (controlling the fr quency), while timer M controls the on time.

Timer A, which determines frequency, is set up as shown Figure 3. Both the threshold and trigger are connected to t timing capacitor. The oscillator operates in the following cyc

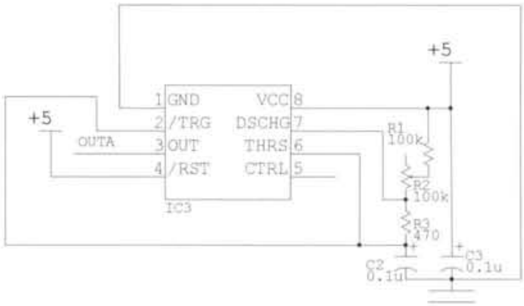

Figure 3: Timer A schematic

1. Discharge is disabled and capacitor C2 is charged throu R1, R2 (note that R2 is a variable resistor, we are only inte ested in the effective resistance in the circuit, not the ma mum resistance of R2) and R3. The output is high.

2. The capacitor is charged to 2/3 V (V is the supply volta to the IC). Consequently, the output is low and discharge enabled. Capacitor C2 is discharged through R3 to ground.

3. Capacitor C2 is discharged to 1/3 V (where V is the supp voltage to the IC). The output is high and discharge is di abled. Go back to step 1.

The period of such a configuration is T=0.693(R1+R2+2R3)C where T is the period (time) measured in seconds, R1, R2 ar R3 are resistance measured in Ohms and C2 is capacitan measured in Farads. The amount of time per period when t output is low is R3xC2. For triggering another 555 timer, t low-output period can be short. In other words, R3 can be small fraction of the sum of R1 and R2. The design can tra larger resistors R1, R2 and R3 for a smaller capacitor C2 vice versa. For reduced power consumption, however, the to tal of R1 and R2 should be more than 10 kΩ. Because resi tors are available in many values, it is easier to first sele the value of the capacitor, then select resistors of appropri ate value.

A 0.1 μF capacitor was used for timing and a 470 resistor for R3. These values generate a low pulse of abo $(470 \times 0.1 \times 10^{-6})$s = 47 μs, which is long enough to trigg timer M. We want timer A to have a frequency 100 Hz (period of 10 ms). Recall that the period

$$T = 0.693\,(R1+R2+2R3)\,C2.$$

With the known terms R3 = 470 Ω, C2 = 0.1 μF and

$$T = 10\text{ ms},\ R1+R2 = (T/(0.693C))-2R3 = 143\text{ k}\Omega.$$

For flexibility, R1 is a 100 kΩ resistor in series with R2, a 100 kΩ variable resistor for a range of total resistance between 100 kΩ and 200 kΩ. With this variable resistor, you can tune the frequency of the PWM by adjusting R2.

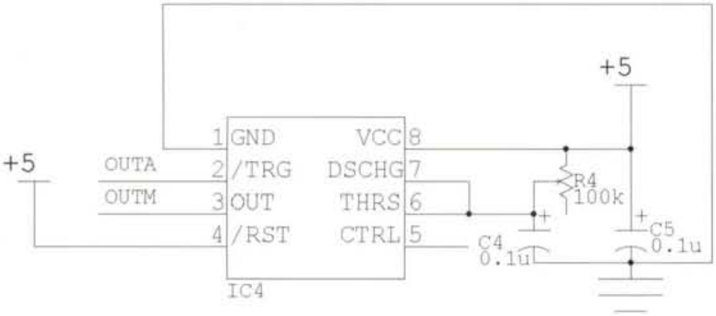

Figure 4: Timer M schematic

Timer M, which determines the on time, is set up as shown in Figure 4. As a monostable timer, the output of timer M is normally low, and the capacitor is normally discharged. However, when the trigger receives a low pulse (from the output of timer A), the output becomes high and the capacitor is no longer discharged. The capacitor is charged to 2/3 V (where V is the supply voltage to the IC) and then triggers the timer output to become low and enable the discharge of the capacitor. The duration of high timer output is T = 1.1 x R4 x C4. Again, we are only interested in the effective value of R4, not the maximum resistance. For a 100 Hz PWM signal, the duration of high output can be up to 10 ms. Since the author had a 100 kΩ variable resistor available at the time of writing this article, the design calls for a 0.1 μF capacitor. Optimally, based on the equation, the resistance R for a 10 ms pulse is 10 ms/(0.1 μF x 1.1) = 90.9 kΩ. The 100 kΩ variable resistor covers the entire range and can therefore control the duration of pulses from 0 to 10 ms.

