Active Sensor Project

EEE SECOND YEAR

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ABSTRACT

The main objective of this project was to produce an instrument capable of measuring the depth of a column of water by use of ultrasound emission and detection. This was to be achieved by a team of students, and will give each team member an insight into the dynamics of group working. The team was exercised in the design, construction and testing of a range of analogue and digital circuits. The project also necessitated some investigation in piezoelectricity and ultrasonic theory.

INTRODUCTION

The ‘active sensor’ in this project is a depth sensor. It works by implementing what is known as the ‘transit-time method’. The sensor transmits an ultrasound pulse, and this signal returns to the sensor after echoing back off a solid surface (the sea-bed or the bottom of a tank). The time taken for this signal’s transit is recorded and, using the velocity of ultrasound waves in water, the distance travelled by the wave is calculated. Transducers could achieve the emitting and collecting of these waves. Transducers produce bursts of ultrasound when a voltage ‘spike’ (of short duration) is applied across them. Conversely when a burst of ultrasound enters a transducer, a voltage spike is created. These ultrasonic generators make use of the piezoelectric effect to convert electrical energy to mechanical sound waves and vice-versa. The piezoelectric effect is the generation of a potential difference across opposite faces of certain non-conducting crystals as a result of the application of mechanical stress between these faces.

There are three main sections to the device.

(i) The transmitter.
(ii) The receiver.
(iii) The counter

The total time taken for the sound to depart and return will not give the depth of the column of water, it would give the distance of the round trip. The time taken by the signal to depart and return must be halved in order to calculate the depth of the column.

The equation required to calculate the distance is
d=s*t, or d=s*frequency*no. of clock counts

To simplify the circuit the clock frequency should be set at a value that would make the clock counts equal to the distance travelled in millimetres. The velocity of sound in water is approximately 1500m/s. Therefore, if a counter was used in the circuit that counted at a rate of 1.5MHz during the period of time that the ultrasound was still in transit then, for every clock signal, the distance travelled will be 1mm. If the counter was to start counting as soon as the signal was transmitted, and then stopped at the moment the signal was received, the counter will store approximately the distance in millimetres that the signal will have travelled. However, the distance obtained will be almost exactly twice that required since only the depth is to be measured. Rather than having to halve the final result it is much easier to halve the clock rate used to increment the counter in this circuit. For a depth of 1mm to be measured every clock cycle, the clock would have to be oscillating at a frequency of 750kHz. The distance travelled by the ultrasound signal will be 2mm per cycle. The distance is shown in decimal on four 7-segment displays that are controlled by the counter section of the circuit. The display shows the result in millimetres with a range between 0000 and 9999. By powering the decimal point next to the MSB the display would give depths in metres, to 4 significant figures.

It was assumed for the entire circuit that the voltage drop across all the Integrated Circuits would not be great enough to skew our outputs and that any delays in the circuit would not be in anywhere near the order of magnitude of the things we were measuring. The circuit had room temperature as it’s only operating temperature, as it was not tested for any other temperatures.

THE TRANSMITTER

Refer to diagram 1.

In order to get an ultrasonic pulse from the piezoelectric transmitting transducer, a circuit was devised to impart a train of short 30V pulses to the device. The frequency of the pulse had to be between 1-2Hz, with a pulse width of about 10μs. The frequencies in this range are large enough to give a quick response to changing depths, but small enough to produce easily distinguishable return signals to the receiving transducer. If the frequency were any higher, the return signals would be very polluted with noise from echoes of previous transmitted pulses. The pulse width is small enough to induce a sharp pulse of ultrasound. If the pulse were longer, the piezoelectric material of the transducer would oscillate for a longer time, again producing unacceptable noisy return signals.

