Experiment 6
Pulse-Width Modulation

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3. Background

3.1. Pulse-Width Modulation (PWM)

A pulse-width modulated (PWM) signal is a periodic square wave signal. The difference between a PWM signal and a clock signals is the flexibility of its *duty cycle*.

A periodic square wave is high for some part of its period, and low for the rest of the period. Its *duty cycle* is the percentage of the period for which the signal is high. Usually, a clock wave has a duty cycle of 50%. In a PWM signal, the duty cycle is controllable. The name is derived from the idea that the *width* of the high *pulse* is *modulated* according to some value.

3.2. PWM Applications

PWM has many useful applications in embedded systems. The main two categories are:

1. When a microcontroller does not have a DAC circuit, PWM can be used to *modulate* different analog values.
2. Some devices are built to be used with PWM. The most famous example is servo motors.

   Servo motors usually require a 50-Hz square wave (period of 20 ms). The duration of the high pulse determines the motor's angle. Usually, the full swing of the servo corresponds to a high interval of 1 to 2 ms, whereas a high interval of 1.5 ms corresponds to the neutral servo position [1: https://circuitdigest.com/article/servo-motor-basics].

3.3. Generating PWM with LPC1769

The LPC1769 features a pulse-width modulator peripheral. The generic steps discussed in Experiment 5 for setting up a peripheral device apply here:

1. Power: the PWM circuit is powered on by default.
2. Peripheral Clock (PCLK): recall that the default division factor is 4.
3. Pin functions: a PWM pin must be configured for PWM use.

Additionally, generating a PWM signal in particular requires:

1. Setting the period of the PWM signal using the `MR0` register.

2. Specifying the duty cycle using an `MRx` register, which would control the `PWM1.x` output.
3. The PWM circuit should be enabled to generate a PWM signal, otherwise it will act as a standard timer (or counter).
4. The corresponding `PWM1.x` output should be enabled.

1. There is only one PWM circuit, called `PWM1`. That does not imply that there is a `PWM0` or `PWM2`.
2. There are six PWM channels, referred to as `PWM1.1` to `PWM1.6`.
3. You have the option of more than one pin to pin out any of the channels.

If you care about the accuracy of your PWM output voltage levels, you need to disable the pull-up resistor to avoid affecting the PWM voltage. That can be done using the `LPC_PINCON→PINMODEx` register.

In many applications this is not required.

Exercise

Refer to chapter 8 of the LPC176x manual to determine:

1. Which pins are you going to use for PWM?
2. Which `PINSELx` register should you use?
3. Which `PINSELx` bits should you set?
4. To what value should you set those `PINSELx` bits?
5. How to disable the pull-up resistor?

3.3.1. `MR0` and `MRx`

To fully specify a PWM signal, you need to specify:

1. Its period (or, equivalently, its frequency)
2. Its duty cycle

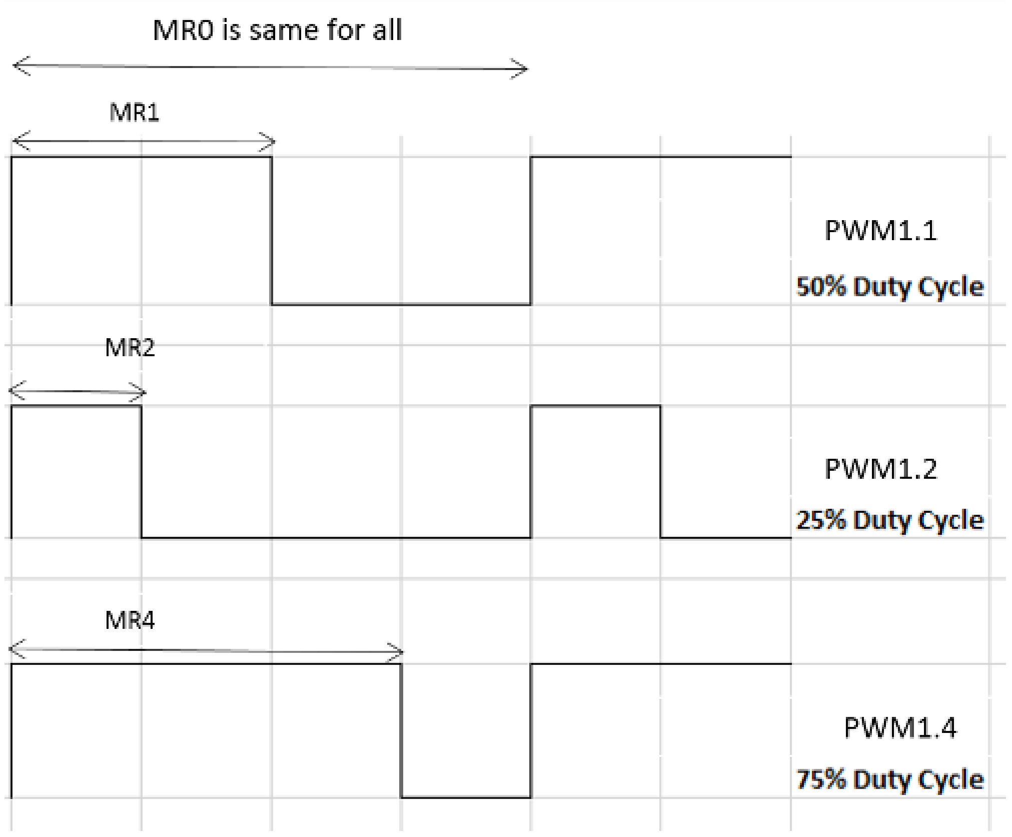
The value of the `MR0` register (aka `PWM1MR0`) determines the period, while any of the `MR1` to `MR6` registers determine the duty cycle for the corresponding `PWM1.1` to `PWM1.6` outputs, as illustrated in the following example.

