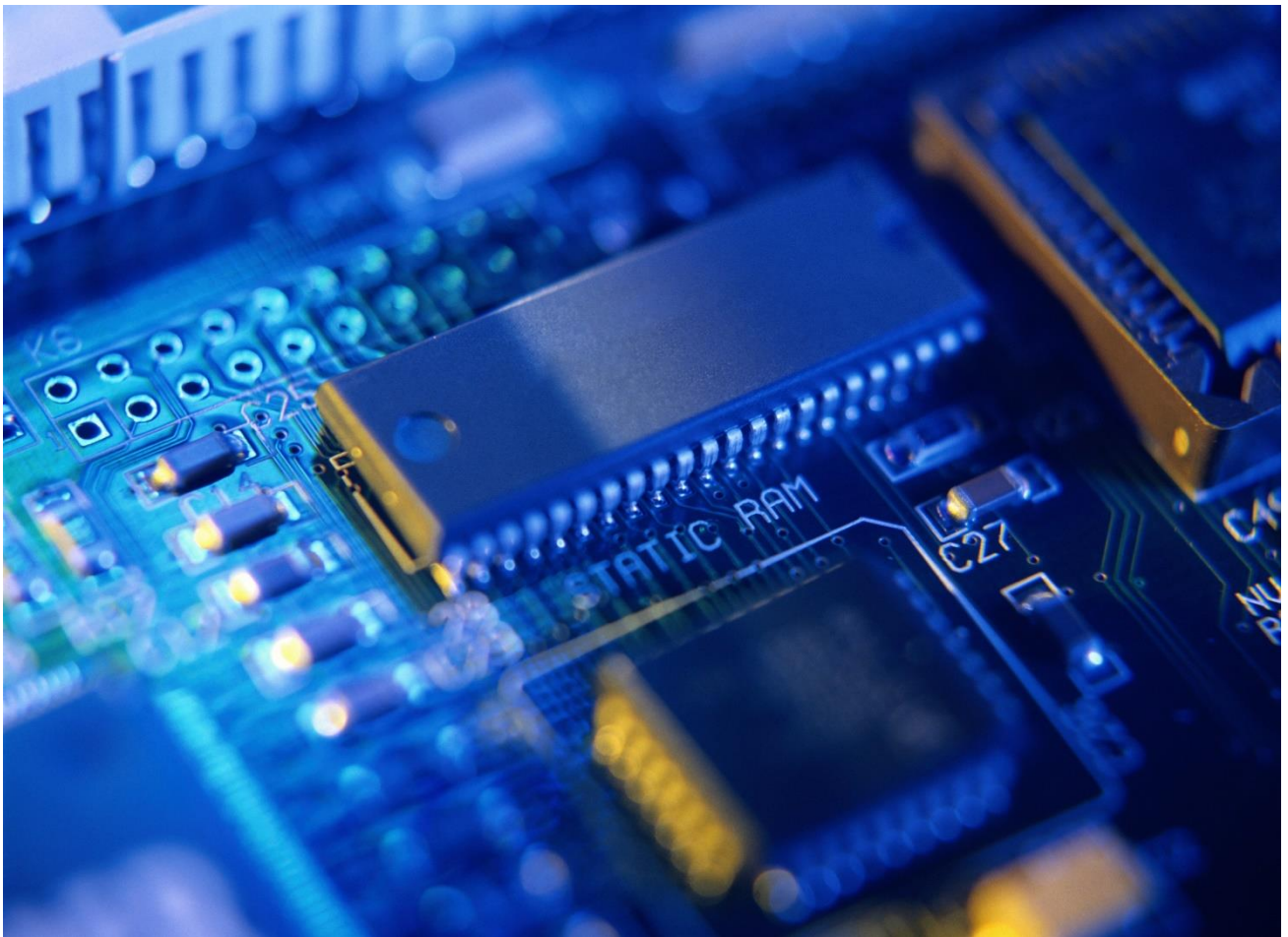


Design of a Portable Ultrasonic Distance Measurement Device



Level 5 Assignment

Submitted By

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Introduction

The term ultrasonic refers to soundwave frequencies exceeding the upper limit of human hearing, i.e., $>20\text{kHz}$ [1]. Ultrasonic devices have numerous applications ranging from cleaning products to industrial control, and even medical treatments. This project will focus on one of its more common applications, measuring distances.

Using electronic components such as a PIC microcontroller, amplifiers and an ultrasonic transmitter and receiver, this project aims to show how such a measuring device could be designed and manufactured.

To succeed in a market already containing thousands of similar products, this project will look to incorporate video capture into the operation of this device, thus providing a multitude of functions for which it may be used.

This report will focus specifically on the design of the ultrasonic measuring device and simply aims to produce a digital output that may be used to trigger and stop the recording of an external device.

Design Requirements

Desired Product Application:

For this project, it had been requested that an ultrasonic measuring device be designed using a PIC microcontroller. The project brief asks that the device is to be handheld and be powered by rechargeable Li-Ion batteries. This should be facilitated through a USB adaptor. The rest of the design has been left open ended.

The design will require some form of display to present measurement data, as well as static and permanent memory, to store and recall this data from.

To distinguish this product on the market, a design choice has been made to integrate automatic video capture compatibility into this device. An initial idea on how to achieve this using an ultrasonic measure is detailed below:

- Set the device between two points within its specified range.
- Take an initial measurement reading and set it as the 'default value' within the microcontroller.
- Continue to measure the distance every second until a deviation of $\pm 5\%$ is detected.
- This should indicate something, or someone, has moved between the chosen two points.
- Using an output from the PIC, send a HIGH signal to a video capture device and begin recording the area. (This may be possible using the integrated USB connector.)
- Whilst recording, continue to measure distance.
- Once the 'default value' is detected again, begin a timer, and wait 10 seconds.
- If the distance remains within tolerance of the 'default value', set the output to LOW and stop recording.
- All video footage will be stored externally from the microcontroller.

Using the information above, a very basic design concept can begin to be envisioned. To move this design forward, research will now be conducted into the major design components such as ultrasonic theory, microcontroller selection, power requirements and circuit design.

Project Research

Ultrasonic Theory:

Ultrasonic measurement devices operate by calculating the time taken for a soundwave to travel between two points. This requires three distinct processes:

1. Generate an ultrasonic signal through a transmitter i.e., converting an electrical signal into pulses of sound. This signal is commonly produced between 40kHz to 200kHz in handheld devices [2].
2. Detecting and converting the return echo from these pulses back into an electrical signal through a receiver.
3. Measuring travel time of the ultrasonic wave and calculating the distance travelled [3].

By measuring the time taken for the ultrasonic signal to travel through the air and echo back to the receiver, the following calculation can be used to determine distance:

$$Distance (m) = \frac{Speed \left(\frac{m}{s} \right) \times Time(s)}{2}$$

When operating in video capture mode, a deviation of $\pm 5\%$ will be used to trigger a HIGH signal to the recording device. For this, the equation below will be used:

$$\pm Distance Tolerance (m) = \frac{Speed \left(\frac{m}{s} \right) \times Time(s)}{2} \times 0.05$$

With distance being calculated and the device measuring time, these formulas require the speed of the ultrasonic signal to be known. As ultrasonic signals are simply higher frequency soundwaves, the speed of sound through air can be researched and substituted into the equation.