A 555 timer operating in astable mode was programmed to deliver a square wave of frequency 1-2Hz. The frequency of the oscillation of the timer is given by:

$$f = 1.44 / (R_a + R_b) C_1$$

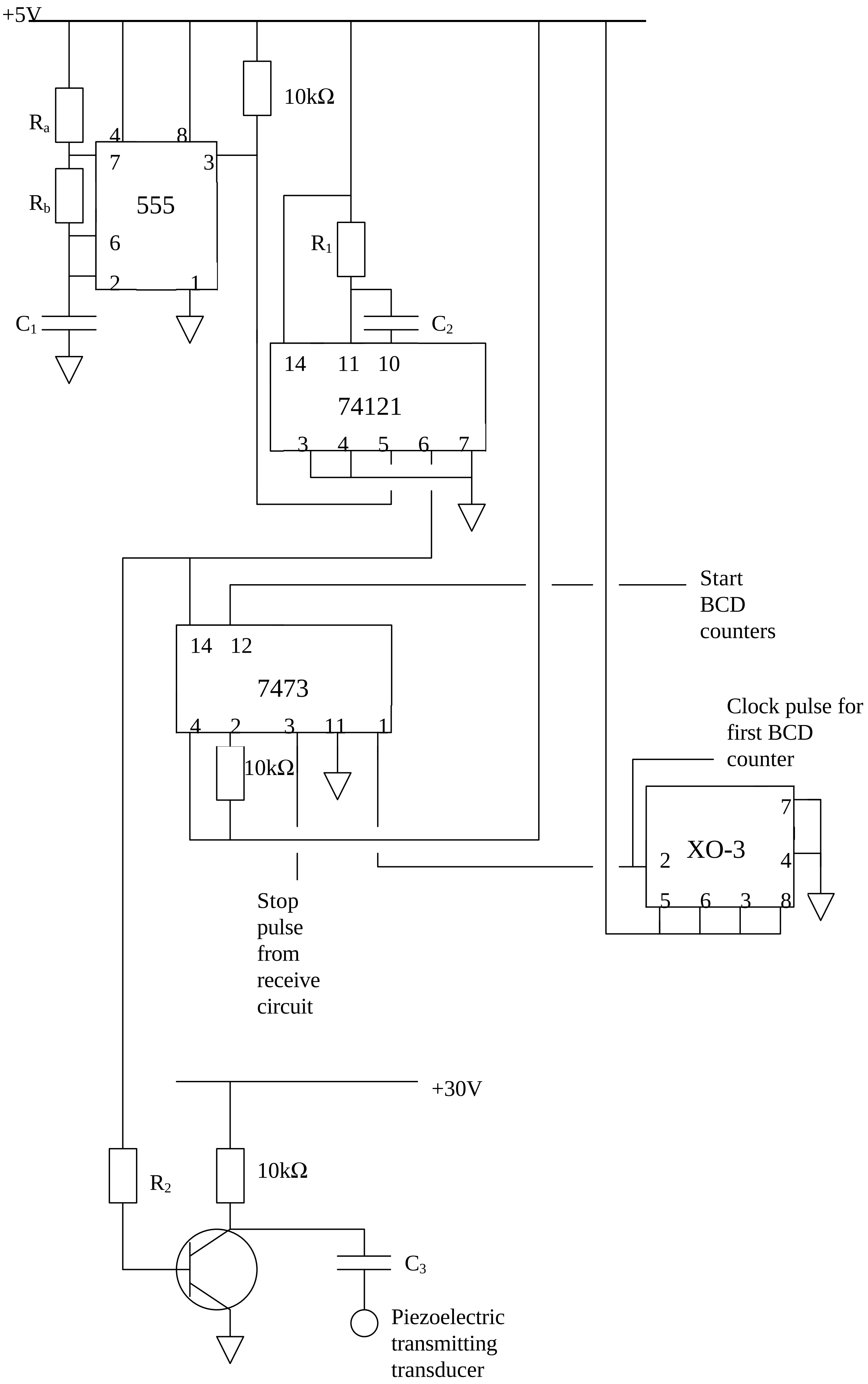
At 1Hz this gives: $1.44 = (R_a + R_b) C_1$
At 2Hz this gives: $0.72 = (R_a + R_b) C_1$
Resistors (R_a and R_b) of value 33kΩ and a capacitor (C_1) of value 10μF were chosen to give a frequency of 1.45Hz. The signal was read on an oscilloscope and found to be between 1.5-1.6Hz, but still within the accepted range.

