INTRODUCTION

This application note describes the principals of operation and basic design process for ultrasonic range detection. Microchip offers a wide range of PIC® microcontrollers (MCUs) and analog devices that readily pair with Murata Electronics ultrasonic devices to create a complete ultrasonic solution.

Ultrasonic range detection can be accomplished with an op amp and any PIC® MCU with four available I/O pins, including an integrated internal comparator.

OVERVIEW

An ultrasonic transmitter broadcasts a 40 kHz pulse or several oscillations at that frequency of sound. A square wave of one to several wavelengths is driven from the PIC microcontroller to the ultrasonic device, to create the pulse. The pulse is reflected by any object of greater density than air, and part of the emitted pulse returns to the receiver. The round trip travel time is measured and converted to distance via the speed of sound.

Sound requires a medium to travel through, such as air, water or steel. In general, the denser the medium, the faster sound propagates through it. The speed of sound in air varies based on temperature, humidity and altitude. At room temperature it can be assumed to be constant at approximately 343 m/s. This is an ideal speed to use microcontrollers to time the round trip duration of an emitted pulse over a few meters.

The type of reflection surface is not critical; at 40 kHz almost all surfaces reflect the oncoming sound wave. Perpendicular contact with a surface is preferable as the deflected pulses are directed back towards the receiver. As the angle of incidence with the surface increases, the proportion of the pulse reflected back to the receiver decreases.

ULTRASONIC DEVICES

An ultrasonic transducer operates similar to a Piezo buzzer, but at a higher, inaudible frequency. When an electrical current is passed through the piezoelectric device, it deforms or bends and returns to its original shape when the current is removed. When a 40 kHz square wave is applied to the pins of the device, a 40 kHz sound pulse is radiated. An ultrasonic receiver works in the opposite fashion, producing a voltage, but at a much lower amplitude from incoming ultrasonic sound.

FIGURE 1: ULTRASONIC TRANSDUCER

Ultrasonic devices can be a transmitter, receiver or both, and come in an open or closed waterproof type. This application uses separate receive and transmit open type devices. This type is the easiest to use as larger drive voltage is required to use waterproof transmitters.

Figure 2 shows the equivalent circuit of an ultrasonic device. It acts as a capacitive load, but because of inductive and capacitive aspects, it is tuned to a 40 kHz resonant frequency. The transmitter is tuned for maximum output while the receiver is tuned for maximum voltage output at an incoming 40 kHz signal. This has an attenuating filtering effect on all other frequencies and is useful in eliminating noise when amplifying the received signal. Typical values for the devices used in the demo are listed at the bottom of the figure.
DRIVING AN ULTRASONIC DEVICE

Driving the capacitive ultrasonic transmitter with a differential signal gives the greatest transmit strength while maintaining a 0.0V offset across the device. Driving the pins differentially also eliminates the need for a negative supply to drive the device.

One issue with ultrasonic transducers is that they will continue to oscillate or ring after the removal of the drive signal. This ringing is due to the resonant mechanical behavior of the transducer. The transducer is tuned to ring like a bell at its specified ultrasonic frequency when driven, and it takes a short period of time for the ring to damp out after the drive is removed. While the transmitter is ringing, the signal will couple through the PCB or travel through the air between the transmitter and receiver, and look like a received signal. Therefore, a delay before the receiver is turned on is needed to ensure that the ringing has damped out, and any signal received is that of a reflected pulse. The amount of time required for the ringing to damp out determines the minimum detectable distance of the receiver (see Figure 3).

PRODUCING 40 kHz WITH A PIC MCU

Ultrasonic devices should be driven as close as possible to their specified frequency to maximize the output power. The 8 MHz internal oscillator of the PIC16F690 can easily be divided down to create a 40 kHz drive signal. Two I/O pins of a PIC microcontroller can be used to generate the differential 40 kHz signal that drives the ultrasonic transmitter. This application uses Timer0 interrupt-on-overflow to create the time basis for output. Figures 1, 2 and 3 in this document go into greater detail on how this is accomplished.