Generally, ultrasonic devices assume a constant speed of sound of 343m/s [4]. This is the known speed of sound through air at 20°C. Additional research into the effect of temperature on the speed of sound showed that for each one degree Celsius of temperature change, the speed of sound will proportionally change by 0.6m/s.

The reason most devices assume this constant speed of 343m/s is due to the short-range characteristics of ultrasonic measures. Typically, handheld ultrasonic measuring devices operate over a maximum range of three to eight meters. As a result, the time measured by these devices is very small and minor speed changes equate to negligible distance inaccuracies when considering design tolerances [5].

Much like temperature, humidity can cause very small fluctuations in the speed of sound. This effect however is even smaller than that of temperature and therefore, will be deemed negligible for this project.

Using the research notes above, several design specifications can be made:

- Two ultrasonic transducers will be required with operating frequencies between 40kHz-200kHz. The microcontroller should have a clock rate of at least 1MHz to continually transmit and receive this data simultaneously.
- The chosen PIC microcontroller will also need to contain some form of permanent memory to store not only required coding, but also calculation data. A small Arithmetic Logic Unit (ALU) will also be required to perform the calculations.
- A design choice of 4M has been made for the maximum range of this device due to range limitations of smaller transducers.

Ultrasonic Transducer Selection:

The transducer selected for this design is the MA40S4S from MURATA [6].

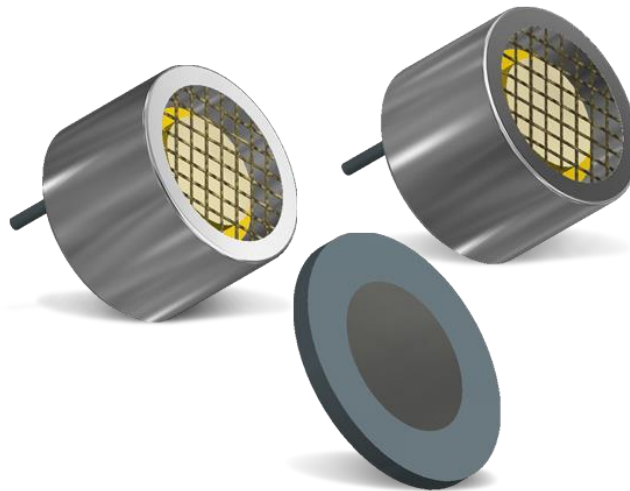


Figure 1 - PUI Audio, Inc. UTR-1440K-TT-R [25]

This transducer is capable of functioning as either a transmitter or receiver. Using two of these transducers will therefore satisfy design needs as well as ensuring compatibility with one another.

Per the datasheet [7], this device operates at 40kHz and has a drive requirement of 20V peak to peak. The required Li-Ion batteries typically output 3.6V, a design choice will have to be made to either amplify the input signal to these transducers or connect multiple batteries in series. This will be discussed in depth within the Circuit Design chapter of this report.

As the datasheet specifies a “peak to peak” voltage is required, it is essential that the chosen microcontroller is able to utilise pulse width modulation (PWM) for the drive signal of these transducers.

When acting as a receiver, this device will produce an analogue output signal ranging between 2-5V. This signal should not therefore require voltage adjustment and can be fed directly to the microcontroller for A/D conversion.

The datasheet also states that these transducers have a maximum operating range of eight meters. Considering the echo return required for a handheld ultrasonic measure, this range will meet the four-meter design specification.

This product is also IP65 rated and capable of operating between -40° to 85°C. This ensures it can operate in external environments that will aid in the marketing of the product and will allow for outside video capture.

PIC Microcontroller Selection:

From the original project brief and the research conducted into ultrasonic devices, there are several requirements needed of the PIC microcontroller:

1. Clock Rate:

Clock rate simply refers to the cycles per second able to be generated or translated by a given device. Within most PIC microcontrollers, this typically is available in the MHz range [8].

For this design, a minimum clock rate of 1MHz has been selected. This will be more than sufficient to drive and translate ultrasonic signals of 40kHz and communicate very simple scripts for internal calculations.

2. Analogue to Digital Converter (A/D):

For the microcontroller to be able to compute the signal produced by the ultrasonic receiver, a A/D converter will be required. This will essentially create a string of binary information proportional to the analogue input. This binary information can then be computed within other sections of the microcontroller such as the ALU.

3. Pulse Width Modulation (PWM):

In order to drive the ultrasonic transmitter, a fluctuating input signal is required. To produce this signal from a microcontroller operating at 5V DC, PWM will be required. PWM is used to vary the duty cycle of an input DC signal and creates a square wave output at a given frequency.

The clock rate of the microcontroller will determine the frequency at which this signal can be produced. The selected 1 MHz clock rate will have no issue producing the desired 40kHz output signal. To produce a 40kHz output signal, the PWM module itself will require 16B operation.

4. Permanent Memory:

To store the required coding and calculations for this device, the chosen microcontroller will be required to have permanent memory in the form of ROM, EPROM or EEPROM.

Due to the simplicity of the required device coding and function, a permanent memory of 8kB should be sufficient for this design.

5. Volatile Memory:

Volatile memory can be provided in the form of RAM or SRAM within a microcontroller and will temporarily store data until power is removed from the device. For this design, it will be required to store information regarding calculation results, distance measured and default distance when used for video capture.

For this application a volatile memory requirement of 2kB has been selected.

6. Timers:

To measure the time taken between transmitting and receiving the ultrasonic signal, the microcontroller will require a dedicated timer. With expected travel time being very short, the expected results will be measured in a mS range, i.e., between 0 to 1000mS.

For a timer to operate within this range, a 10bit timer will be required. Alternatively, multiple smaller timers could be cascaded together.

7. Arithmetic Logic Unit (ALU):

For the microcontroller to be able to perform calculations, an ALU is required. To process the information supplied by the timer, a 10bit ALU will also be needed.

Using the specifications outlined above, research was conducted to find a suitable PIC microcontroller.

The product selection tool supplied on the Microchip website [9] allows the user to search for devices compatible with the specification selected. From this tool, the PIC 16F 88 was chosen for this project [10].