This pulse was of acceptable frequency, but the width needed to be narrowed. This was done using a 74121 monostable. A monostable maintains a steady state (in this case logic low) producing a logic high pulse when hit by the falling edge of an input signal (in this case the 1.5Hz square wave from the 555 timer) before returning to its stable logic low state. The width of the output pulse can be determined by choosing suitable values for an external resistor and an external capacitor, connected to pins 10 and 11. The pulse width is given by:

$$t = R_1 C_2 \ln 2$$

A resistor (R_1) of value 10kΩ was chosen, along with a capacitor (C_2) of value 1.5nF. This gives a theoretical pulse width of 10.4μs. The signal was read off the oscilloscope, and the pulse width was found to be in the region of 10μs.

This signal was then sent to set a 7473 bistable, which would start the BCD counters, and to the ultrasonic drive circuit. This circuit had to deliver a 30V pulse to the piezoelectric transmitting transducer, for each of the 10μs pulses in the signal. During the logic low part of the signal, the transistor does not allow any current to flow through it to ground, and the capacitor (C_3) is charged. When the base of the transistor is hit with the short logic high pulse, a path is opened for current to flow to ground,


+5V
Ra
Rb
C1
4
8
7
3
555
6
2
1
10kΩ
R1
C2
14
11
10
74121
3
4
5
6
7
Start BCD counters
14
12
7473
4
2
3
11
1
10kΩ
Clock pulse for first BCD counter
7
XO-3
2
4
5
6
3
8
Stop pulse from receive circuit
+30V
R2
10kΩ
C3
Piezoelectric transmitting transducer

and the capacitor discharges. The output current for the monostable at logic high is about 400µA, whilst TTL logic high is about +5V. A resistor (R_2) of value 10kΩ is chosen to give a voltage drop of 0.0004 x 10000 = 4V, leaving an acceptable voltage to open the base of the transistor. The capacitor used had a value of 100nF. When the base is opened, the capacitor discharges very quickly creating a potential difference of approximate magnitude 30V across the piezoelectric transmitting transducer for about 10µs, causing it to produce the desired short ultrasonic pulse. The drive circuit was tested with a +15V rail, and the pulse to the transducer read off the oscilloscope. The nature of the pulse met requirements. At this point, the counters should have started, and the transmitting part of the system has done its job.

COUNTER CIRCUIT

The purpose of the counter is to measure and display the depth of the column of water.

The counter/display circuit can be divided into three parts – the first is the counter, the second is the Binary-to-Decimal (BCD) Decoder, and the third is the 8-segment display. These individual elements shall be discussed below.

The Counter

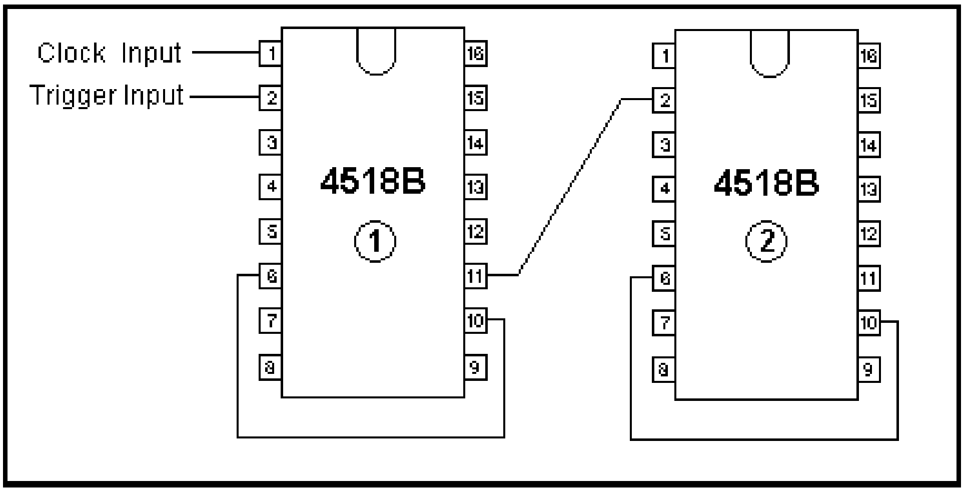
The counting circuit consists of two dual BCD counters connected together to make a four bit asynchronous counter. Both of these counters are 16-pin 4581B's.

