Ultrasonic Water Level Measurement

A DISSERTATION SUBMITTED IN PARTIAL FULFILMENT FOR THE DEGREE OF

Master of Technology

IN THE

FACULTY OF ENGINEERING

BY

AKSHAY KUMAR
PRACHET VERMA

GUIDED BY

PROF. BHARADWAJ AMRUTUR

DEPARTMENT OF ELECTRONIC SYSTEMS ENGINEERING
INDIAN INSTITUTE OF SCIENCE, BANGALORE

JUNE 2015

COPYRIGHT © 2015 IISc
ALL RIGHTS RESERVED
Synopsis

This project focuses on developing an ultrasonic water level sensor that can measure the level of water of any tank, big or small. The sensor measures the level non-intrusively in tanks with depth up to 10m with high accuracy at low power, using cheaply available transducers that are generally used for distances up to 4m. The sensor must be low-cost so as to be scalable, so that it can be plugged into a sensor network. Analytics on data collected by a network of such a sensor can provide insight into the water balance of a distribution network and potentially detect leaks and anomalies. This report discusses end to end design of this sensor, from characterising the transducers to developing the transmission circuit and analog front-end, to the algorithms and industrial design.
Acknowledgements

First and foremost, we thank our advisor, Prof. Bharadwaj Amrutur, for giving us an opportunity to do this project under his patient guidance. We will be forever grateful to him for his encouragement, counsel and pragmatism, which has benefitted immensely both, this project, and us personally.

We sincerely thank our reviewers, Prof. Joy Kuri and Prof. T. V. Prabhakar, for their support and suggestions in improving this project through positive criticism.

We thank Robert Bosch Center for Cyber-Physical Systems for funding our project. We thank Alok Rawat, RBCCPS, for the design and manufacture of the prototype for the product.

We would like to express our sincere gratitude to Prof. Mohan Kumar, Sheetal Kumar and Anjana from Department of Civil Engineering, IISc, for their valuable suggestions and feedback through the course of this project.

Thanks are also in order to Ashwin Srinivas and Ninad Sathye, IBM, and Hiteshwar Rao, RBCCPS, for their insightful inputs during this project.

Sincere thanks are due to Pratik Jain and Mallikarjun Sunkenapally, our lab- and batch-mates, for their continued support towards the completion of this project.

We would like to thank our labmates, Viveka, Pushkar, Sagar, Bhargava, Kaushik and Manikanadan, for bearing with us through this project.

We thank all the teaching and non-teaching staff of DESE and ECE, as well as all students of M. Tech, DESE, for their kind support and constant encouragement.
Notations

- **WDN**: Water Distribution Network
- **NRW**: Non-Revenue Water
- **IoT**: Internet of Things
- **GLR**: Ground Level Reservoir
- **OHT**: Over-head Tank
- **BVD**: Butterworth-van Dyke Model
- **PZT**: Lead Zirconate Titanate
- **VCA**: Voltage Controlled Amplifier
- **LNP**: Low Noise Preamplifier
- **VGA**: Variable Gain Amplifier
- **LPF**: Low Pass Filter
Contents

Table of Contents ix

List of Figures xiii

1 Introduction 1
  1.1 Background . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 1
  1.2 Motivation . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 2
  1.3 Functional aspects . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 2
  1.4 User Survey . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 3
  1.5 Characteristics and performance . . . . . . . . . . . . . . . . . . . . . . . . 3
  1.6 User aspects . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 4
  1.7 Environment aspects . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 4
  1.8 Power supply . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 5
  1.9 Reliability . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 5
  1.10 Wish scope . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 5

2 Study 7
  2.1 Related work . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 7
  2.2 Functional concept . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 7
    2.2.1 Why ultrasonic? . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 7
    2.2.2 Principle of operation . . . . . . . . . . . . . . . . . . . . . . . . . . . . 8
    2.2.3 Case study: HC-SR04 . . . . . . . . . . . . . . . . . . . . . . . . . . . . 9
    2.2.4 Case study: Electronet Level Transmitter ULT-200 . . . . . . . . . . . 9
  2.3 Module study . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 11
    2.3.1 Transducers . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 11
      2.3.1.1 Deriving components of BVD Model . . . . . . . . . . . . . . . . . 12