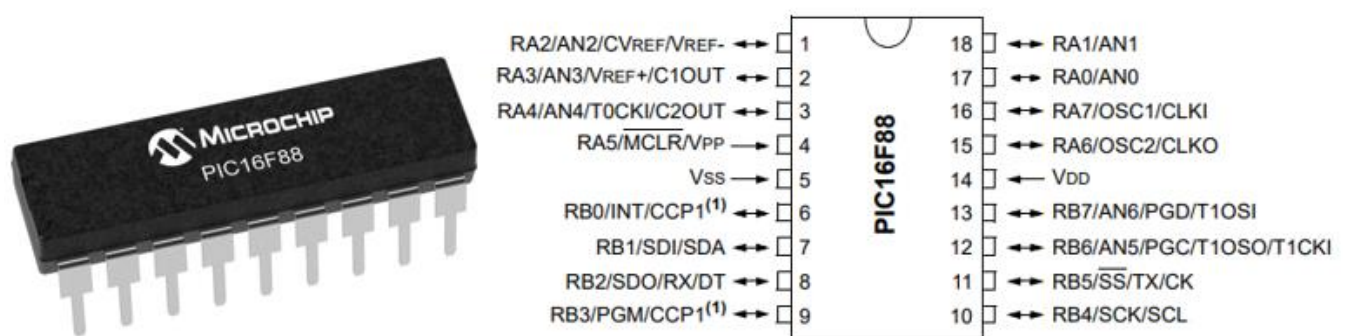


Figure 2 - PIC 16F 88 Microcontroller and Pin Outs

PIC 16F 88 Specifications:

- Clock rate can be selected at either 1, 2, 4 or 8MHz.
- 10-bit A/D converter.
- 16-bit Capture Compare, PWM (CCP) module. This is a specifically designed module for waveform generation using PWM in microcontrollers [11] .
- 68kB of ROM is available within this microcontroller via 8 banks of 4kB. 2kB of EEPROM is also provided in 8 banks of 256B.
- 3kB of volatile memory is provided in the form of 8 banks of 368B SRAM.
- Three timers are integrated, two 8bit timers and one 16bit timer.
- A 16bit ALU is found within the STATUS register of the I/O ROM space.

All of the specifications above have been sited directly from the PIC16F88 datasheet provided by Microchip [10].

A block diagram highlighting system operation within the microcontroller can be found on the following page [10, p. 7].

FIGURE 1-2: PIC16F88 DEVICE BLOCK DIAGRAM

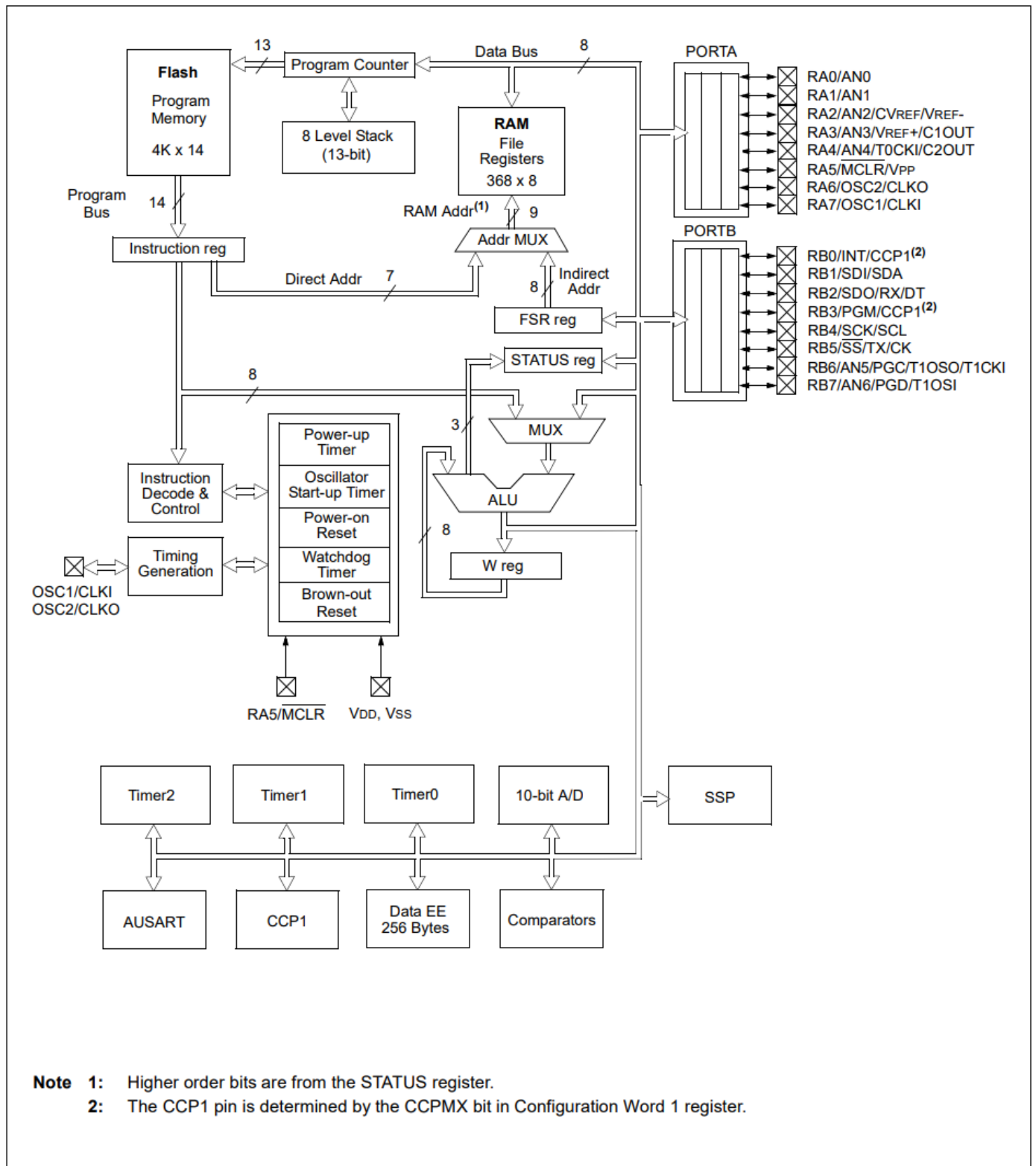


Figure 3 - PIC 16F 88 Block Diagram [10, p. 7]

Display Methods:

To visibly display results and aid in device operation, some form of display module will be required. Due to the simplistic requirements of this device's display, i.e., only displaying a numerical value, a basic display method such as a 7-segment LED display can be used.

LED 7-Segment Display:

7-segment LED displays are the most basic form of presenting numerical data from a microcontroller. They provide seven LED segments that are each assigned to an input pin labelled A-G.

For a common cathode display, i.e., all negative LED terminals are grounded, HIGH input values will turn on the assigned segment. For common anode devices, the opposite is true. By selecting a specific sequence of HIGH and LOW inputs, numbers ranging from 0-9 can be displayed. A separate pin label DP is also provided that will control a decimal point LED next to the numerical value [12].