The active-high input of the first counter is connected to an EXO-3 crystal clock oscillator, with the active-low connected to the output of a 7473 Bistable multivibrator. The clock input is constantly fed to the counter, but it only counts every half-second while the output pulse from the multivibrator is high, and also while the reset input is low.

The counter circuit counts at a preset speed, calculated to display the correct distance without further calibration. The speed of the clock was preset to 750KHz as detailed previously.

As the counter is only to count between the time the firing pulse is sent and received, the reset pins for all four counters are tied together and connected to the receive circuit. When a high pulse is sent from the receive circuit, the counters are reset, and the counter resets, showing a new depth value.

The pin configuration for the counters can be seen below. Note that Output OP0 is the least significant bit (LSB) and output OP15 is the most significant bit (MSB).



Counter 1	Counter 2

1. XO3 Clock Input	9. Ground	1. Ground	9. Ground
2. 7473 Trigger Input	10. To Pin 6	2. Clock In	10. To Pin 6
3. OP0	11. OP7 & Clock out	3. OP8	11. OP15
4. OP1		4. OP9	12. OP14
	13. OP5	5. OP10	
6. OP3	14. OP4		14.OP12
7. Reset		7. Reset	15. Reset
	16. +5V	8. Ground	

Table 1: pin configuration for the counters

Above is the function diagram for a

be seen as the active-high inputs, while 2 and 10 are the active-low inputs. On

connected to pin 10 – this supplies each successive counter with the appropriate

as the master resets – all four of these in the circuit are tied together and

In building this part of the circuit, a few problems were encountered. The first was

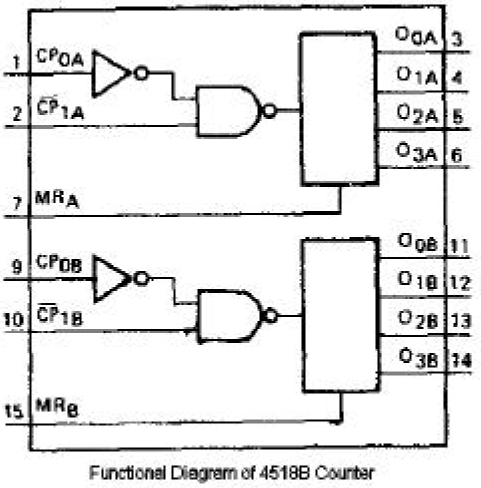


Diagram 3: one of the counters

The Decoder

The decoder circuit is made up of four 4511 BCD-to-seven segment decoders
take the output from the counters and convert it from binary-coded-decimal to seven drive lines for powering the seven-segment displays. The construction of this part of

+5V and ground rails, and the relevant connections from the counter.

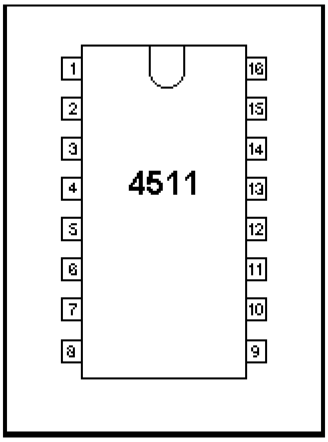


Diagram 4: the 4511

The pin configuration for the 4511 can be seen below:

1. Input B
2. Input C
3. No Connection
4. No Connection
5. No Connection
6. Input D
7. Input A
8. Ground
9. Output e
10. Output d
11. Output c
12. Output b
13. Output a
14. Output g
15. Output f
16. +5V

Table 2: pin configuration for the 4511

There was some confusion with the connections between the counters and the decoders as the inputs are out of sequence: they are not in an ABCD order but a BCDA order, which meant care had to be taken while connecting the chips together.