Prototyping the Circuit

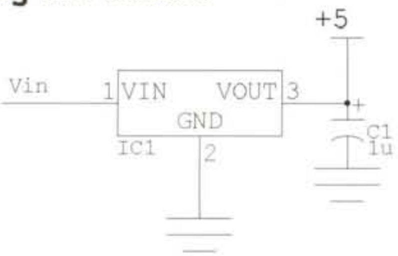

Figure 5: 7805 Regulator set up.

With the wide use of regulated 5 V supply for most complementary metal oxide semiconductor/transistor transistor logic (CMOS/TTL) ICs, a regulated 5 V supply will be used whenever possible. For cost effectiveness and convenience, a 9 V battery and a 7805 linear regulator to regulate the voltage to 5 V is recommended for use. A wall transformer that provides 9 Vdc to 12 Vdc, can be used as well. For this project, the power consumption should be less than 50 mA at 5 V, which makes the 9 V battery and 7805 regulator solution very reasonable.

The 7805 linear regulator is easy to set up (see Figure 5). The 1 μF decoupling capacitor is not required, but it is good practice to use one to ensure stable regulated voltage.

The following components are needed for the circuit:

Two 555 IC timers (or one 556 dual timer IC)
Two 0.1 μF capacitors for IC decoupling
Two 0.1 μF capacitors for timing
One 1 μF (exact value is not important)
  for the overall regulated voltage
One 100 kΩ resistor for timer A
One 100 kΩ variable resistor for timer A
One 100 kΩ variable resistor for timer M
One 7805 linear regulator
  (if you do not have a regulated 5 V supply)
One LED (optional to demonstrate PWM visually)
One 220 Ω current limiting resistor (optional, for the LED)

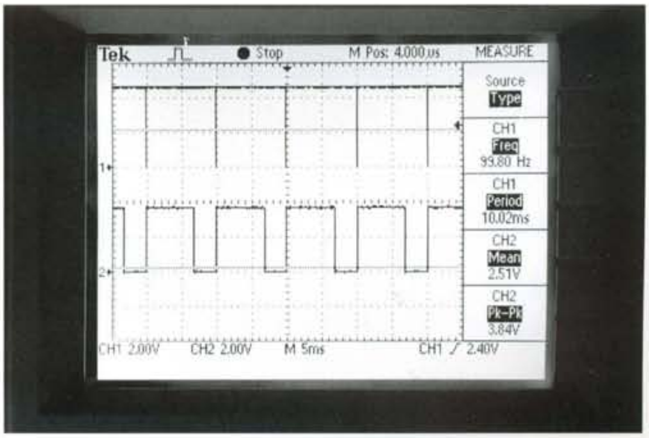

Photo 1: Oscilloscope screen shot of Timer A (frequency output at channel 1) and Timer B (duty cycle output at channel 2)

Experimenting with the Circuit

There are many ways to construct a prototype circuit. If you are interested in learning how to wire wrap a circuit prototype, please refer to the wire wrap article (Issue 6, page 36). You can also construct the prototype on a breadboard or a soldered prototype board.

After the prototype is constructed, you can start to experiment with it. The first task is to measure the period of the output of timer A. Use either an oscilloscope or a multimeter to measure frequency. Some multimeters that can measure frequency cost as little as $60 US. Since we used a variable resistor in the timer A circuit, you can adjust the variable resistor and watch the frequency change. See Photo 1 (channel 1) for a screen shot of the output from timer A on an oscilloscope. Connect the output of timer M to an oscilloscope to observe the actual wave (see Photo 1 channel 2), or connect the output to a voltmeter to observe the average voltage. Adjust the variable resistor in the circuit of timer M to adjust the duty cycle. Photo 2 shows an oscilloscope screen shot of timer A and timer M set to a different duty cycle.