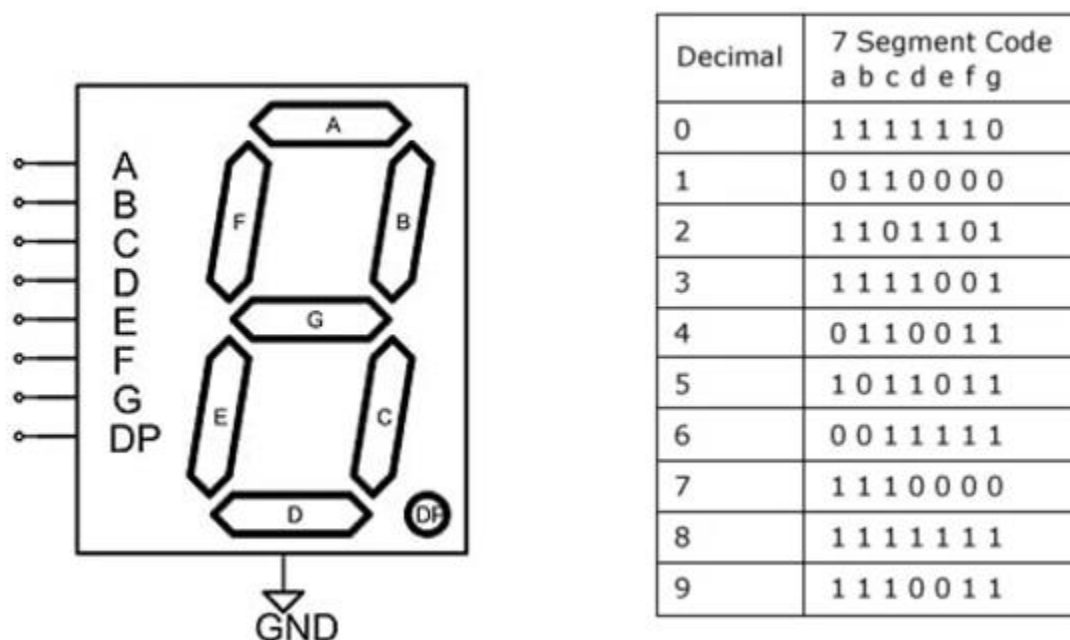


Figure 4 - 7-Segment Display and Binary Sequence Reference [12]

These inputs can be connected to general purpose I/O pin on the microcontroller. If a PIC microcontroller was used for this application, the sequenced binary information would be stored within the ROM of the microcontroller. A script would then have to be written to recall this data to match the distance value calculated by the ALU.

To aid this process, special driver chips have been designed to convert a serial line of data from a microcontroller to a binary code for multi-digit LED 7-segment displays. This only requires three I/O pin from the microcontroller and eliminate the need to write code for this application. These ICs are also pre-programmed with the required binary sequences eliminating the need to code on the microcontroller.

For this design a MAX7219 driver chip will be used [13]. These chips are able to control up to eight separate LED segment modules via serial data transfer from a microcontroller.

Per the datasheet [13], the MAX7219 chips are also powered via a standard 5V supply. This will allow the driver to be connected in parallel with the PIC16F88 without additional circuitry.

The connection diagram for the MAX7219 is shown below.

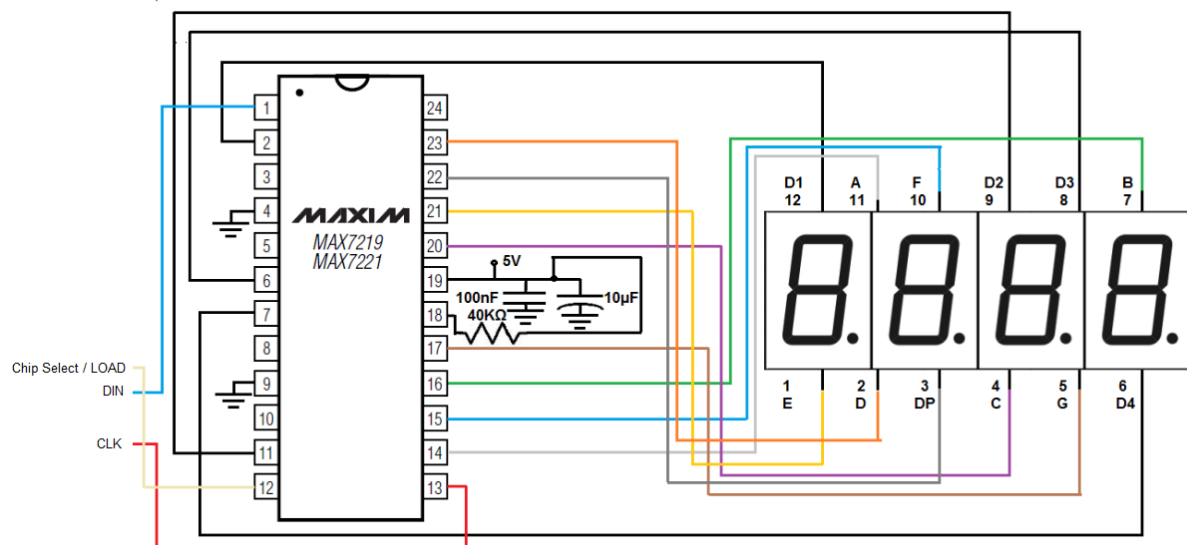


Figure 5 - Connection Diagram for the Max7219 [13]

To display range values between 0-4m at a resolution of 1mm, a four digit 7-segment display will be required, i.e., for a 0-1000mm display. These displays are simply comprised of four single 7-segment displays and are provided with four additional input pins. These pins are assigned to four different registers within the driver chip that are each responsible for a single digit.

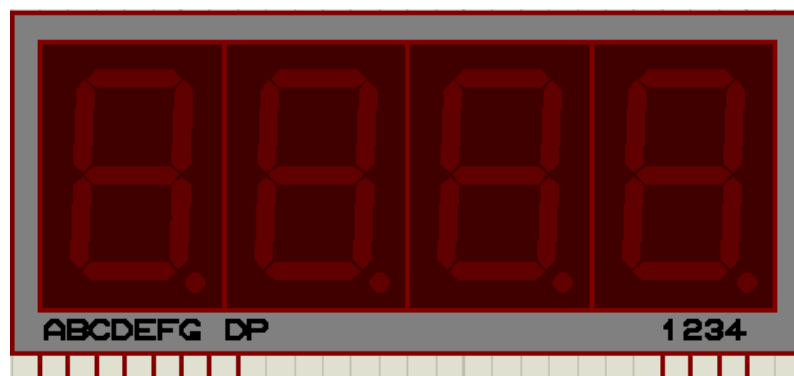


Figure 6 - Four Digit 7-Segment LED Display [12]

Whilst other display methods are available such as liquid crystal, LED matrix and E-ink displays, the simplicity of this application only requires the used of the four digit 7-segment module. The 7-segment displays are also relatively cheap compared to the other methods and are far easier to interface with the microcontroller.

For this project, the HDSP-B0xG four digit 7-segment display from Avago Technologies will be used [14]. This is a common cathode device that operates through a 5V signal as supplied by the MAX7219.

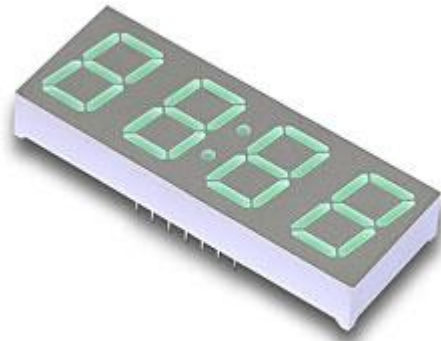


Figure 7 - HDSP-B0xG Four Digit 7-Segment Display [14]

The pin connections for this device are shown below.

Pin Configuration

Pin	HDSP-B01G/B03G/B05G/B07G/B09G
1	Anode E
2	Anode D
3	Anode DP
4	Anode C
5	Anode G
6	Digit 4 Common Cathode
7	Anode B
8	Digit 3 Common Cathode
9	Digit 2 Common Cathode
10	Anode F
11	Anode A
12	Digit 1 Common Cathode

Figure 8 - Pin Connection HDSP-B0xG [14]

Lithium-Ion Batteries:

With the ultrasonic transducers and PIC microcontroller selected, the final major component to be researched is the Lithium-Ion batteries and the ability to charge them via a USB connector.