The Display

The display array consists of four, seven-segment displays plugged in to a purpose built circuit board with breadboard style connectors. The seven outputs, labelled *a* to *g* connect directly to the matching terminals on the display board. This was relatively simple except there were 7 connections for each display, and four displays, plus a ground connection giving a total of 29 parallel connections. The inputs to the display board can be seen below.

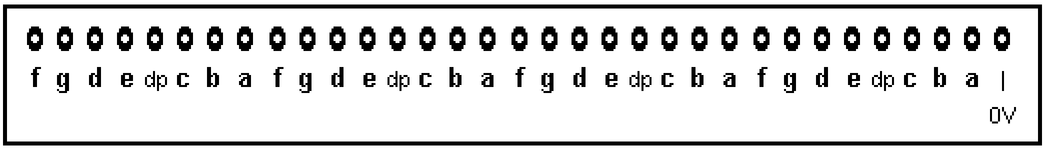


Diagram 5: the display array

dp’ connections are for the decimal points on the display and they are not used for this circuit.

Refer to diagram 6.

transducer and manipulate it in such a way, that it is able to be used by the other parts

The first problem encountered is that the signal from the transducer is of a very low
voltage, in the region of 5mV, this must be amplified if it is to be used with TTL logic
setup in non-inverting mode, a gain of approximately 1000
can be achieved using a 100 ohm resistor and a 100K ohm feedback resistor, which

However, the input signal also contains some echo effect, caused by the reflection of
the ultrasound wave. These echoes must be filtered out
undesirable operation of the system.

To filter out the echoes we used a LM311 voltage
the op-amp was put through a capacitor and diode, in order to remove any DC offset,
and to remove all negative parts of the signal, as the
negative parts to pass through. We chose to use a 100nF capacitor, because the
ultrasound wave is at 1MHz, so we needed a small capacitor to enable it to charge and

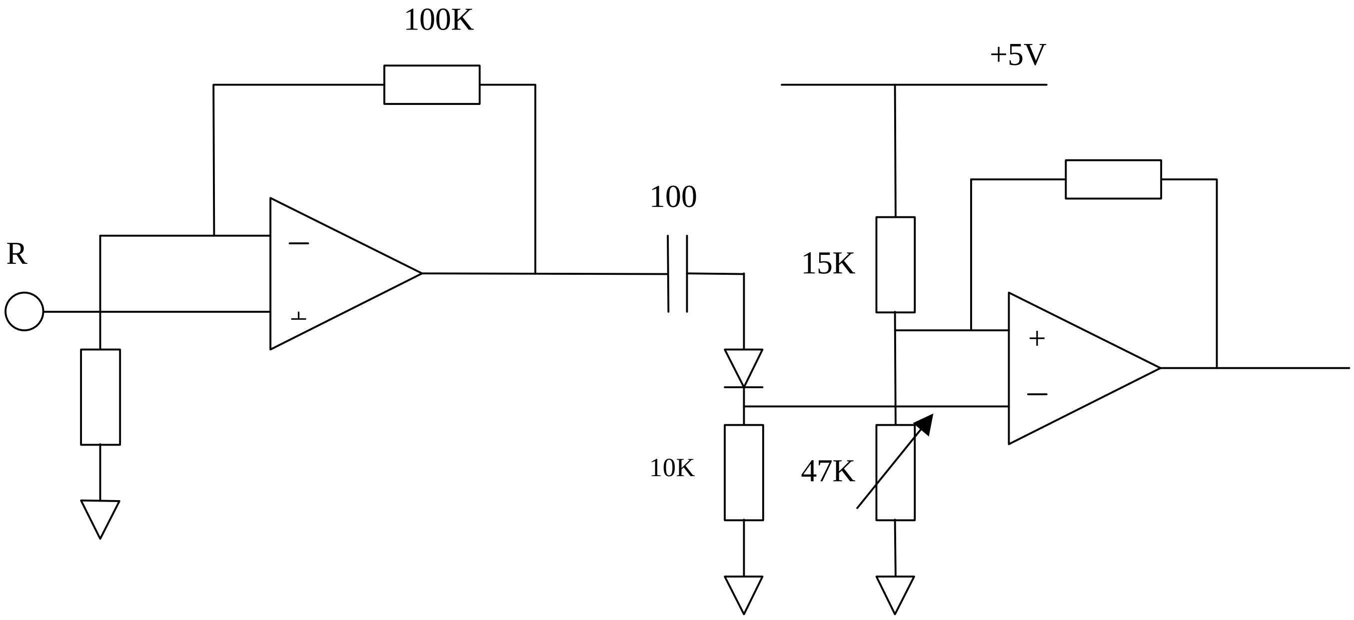
The voltage level that the comparator uses as a cut-off was created using a simple