Example 1. Period and Duty Cycles

If `MR0` is set to 80, then:

Register	Value	Duty Cycle	PWM Channel
`MR1`	40	50%	1 (`PWM1.1`)
`MR2`	20	25%	2 (`PWM1.2`)
`MR4`	20	75%	4 (`PWM1.4`)
`MR5`	72	90%	5 (`PWM1.5`)

The figure below shows the different PWM outputs for the same `MR0`.



Single Edge Controlled PWM

In the example above, the periodic signal on all channels will go high at the beginning of the period, and each channel will be reset when matching the number in the corresponding `MR1` to `MR6` register.

This PWM configuration is called *single edge controlled PWM*.

In summary:

1. Control the period duration of the PWM signal by setting the `MR0` register.
2. Use the appropriate `MRx` register to control the duty cycle of `PWM1.x`, where `x` is a number between 0 and 6.

Example 2. A PWM Period of 1 Second

```
LPC_PWM1->MRx = 1000000; // PWM period is 1 second.
```

To have different PWM channels be set and reset at different times, some PWM channels can be configured as *double edge controlled PWM* signals.

> *Double Edge Controlled PWM*
>
> In double edge controlled, you can control when to set or reset the pulse within the period, and whether to set or reset first.
>
> The `MR0` register still controls the duration of the full period.

Example 3. Double Edge Controlled PWM

PWM channel 2 (`PWM1.2`) is set by `MR1` and reset by `MR2`.

So, setting `MR0` = 100, `MR1` = 50, and `MR2` = 75 will result in a signal that is low at the beginning of the period, becomes high in the middle of the period, and goes back to low in the middle of the second half of the period.

In contrast, setting `MR0` = 100, `MR1` = 75, and `MR2` = 50 will result in a signal that is high at the beginning of the period, becomes low in the middle of the period, and goes back to high in the middle of the second half of the period.

> PWM channels can be configured to be *single edge controlled* or *double edge controlled* using the `PWMSELn` bits of the *PWM Control Register* (`PWM1PCR` or `LPC_PWM1→PCR`).
>
> For details, see Table 444 and Table 452 in the LPC176x manual.

3.3.2. PWM vs. Timers

From a hardware point of view, PWM is based on the standard timer block, and inherits all of its features [lpc1769-manual].

Let us review the relation between the timer counter, the prescale register, and the prescale counter. `TC` is a 32-bit register that is incremented every `PR` + 1 cycles of `PCLK`, where `PR` is the *Prescale Register* (`PWM1PR` or `LPC_PWM1→PR` in CMSIS).

> Recall that you can use the default value of the `PR` register (0) to simply increment `TC` every `PCLK` pulse.

IF `PR` is set to a non-zero value, `TC`'s frequency would be given by:

$$\texttt{TC}\text{ frequency in Hz} = \frac{\text{System clock}}{\text{PCLKdivisor} \times (\text{PR} + 1)}$$

where *PCLK divisor* is 1, 2, 4, or 8, depending on the setting of the `PCLKSELx` register (default is 4).

For *system clock*, you can use the `SystemCoreClock` variable, which is set by CMSIS to the CPU clock speed.

Example 4. Setting the Prescale Register

To set the prescale register such that TC is incremented every 1 µs (frequency of 1,000,000 Hz):

```
LPC_PWM1->PR = SystemCoreClock / (4 * 1000000) - 1;
```

If MR0 is set to 100, every 100 pulses of the *PWM Timer Counter* register (PWM1TC, or TC for short), a new PWM period starts. That happens even if TC is not reset. This is an important operational difference between pure timers and a PWM signals. The other crucial difference is the control of the duty cycle, which is at the heart of the the PWM concept.

3.3.3. Summary of Important PWM Control Registers

- LPC_PWM1→LER is used to latch the new MRx values. You must use it every time you change any of the MRx values.
- LPC_PWM1→PCR is used to enable PWM1 with single or double edge operation. If ignored, PWM will act as a counter.
- LPC_PWM1→TCR is used to enable, disable, or reset counting in the TC register. You should use it at least once to enable counting.
- LPC_PWM1→MCR is similar to the timers' MCR registers. It can be used to generate interrupts or reset TC when matches occur if needed.

4. Tasks

1. Basic operation: Write a program that generates a PWM signal, and use it on an external device.
2. Control a servo motor: Rotate a servo motor 90 degrees to the right, move it back to the neutral position, then rotate it 90 degrees to the left.
3. Show different colors on an RGB LED using at least two PWM signals

5. Resources

[lpc1769-manual]

NXP Semiconductors. 'UM10360 LPC176x/5x User manual'. Rev. 3.1. 2 April 2014. http://www.nxp.com/documents/user_manual/UM10360.pdf

6. Grading Sheet

Task	Points
Basic operation	3
Servo Control	7
Bonus: RGB	+2