ix
<table>
<thead>
<tr>
<th>Chapter</th>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2.3.1.2 Relation between power and frequency</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>2.3.1.3 Effects of transducer construction</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>2.3.1.4 Maximising power</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>2.3.1.5 Cross pick-up due to coupling</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>2.3.2 Measuring time of flight</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>2.3.2.1 Algorithms</td>
<td>20</td>
</tr>
<tr>
<td>2.4</td>
<td>Industrial design</td>
<td>21</td>
</tr>
<tr>
<td>2.5</td>
<td>Target scope</td>
<td>22</td>
</tr>
<tr>
<td>3</td>
<td>Design</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>3.1 Module partitioning</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>3.2 Hardware design</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>3.2.1 Transmitter</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>3.2.1.1 Excitation</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>3.2.1.2 Matching circuit</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>3.2.1.3 Complete transmitter circuit</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>3.2.2 Receiver</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>3.2.2.1 Amplifier</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>3.2.2.2 Envelope detection</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>3.2.3 Controller</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>3.3 Software design</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>3.3.1 Algorithm</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>3.3.1.1 Length and pattern</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>3.3.1.2 Gain and ignore</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>3.3.2 Sequence of operations</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>3.3.2.1 System operation</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>3.3.2.2 Measurement</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>3.3.2.3 Initialisation sequence</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>3.4 Industrial design</td>
<td>36</td>
</tr>
<tr>
<td>4</td>
<td>Engineering and fabrication</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>4.1 Hardware</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>4.1.1 Board Design</td>
<td>39</td>
</tr>
</tbody>
</table>
List of Tables

1.1 Target features of the sensor ........................................ 4

2.1 Specifications for HC-SR04 ......................................... 9
2.2 Specifications for Electronet Level Transmitter ULT-200 .......... 10

3.1 Gain, pulses and ignore versus distance ............................... 32

4.1 PCB Details ............................................................. 41
4.2 PCB Details ............................................................. 41

5.1 Experimental Results of ULT-200 ..................................... 51
## List of Figures

2.1 Block diagram .............................................. 8
2.2 HC-SR04 ......................................................... 9
2.3 ULT-200 ......................................................... 10
2.4 Butterworth-van Dyke model for transducer .................. 11
2.5 Easy model for transducer ................................. 11
2.6 Extended BVD model ........................................... 12
2.7 Extended BVD model used to simulate transmitter samples a. A and b. B .... 13
2.8 Extended BVD model used to simulate transmitter samples a. A and b. B .... 14
2.9 Power dissipated in resistances of BVD model of transmitter simulated in transmitter B in figure 2.7 ......................... 15
2.10 Input impedance curve of the receiver type B ................ 16
2.11 Simulated rise time of transducer voltage .................... 17
2.12 Experimental Rise time of transducer voltage ................ 17
2.13 Experimental results for number of cycles .................... 18
2.14 Experimental results for cross pickup between transmitter and receiver .... 19
2.15 Sample received waveform. X-axis: Time(s), Y-axis: Voltage(V) .......... 20
2.16 Correlation vector options .................................... 21

3.1 Block diagram of transmitter ................................. 24
3.2 Block diagram of excitation circuit ........................... 24
3.3 Matching circuit ................................................. 25
3.4 Series-Parallel Transformation ............................... 26
3.5 Circuit diagram of transmitter ............................... 26
3.6 Block diagram of receiver .................................... 26
3.7 Block diagram of VCA 2615 ................................. 27
3.8 Differential to single ended output ........................... 28
<table>
<thead>
<tr>
<th>Figure No.</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.9</td>
<td>Passive LPF</td>
<td>28</td>
</tr>
<tr>
<td>3.10</td>
<td>a. (1 525) b. (2 321)</td>
<td>31</td>
</tr>
<tr>
<td>3.11</td>
<td>Autocorrelation of a. Vector (1 434) b. Vector (2 311)</td>
<td>31</td>
</tr>
<tr>
<td>3.12</td>
<td>Flowchart: Sensor operation</td>
<td>33</td>
</tr>
<tr>
<td>3.13</td>
<td>Flowchart: Measurement</td>
<td>33</td>
</tr>
<tr>
<td>3.14</td>
<td>Flowchart: Initialisation Sequence</td>
<td>35</td>
</tr>
<tr>
<td>3.15</td>
<td>Level sensor mounting</td>
<td>36</td>
</tr>
<tr>
<td>3.16</td>
<td>Sensor mounted on tank</td>
<td>37</td>
</tr>
<tr>
<td>4.1</td>
<td>Board Layout a. Top layer b. Bottom layer</td>
<td>40</td>
</tr>
<tr>
<td>4.2</td>
<td>Fabricated Board a. Top layer b. Bottom layer</td>
<td>40</td>
</tr>
<tr>
<td>4.3</td>
<td>Assembled board</td>
<td>40</td>
</tr>
<tr>
<td>4.4</td>
<td>Timer A0 for transmitting 40kHz pulses</td>
<td>43</td>
</tr>
<tr>
<td>4.5</td>
<td>Timer A1 for setting sampling rate</td>
<td>44</td>
</tr>
<tr>
<td>4.6</td>
<td>Graphic User Interface</td>
<td>47</td>
</tr>
<tr>
<td>4.7</td>
<td>Installation on a tank</td>
<td>47</td>
</tr>
<tr>
<td>4.8</td>
<td>Clamping mechanism</td>
<td>48</td>
</tr>
<tr>
<td>4.9</td>
<td>Bottom view; transducers are shown</td>
<td>48</td>
</tr>
<tr>
<td>5.1</td>
<td>Histogram for short distances a. 180cm b. 240cm</td>
<td>49</td>
</tr>
<tr>
<td>5.2</td>
<td>Histogram for long distances a. 480cm b. 780cm</td>
<td>50</td>
</tr>
<tr>
<td>5.3</td>
<td>Scatter plot</td>
<td>50</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