cut-off voltage, should we need to do so.

The signal from the monostable configured for a
10ns pulse. This pulse was sent to both
order to first halt the counting, and secondly to enable the output to be displayed. A
small delay between these two operations was produced by feeding one of the outputs

buffer, separating the two outputs. This second output was also sent into a pair of
74121
output, before sending a signal to reset the counters, allowing the process to begin
again.

Amplification



CONCLUSION

The project was mostly successful. The circuit was completed within the allotted time of six weeks, however due to time constraints we were unable to attach the transducers and test our 'active sensor' by measuring the depth of a water tank. However, all four members of the group and the lab technician in charge of our laboratories were confident that the system would function if testing had occurred.

The project also achieved its other function of giving us real practice with electronic circuit techniques, i.e. noise filtering and converting voltages to transistor logic values using a comparator.

The group worked well together and always made sure that all members of the group were involved at all stages of development and testing and that everyone had at least a working knowledge of each part of the circuit. It could also be seen that despite careful planning, problems will arise, and it can be seen that our ability to overcome these problems is our measure as engineers.

POSSIBLE APPLICATIONS

Many improvements could be made to our circuit to make it commercially viable as our simple circuit, despite it's genuine usefulness, would be utterly unsuitable for commercial use. The circuit could be split into parts that would be submerged and parts that would be part of an instrumentation and control system on board a sea vessel. The part of the circuit to be submerged would have been watertight, but in such a way that it's performance is not affected. If the circuit were to be used on a submarine it would not always be at the same pressure. A suitable pressure range would have to be implemented. The circuit could be on a pleasure ship in the Caribbean Sea, or it could be on an ice-cutter in the Arctic Ocean. Hence, it can be seen that quite a serious temperature range would be required of the circuit. From less than the melting point of ice water to more than the temperature of the warmest body of water in the world.

If the sensor was attached to a ship sailing in shallow waters it's purpose may be to ensure that the ship is not in danger of running aground. However in a scenario where the sensor happens by chance to be measuring a comparatively deep narrow trench in otherwise shallow waters, the ship could be in danger without anyone realising. To avoid this and other similar possibilities an array of sensors could be affixed at different points on the ship. These sensors could display the respective depths beneath them and/or they could be averaged or subjected to other analysis and manipulation.

If a portable version of this circuit was made it could have an option to switch between use in air and under water. The value for the speed of ultrasound that the circuit uses in calculations is determined by the clock speed programmed into the XO-3. The clock speed we originally had in the circuit allowed for calculations using the speed of sound as 1500m/s (speed of sound in water). Consider that an alternative clock speed that gives the speed of sound as 330m/s (speed of sound in air) is added, and a switch is installed that would switch between the two XO-3 set-ups. The result would be a circuit that, at a flip of a switch, can be used for transit-time distance measurements both on land and below water.

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