Li-Ion batteries are rechargeable batteries that typically operate at 3.6V [15]. They are able to be connected in series or parallel depending on the electrical requirements of a circuit.

For this design, two Lithium-Ion batteries will be connected in series to produce a supply voltage of 7.2V. Through the use of a voltage regulator, this voltage will be able to provide a constant 5V to the PIC microcontroller.

The 3.6V Li-Ion supply is average voltage supplied by the battery for the majority of its operation. At maximum charge, this value can exceed 4V and at minimum charge this value can fall to 3V [15]. Once this minimum value is reached, Li-Ion batteries normally disconnect via cut-off circuitry. By selecting an average 7.2V supply and using a voltage regulator, this design will be able to maintain a constant 5V supply to the microcontroller regardless of charge levels.

Type A USB connectors operate at a maximum capacity of 5V and 500mA [16]. These are by far the most common USB connection type and will therefore be used for this design. To ensure a Li-Ion battery is compatible with this charging method, the charging current will need to be specified within its datasheet.

Using these specifications, a Panasonic PA-L28 7.2V Li-Ion battery has been selected for this design [17].

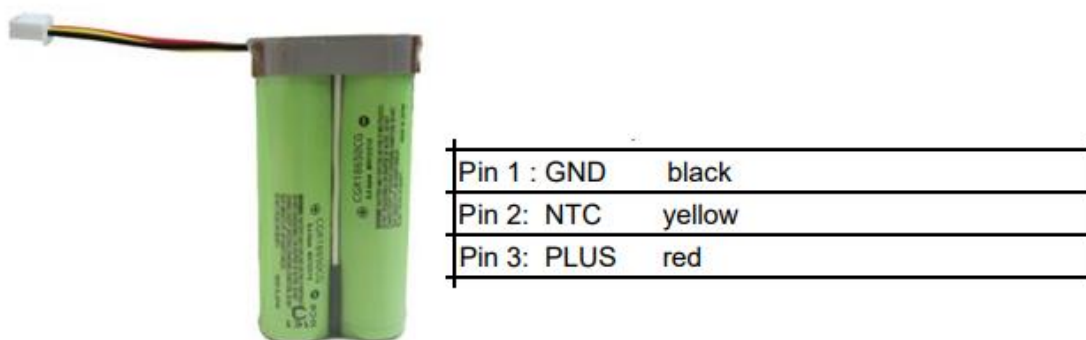


Figure 9 - Panasonic PA-L28 Li-Ion Battery and Wire Connections [17]

Whilst the datasheet for this device specifies a current of 450mA is sufficient to charge this battery, a 5V supply from a USB will never be able to fully charge a 7.2V product. For this type of application, Microchip has designed specific chips to amplify and regulate USB voltages at standardised Li-Ion levels.

An example of one such chip is the MCP73862/4 that is able to amplify a USB input to 8.2V i.e., the upper limit of two Li-Ion batteries connected in series.

This chip is also designed to monitor several conditions of the Li-Ion batteries such as temperature, voltage and charge current. Using this information, the chip can disconnect the charging process should the battery overheat, draw too much current or when they reach maximum charge. This prevents the battery from being damaged and increases efficiency of the charging process.

For these reasons, a MCP73862/4 will be used within this design.

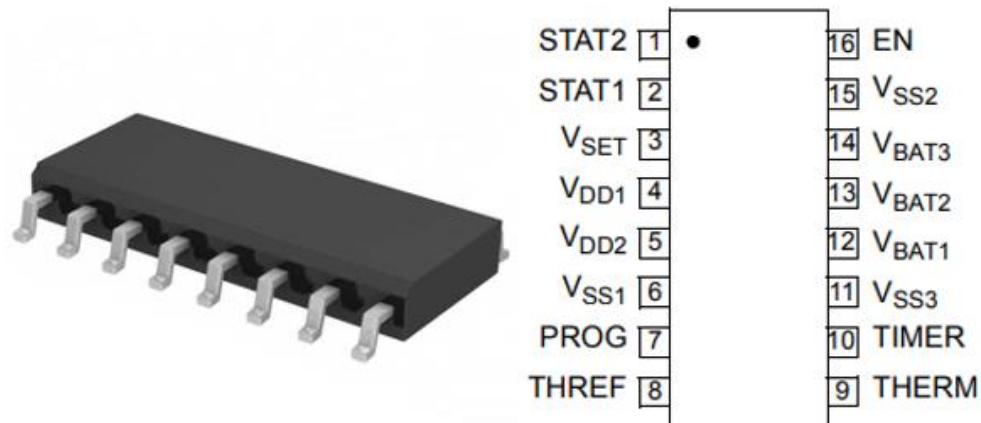


Figure 10 - Microchip MCP73862/4 Chip and Pin Outs [18]

To function at a charging voltage of 8.2V, the datasheet specifies pin 13 (V_{BAT}) should be used as the battery's anode connection [18].

To complete this charging circuit, a female type A USB connector will be added to this design. Type A USB connectors all have the same pin out [19]:

<u>USB Pin</u>	<u>MCP73862/4 Connection</u>
Pin 1: Vcc (+5V)	Connected to V_{DD}
Pin 2 – D- (Data output)	Connected to STAT 2
Pin 3 – D+ (Data input)	Connected to STAT 1
Pin 4 – GND	Connected to V_{SS}

Figure 11 - Type A USB connection onto MCP73862/4 [18] [19]

Circuit Design

With appropriate devices selected and connection diagrams obtained, the circuit design process of this project can begin.

Voltage Control:

Within the research, several voltage requirements were outlined for different sections of the device.

- Li-Ion Batteries – 7.2V
- All control chips and the LED display – 5V
- Ultrasonic Transducers – 20V

As already discussed, the MCP73862/4 Li-Ion charger controller will produce a regulated 8.2V supply to the Li-Ion batteries. This controller simply requires a 5V supply to operate that will be provided by the USB when connected.

For the PIC microcontroller, display driver and 7-segment display, a simple overvoltage protection circuit can be used to limit the batteries 7.2V supply to a constant 5V. This can be achieved using a low value resistor and back-to-back 5.1V Zener diodes as shown below.

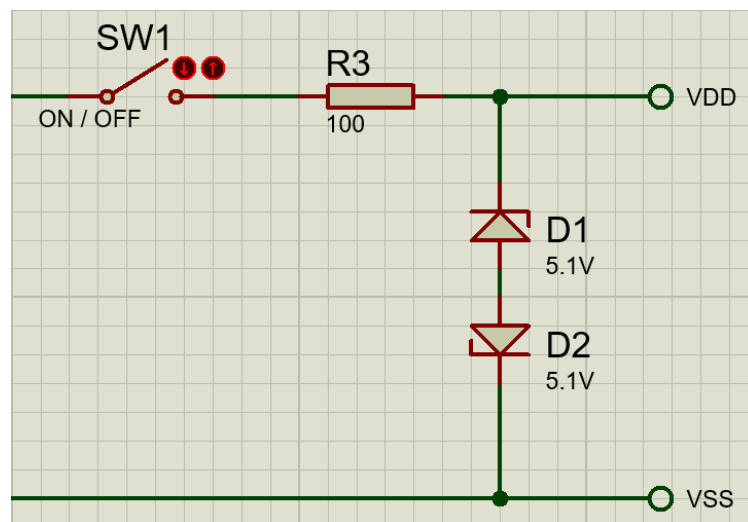


Figure 12 - Overvoltage Protection for PIC Microcontroller

The integrated switch will allow the device to be turned on and off. It will also disconnect sensitive components from the circuit whilst the device is charging.