1.1 Background

Around 1.2 billion people, or almost one-fifth of the world’s population, live in areas of water scarcity[1], and by 2025 water scarcity is expected to affect more than 1.8 billion people—hurting agricultural workers and poor farmers the most[2]. Inadequate sanitation is also a problem for 2.4 billion people—they are exposed to diseases, such as cholera and typhoid fever, and other water-borne illnesses. Two million people, mostly children, die each year from diarrheal diseases alone. Water scarcity is among the main problems to be faced by the World in the 21st century. Water usage has been growing at more than twice the rate of population increase in the last century, and, although there is no global water scarcity as such, an increasing number of regions are chronically short of water. [3]

The crying need for water conservation in our country is not unfamiliar to us. With a population of 1.2 billion, high temporal and spatial variability in water availability, and over-exploitation of surface and groundwater in recent years, the country is facing water scarcity in several parts.[4] And this will only worsen with time. Smallholder farmers in South Asia are particularly vulnerable—India alone has 93 million small farms. These groups already face water scarcity. Some studies predict crop yields up to 30 percent lower over the next decades, even as population pressures continue to rise.[2] Water security is linked to food security, which in turn is linked to energy.
1.2 Motivation

The SAC-PM Report for Technology Interventions in the Water Sector\[4\] from April 2014 states as one of it recommendations, a proposal for creation of templates for instrumentation of urban water distribution networks with sensors and control valves, and managed using a network management and control system for efficient and equitable distribution of water. The reason for this is that most of the urban Water Distribution Networks (WDNs) are poorly instrumented, badly maintained, and not monitored for their health or performance, which leads to the following problems:

1. Loss of water through leaks: Municipalities in India officially report that 30-35% water is lost in leakages.

2. Intermittent supply and disruptions in supply: Due to poor monitoring of the health of pipelines and lack of timely maintenance.

3. Inequitable distribution of water to customers.

4. Since the WDN is poorly instrumented and water supply is not metered, only a small fraction of the cost of water supply is recovered from customers. Non-revenue water (NRW) is estimated to be as high as 50% in India.

The report goes on to say that affordable safe water for all must be a national mission, with an emphasis on affordability. It also categorically mentions that a grand challenge is to develop sensors for water quantity and quality at personal, domestic, community and higher levels, and that real-time water quality monitoring at various levels, linked through wireless networks is an urgent need.

On a campus scale, the need for such a project is only stressed further by the recent shortage of water in the Institute due to erratic supply from the BWSSB\[5\].

1.3 Functional aspects

The project being proposed is a low-cost, low-power, non-intrusive water level sensor with a range of at least 8m.

At one level, a wireless network of these sensors can be then used to continuously log data from various nodes in the water distribution network and perform analytics, and at another level,
these analytics can be used to control various pumps and valves in the WDN to form a closed loop system. Such automation would be ideal in a country like ours to regulate the supply and purity of water being distributed and keep a check on leakage, water theft and ensure water security. The analytics on such a system can be used to keep track of the usage and wastage of water, demand and supply cycles and study the seasonal changes and topographic factors that affect water consumption in the country. Such data would also be extremely useful in promoting water conservation by providing first hand information of their footprint to consumers.