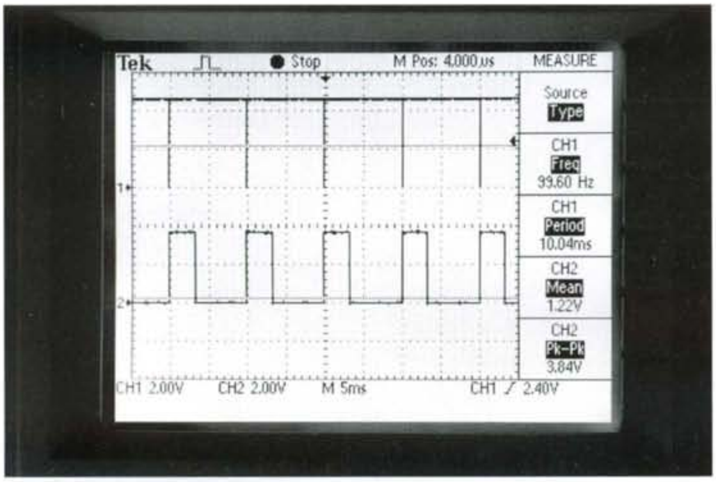

Photo 2: Oscilloscope screen shot of a duty cycle different from that of photo 1.

If you need to convince yourself that fast pulses are not visible to the human eye, you can visualize the effects using an LED. Do not connect an LED directly between the output of timer M and ground! Doing this will damage possibly both the timer IC and the LED. Most LEDs have a maximum continuous current of about 20 mA. To limit the current, you should connect an LED in series with a 220 Ω resistor between the output of timer M and grou (see Figure 6). Because an LED has a voltage drop of about 1.7 the resistor is responsible for about 3.3 V of voltage drop. A cording to Ohm's law, the current passing through the 220 resistor should be about 3.3 V/220 Ω = 15 mA. You can use smaller current limiting resistor if the maximum continuous cu rent of the LED is more than 15 mA. As the variable resistor the timer M circuit is adjusted and the duty cycle changes, t brightness of the LED changes accordingly.

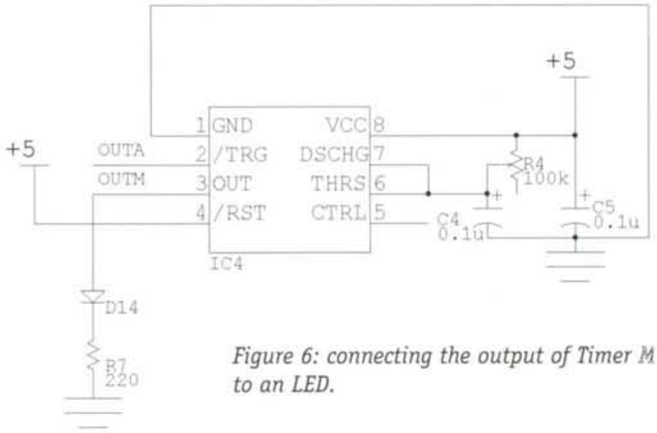

Figure 6: connecting the output of Timer M to an LED.

You should not connect the output of timer M to a motor. A though a CMOS timer output can drive up to 50 mA (sufficie for LEDs), it is no match for the demands of a motor! Furthe more, the timer IC has no protection against the electromagne feedback (EMF) of an inductive load (such as a direct curre motor). Connecting the output of a timer to a motor probab will permanently damage the timer.

The Next Project

This project seems to have very little to do with robots. Howev knowledge of the operation of the 555 IC will be useful for ma robot projects. Even more importantly, the technique of Puls width Modulation is very useful in controlling the strength of motor. In the next article (see next page), we will look into t techniques of controlling a direct current motor, and the PW circuit will be a component of that project. RS