To amplify the signal required for the ultrasonic transducers, another IC in the form of an audio amplifier can be used. A type D audio amplifier can be used for this application as the signal being produced via the PIC microcontroller has undertaken PWM.

For this project, a MD8002A audio amplifier will be used [20]. This is a type D audio amplifier designed for amplification of input signals to 20V. Much like the PIC16F88 and the MCP73286, this IC is powered by a 5V supply allowing it to be directly integrated into this device.

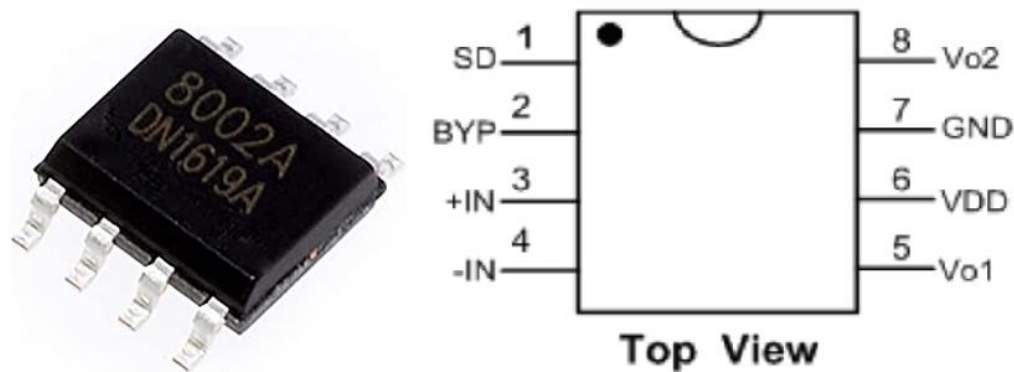


Figure 13 - MD8002A Type-D Audio Amplifier [20]

Within the datasheet, the table below was found describing the connection requirements of each pin [20].

Pin NO.	Pin Name	Description
1	SD	The device enters in shutdown mode when a high level is applied on this pin
2	BYP	Bypass capacitor pin which provides the common mode voltage
3	+IN	Positive input of the first amplifier, receives the common mode voltage
4	-IN	Negative input of the first amplifier, receives the audio input signal
5	Vo1	Negative output
6	VDD	Analog VDD input supply.
7	GND	Ground connection for circuitry.
8	Vo2	Positive output

Figure 14 - MD8002A Connection Requirements

The final task before constructing this circuit is to assign the I/O pin from the PIC microcontroller for their appropriate tasks. All pin information can be located within the PIC16F88 datasheet [10, pp. 8,9].

This design will require seven free I/O pins on the microcontroller.

1. Transmitter Output:

As the ultrasonic transducers require an alternating signal, the PIC microcontroller must output a PWM signal. Per the datasheet, this can be achieved via pin 9 (RB3).

2. Receiver Input:

The ultrasonic receiver will produce an analogue signal. This will require an analogue input connected to the A/D converter within the PIC. For this, pin 17 (RA0) can be used.

3. Manual Measurement:

To manually measure distance, a push button connected to a clock input will be used. This input shall be connected to pin 11 (RB5).

4. Video Capture Selection:

To begin automatic video capture, the clock input on pin12 RB6 will be used.

5. Signal Output to Display Driver:

The distance calculated within the microcontroller will be produced within the ALU module. Pin RB0 can be used for direct serial transfer to the HDSP-B0xG display driver.

6. Serial Clock to Display Driver:

The display driver also requires a clock input from the PIC microcontroller. CLK0 on pin 15 can be used for this.

7. Video Capture Output:

To begin video capture, a HIGH output signal will be required. This can be supplied by any remaining digital output pin. For this design, Pin 3 RA4 will be used.

Using the information compiled within this report and the researched datasheets, the circuits on the proceeding pages were created using Proteus8 software.

Li-Ion Battery Charging and Overvoltage Protection:

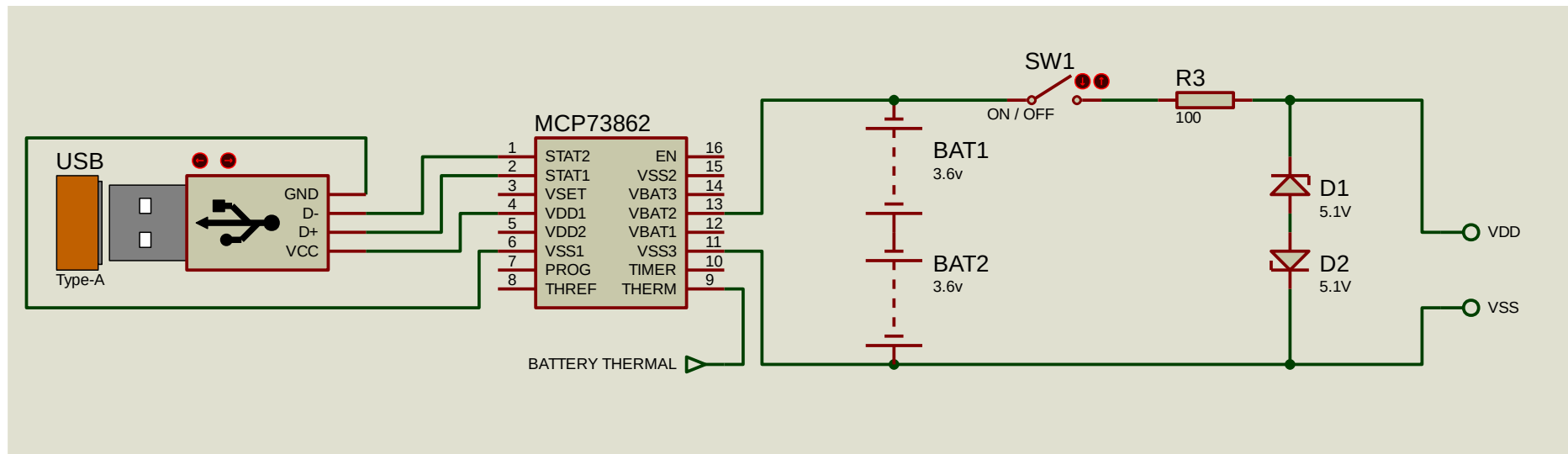


Figure 15 - Proteus8 Simulation of Li-Ion Charging Circuit

Ultrasonic Measuring Device Circuitry:

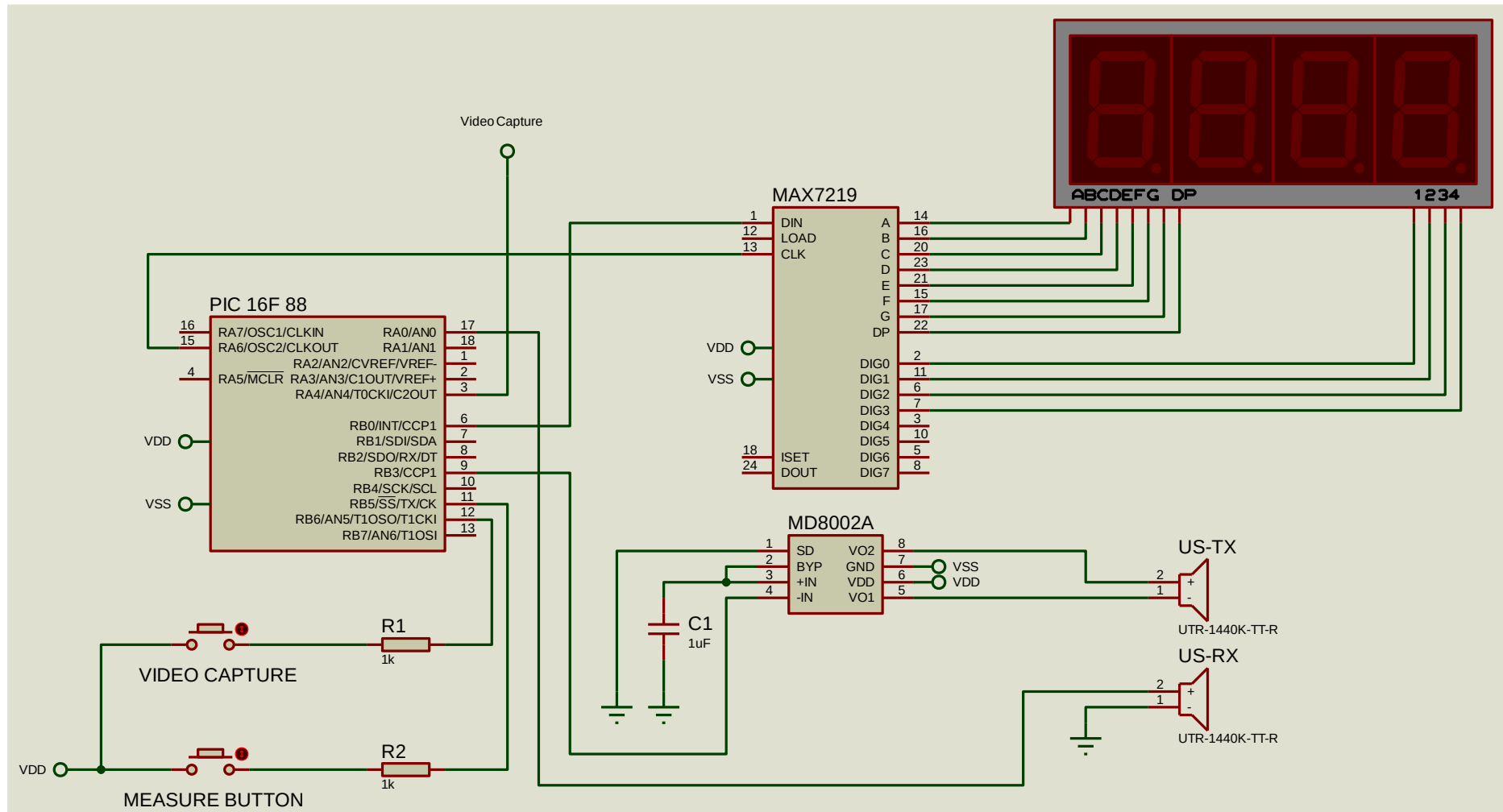


Figure 16 - Ultrasonic Measure Circuit using a PIC16F88 Microcontroller

System Operation Flowchart

For this project, a flowchart will be used to describe the general operation of this device. During manufacturing, software engineers would use this flowchart to write sequenced coding that would allow the PIC microcontroller to function as intended.

Figure 17 on the following page shows the operation flowchart created for this project.

This flowchart is colour coded for different mode operations:

- Green boxes indicate joint mode operations – i.e., operations performed regardless of mode selection.
- Blue boxes highlight operations only performed when a measurement has been manually requested by the user.
- Orange boxes show process flow within automatic video capture mode.

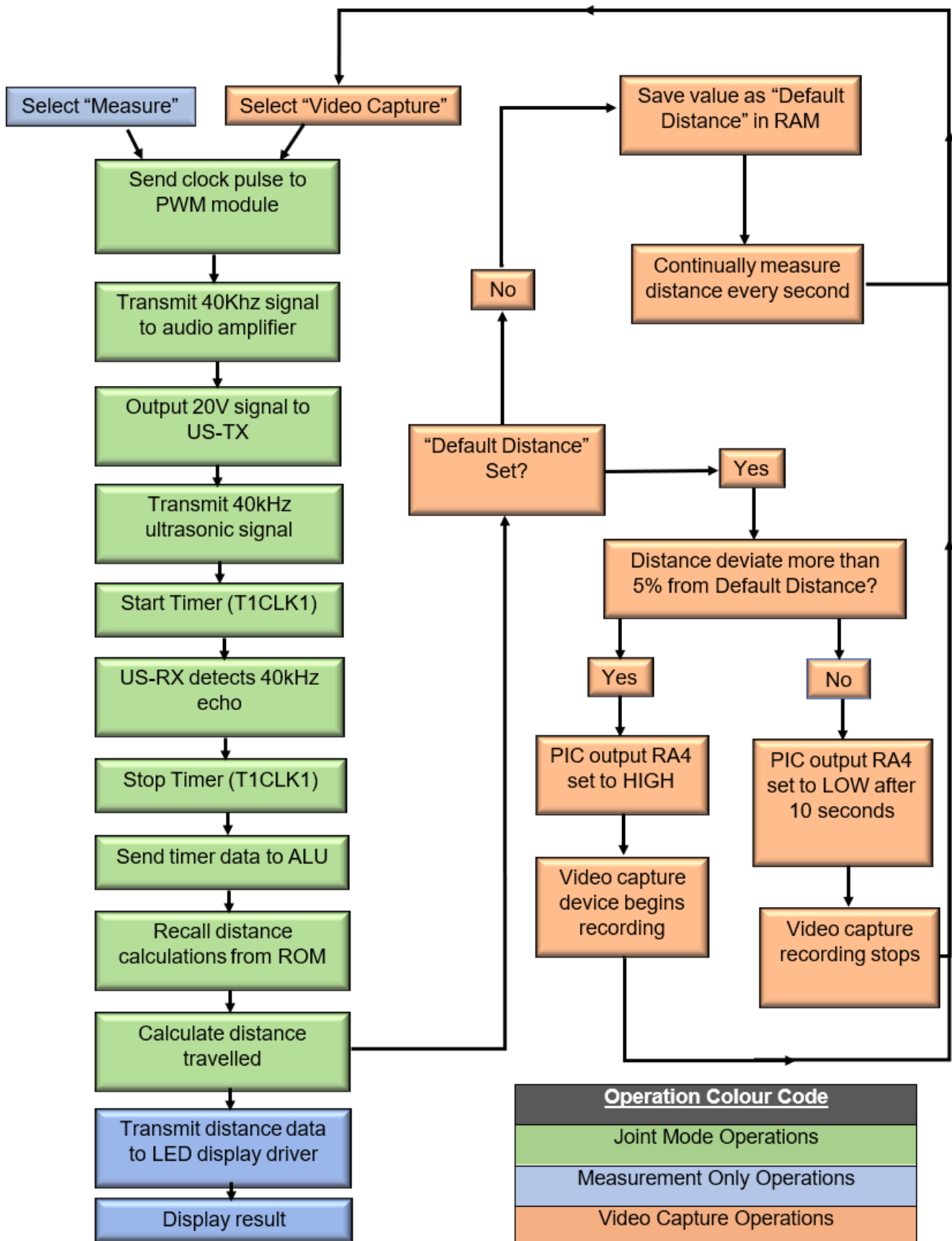


Figure 17 - Ultrasonic Device Operation Flowchart

Parts List and Costing

To create a working prototype of this device, the following components would be required. It is important to note that significant saving can be made when buying these components in bulk.