An alternative, more automated method of driving an ultrasonic device would be to use the ECCP module offered on many PIC MCUs. The module can be set up to output a PWM of a selected frequency on two pins, P1A and P1B, in Half-Bridge mode, with one output inverted. The ECCP module uses Timer2 to establish a time base for PWM. Enabling the Timer2 postscaler allows the user to set the number of pulses generated before setting the interrupt flag. This method allows an ultrasonic pulse to be sent with a single interrupt.

RECEIVING ULTRASONIC PULSE

Once an ultrasonic signal is created and output from the ultrasonic transmitter, the next task is to detect and time a returning reflected pulse. The returning sound wave is significantly attenuated and amplification is necessary before the signal can be detected by a comparator. This amplification can be a single op amp in a difference amplifier configuration.
DIFFERENCE AMPLIFIER

An example circuit for a difference amplifier is pictured in the figure below (see Figure 4). This op amp circuit amplifies the voltage across the ultrasonic receiver connected between the two input pins. The Common mode noise at the output is minimized by matching the input bias current through resistors R2 and R4 and resistors R1 and R3.

FIGURE 4: CIRCUIT FOR A DIFFERENCE AMPLIFIER

The ultrasonic receiver acts like a tuned high Q filter. The difference op amp amplifies the filtering effect of that receiver. The first op amp amplifies and filters the incoming signal versus Common mode noise. All subsequent op amp stages will amplify any noise and require additional filters. Selecting the proper op amp for the first gain stage of the ultrasonic receiver can eliminate the need for more than one op amp and filters.

DATA SLICER

A data slicer is a circuit common to many communication applications. A threshold voltage, V_th, is compared to the amplified input to detect the signal. V_th in Figure 5 is set slightly below the average value of the amplified ultrasonic signal, V_US. Any time an ultrasonic pulse is amplified, the value at the C2IN- pin will fall below the value of C2IN+, causing the value of the comparator to switch. The value of R2 should be much larger than the value of R1, but not so large that it causes the comparator to switch because of noise on the amplified signal. Ideally, R1 is set so that the value of the threshold voltage is just above the noise of the received ultrasonic signal. The closer the threshold voltage is to the received signal, the greater the detectable distance of the receiver.

The C2OUT pin of the PIC microcontroller can be used to debug this stage of the ultrasonic receiver. A common problem is that the threshold voltage is set incorrectly. If it is too low, the detectable range of the receiver will be limited. If it is too high, the comparator will switch from noise spikes on the line making it impossible to tell when a signal is present.
The Timer1 gate function provides an enable signal for the clock signal to the 16-bit Timer1 counter. The output of the comparator, C2OUT, can be selected as an internal source to Timer1 gate. Counting is enabled while the C2OUT signal is low. Once an ultrasonic signal is detected and the C2OUT value changes, counting stops. The value stored in the Timer1 registers, TMR1H:TMR1L, is the round trip time in the form of counts of the ultrasonic signal. Depending on the oscillator speed of the device, these counts will have a specific time value. A flowchart detailing how Timer1 is used to time the returning pulse is available in Section “APPENDIX A: Flowcharts” (see Figure 2).

CONVERTING COUNTS TO DISTANCE

After detecting the returning ultrasonic pulse, Timer1 stores a count value corresponding to the travel time of the ultrasonic pulse. Those counts can be converted to distance by dividing by two and multiplying by the speed of sound. The divide by two is because it is a round trip measurement and can be accomplished by shifting the count value right one bit. Equation 1 shows the derivation of distance.

\[
\text{Distance} = \frac{(\text{TMR1H:L} - 1) \times (\text{Speed of sound} \times 2^{16})}{2^{16}}
\]

\[
\text{Distance} = \frac{1/2 \times \text{TMR1H:L} \times (\text{Speed of sound} \times 2^{16})}{2^{16}}
\]

\[
\text{Distance} = \frac{\text{TMR1H:L} \times \text{Speed of sound}}{2}
\]

MAXIMUM DETECTABLE DISTANCE

There are two ways of increasing the maximum detectable distance in this application: increased transmission power and increased receiver sensitivity. This demo uses I/O pins to drive the transmitter at a maximum of 20 mA and 5V; MOSFET drivers could be used to boost the drive current and voltage. The gain of the receiver at 40 kHz determines what can be detected by the comparator. The demo uses only one op amp as a difference amplifier. Because there is only one gain stage, no filtering is needed. A multi-stage receiver would need to do some filtering between the first gain stage and the comparator to reduce noise. Carefully controlling the threshold voltage to the comparator will also ensure that the smallest return pulse is positively detected.