<u>Component</u>	<u>Quantity</u>	<u>Source</u>	<u>Price (ex VAT)</u>
PIC16F88	1	RS Components [21]	£6.23
MAX7219	1	Farnell [22]	£9.62
MD8002A	1	Sunrom [23]	£4.34
MCP73862	1	Farnell [22]	£2.15
Li-Ion batteries 7.2V	1	Farnell [22]	£18.71
UTR-1440K-TT-R	2	DigiKey [24]	£9.18
Type-A USB Female	1	Farnell [22]	£1.85
HDSP-B08G Display	1	Farnell [22]	£2.42
Pushbutton Switches	2	Farnell [22]	£4.32
Toggle Switch	1	Farnell [22]	£1.42
100Ω Resistor	1	Farnell [22]	£0.13
1kΩ Resistor	2	Farnell [22]	£0.26
1μF Capacitor	1	Farnell [22]	£0.05
Total Component Cost			£60.68

For proof of concept, a prototype using these components can be made on breadboard. If this device went to market, a custom PCB board would be made to connect components in the most efficient and compact manner possible.

The above costing only considers the electrical components within this device. Should the product go to market, a hardcase would be required to securely house components and provide comfortable method of handling the device. An initial design concept for this casing can be seen on the following page.

Product Concept Sketch

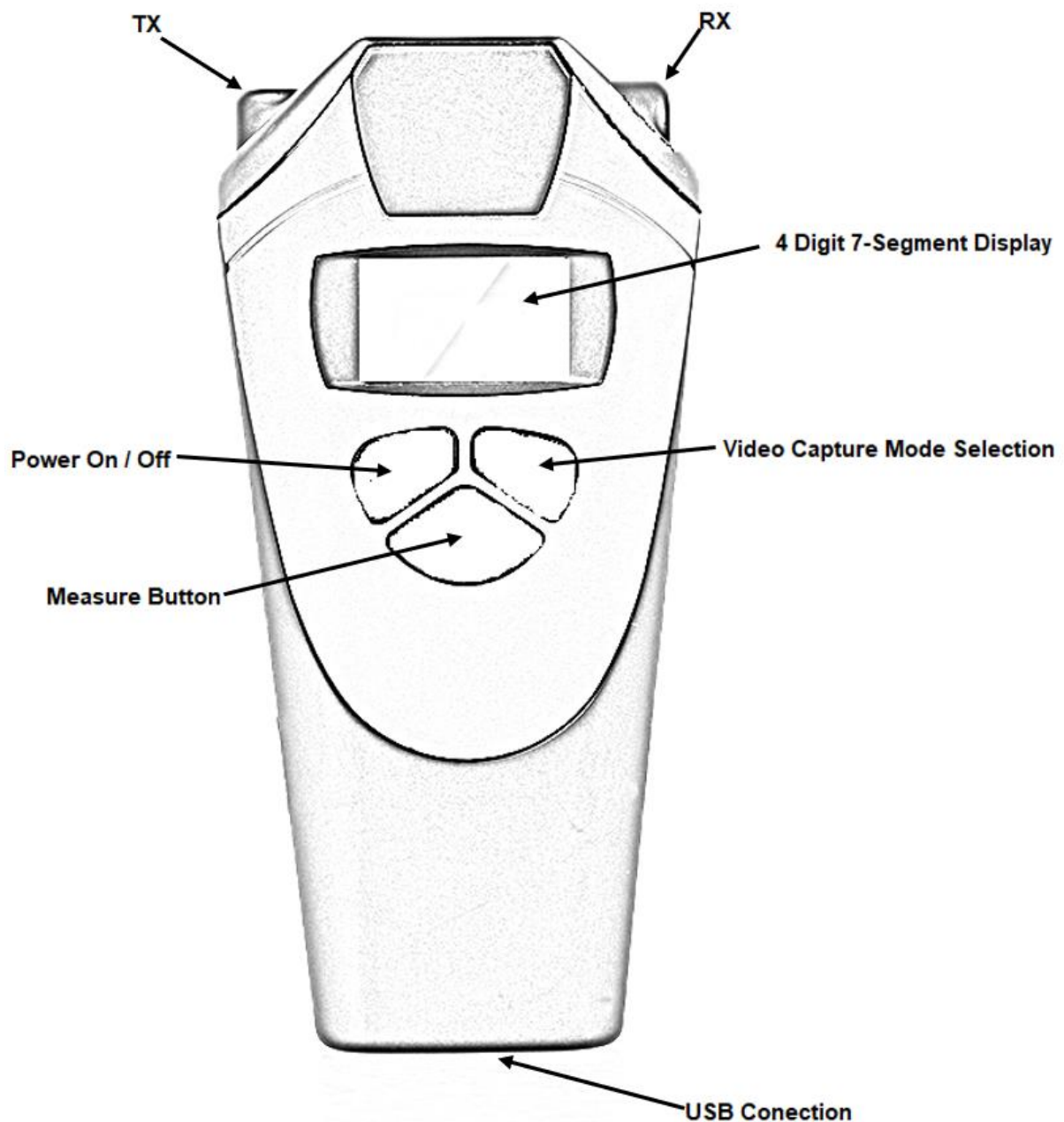


Figure 18 - Product Design Concept

To meet design specifications, this casing would be made via injection moulding from a polymer material. This would provide a solid waterproof casing that when used alongside correct sealing components, would provide the desired IP55 / 65 rating.

Conclusion

Throughout this report, it has been shown how an ultrasonic measuring device can be designed around a PIC microcontroller. Whilst the PIC was able to act as the brains of this device, several other ICs had to be integrated into the design for specific functions. Components such as the MCP73862 was utilised for Li-ion voltage regulation whilst the MD8002A was used to drive the LED display.

The next stage of this project would be to build a prototype of this circuit using the specified components on a breadboard. This would prove functionality as well as allow circuit analysis to be conducted.

Specific testing of the LED display would be recommended due to the lack of loading resistors on the input terminals. Due to the regulated voltage to the microcontroller, this initial design has assumed over-loading of the display is highly unlikely. In addition, twelve additional resistors would increase space requirements of the circuitry and raise manufacturing costs. Should they be required, small resistors, approximately 100Ω , should be sufficient.

Overall, the principles and core components selected throughout this report will enable it to function as a rechargeable, Li-Ion powered, ultrasonic measuring device.

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