LAYOUT CONSIDERATIONS

If a separate transmitter and receiver are used, they should both be aligned in the same direction. The transmitted signal and any subsequent ringing will leak through the PCB to the receiver circuitry. Placing more space or a cutout between the devices on the board will help to minimize this leakage. Ultrasonic transducers are often mounted using rubber or silicon to limit the amount of leaked ultrasonic signal to/from the surrounding material.

CONCLUSION

Ultrasonic range detection is accomplished using a PIC16F690, MCP6022 op amp, and MuRata MA40S4R/S ultrasonic devices. Two port pins of the PIC microcontroller provide enough drive strength to transmit an ultrasonic pulse. Timer0 and Timer1 are used to create a 40 kHz signal and time the returning pulse. The MCP6022 amplifies the signal at the receiver, and the PIC16F690 internal analog comparator is used to detect the presence of the returning pulse in the signal.
APPENDIX A: FLOWCHARTS

FIGURE 1: ULTRASONIC MAIN FUNCTION (FIGURE 1 OF 3)

Power On

US_Init()
LCD_Init()
Math_Init()

Enable Global Interrupts

Clear TMR1H:L
Turn on TMR1

SendPulse()
SendDelay()
DetectReturnPulse()

TMR1 Overflowed 8 times?

YES

Increase number of output pulses to a max. of 16

NO

CountToDistance()
Average Distance()
WriteOutToLCD()
FIGURE 2: ULTRASONIC MAIN FUNCTION (FIGURE 2 OF 3)

DetectReturnPulse()

Turn on Comparator
Clear Comparator Interrupt (C2IF)

C2IF set?

 Minimum distance detected
 ‘numPulses’ set to 0x01

NO

TMR1IF set?

NO

C2IF set?

YES

- Increment Overflow Count
- Clear TMR1IF

NO

YES

8 Overflows?

NO

- Turn off Timer1
- Store Timer1 count
- Turn off Comparator

YES

Return
ULTRASONIC MAIN FUNCTION (FIGURE 3 OF 3)

- Copy 'numPulses' to variable 'i'
- Double number of output pulses
- Preload Timer0 with 0xF1
- Initialize USdrive pin high one low
- Clear Timer0 Interrupt Flag (T0IF)
- Set Timer0 Interrupt Enable (T0IE)

SendPulse()

ISR

Load TMR0 with 0xF3
Toggle USdrive Pins
Decrement 'i'

'i' = 0?

YES

Clear T0IE
Return From Interrupt

NO

TOIE set?

YES

Output last pulse

Set output pins to ground

Return
APPENDIX B: PCB AND SCHEMATICS

FIGURE 1: ASSEMBLY DRAWING AND DRILL SIZE FOR DEMO BOARD

MATERIAL: FR-4, THICKNESS 0.062 COPPER 1 OZ.-SIC LYSR

TWO LAYER BOARD

FINISH:

☑ SOLDERMASK OVER BARE COPPER (SMOBC)
☑ WITH HOT—AIR—LEVEL SOLDER
☐ SMOBC WITH SELECTIVE GOLD PLATING ON LANDS
   INDICATED. 10µ GOLD OVER 50—100µ NICKEL
☐ 60/40 TIN—LEAD REFLOW

SOLDERMASK — DYNACHEM EPIC 200 LPI OR EQUIVALENT.
COLOR—DB6500 BLUE
SILKSCREEN — WHITE INK

USE ARTWORK SET NO. 233—83128A.ZIP REV A

ANY ALTERNATIVES TO THE ABOVE SPECIFICATIONS MUST BE
APPROVED BY THE ENGINEERING DEPARTMENT AT MICROCHIP.
THIS PCB TO BE MANUFACTURED TO MEET ALL ACCEPTANCE LEVELS
OF A CLASS 2 PCB PER ANSI/IPC—A—600F.
FIGURE 2: TOP, BOTTOM, HOLE AND SILK SCREEN LAYER OF DEMO BOARD
FIGURE 3: SURFACE MOUNT AND THROUGH HOLE PAD PLACEMENT
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