The existence of such a sensor in the market is not debated. But an integrated, low cost and easy to install solution is something that is lacking. Also, the low cost sensors presently available are either lacking in range, or are too expensive be be scaled extensively. Water supply boards need to spend a fortune on installing an integrated water quantity management system. With the evolution of the Internet of Things (IoT), a system designed with the flexibility to either plug into an existing infrastructure or support a new protocol would be a perfect fit.

### 1.4 User Survey

The choice of specifications of our sensor is based on our survey of the Karnataka Urban Water Supply and Drainage Board (KUWSDB) at Mysore. As part of the survey, we visited a number of GLRs and OHTs in Mysore and Mandya, and found that most OHTs have capacities between 200,000 and 1 million litres, with depths ranging from 4m to 6m. Some tanks have a dome at the top which adds an extra 1m. Among the GLRs, we found that though their capacity is much more than the OHTs, the heights do not exceed 6.5m and it is the diameter that is increased.

We can therefore safely assume that the maximum depth in tanks and reservoirs in the WDN is 8m.

### 1.5 Characteristics and performance

The target solution is a non-intrusive water level sensor with the following features:
The sensor should be a standalone encapsulation that can be installed under the lid of any overhead or ground-level tank without any constraints of housing, power supply or additional construction, and be capable of long stretches of operation without excessive maintenance. To realise this, it is essential for the sensor to be supplied by a power source that can be gated, so that standby power minimised.

1.6 User aspects

The solution needs to be as user-friendly as can be, so that the operator can be a layman with little or no technical know-how. This is a necessity, as distributed deployment of these units over a large geographical area would make it unviable for a technician to be always at hand. The unit will be easy to install with no permanent fixtures and yet be robust to withstand climatic variations.

The unit will be continuously operational and have a simple mechanism to change the batteries. It will be able to communicate the battery status with the server and notify when the battery is low. The aim is to ensure that maintenance is minimised, and even when required, a technician is not needed.

1.7 Environment aspects

To ensure that the deployment is safe to use and does not contaminate the water under operation, the installation is done on the lid of the tank, and the sensor is not kept in direct contact with the water. The level sensor is housed at the base of the lid, with the transducers looking downwards, perpendicular to the surface of water. The controller, communication and power circuitry can be mounted outside the tank.

### Table 1.1: Target features of the sensor

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Parameter</th>
<th>Range</th>
<th>Unit</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Level</td>
<td>0.1 – 8.0</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Accuracy</td>
<td>±0.1</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Mechanism</td>
<td></td>
<td>Ultrasonic</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Active Power</td>
<td>1.5</td>
<td>W</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Parameter</th>
<th>Range</th>
<th>Unit</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Level</td>
<td>0.1 – 8.0</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Accuracy</td>
<td>±0.1</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Mechanism</td>
<td></td>
<td>Ultrasonic</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Active Power</td>
<td>1.5</td>
<td>W</td>
<td></td>
</tr>
</tbody>
</table>
1.8 Power supply

Energy consumption is a major constraint for any sensor that aspires to plug into an IoT network. Our sensor consumes 1.5W for up to 100ms per reading, which is about 0.15J, in addition to the energy spent in the computation on the controller. Assuming 20mA consumption by the controller for a period of 5s at 3.3V, this burns 0.33J. The total energy thus consumed in making a measurement would be close to 0.5J. If the unit is powered by a battery pack of NiMH batteries with 4800mAh at 6V, which is 103.68kJ, and assuming the communication module and other peripherals also consume the same amount of energy per reading inclusive of standby power, we can collect 103680 readings in one full charge. If readings are collected every minute, the system works for 72 days. The life can be increased by coupling this with a solar panel.

1.9 Reliability

Since the solution is working in tandem with such a crucial lifeline as the water distribution network of a city, it is cardinal for it to be highly reliable. Apart from the periodic maintenance requirements of the sensors and batteries, the system must not have any down-time. It is therefore crucial to ensure that the industrial design is IP-65 compliant so that the operation sensor housed inside the tank is not hampered even if the water in the tank overflows and the enclosure is immersed. Our tests have shown that the transducers themselves are water tolerant and can continue to operate desirably once dried after an immersion.

1.10 Wish scope

The ideal system would be one which can not only monitor the balance of the water in the distribution network, but also detect anomalies in the network with respect to flow and leaks. It should be low cost and scalable, thereby allowing large scale deployments across the country to enable distribution agencies to optimally distribute drinking water and solve the problem of water scarcity on a global scale.
Chapter 2

Study

In this chapter we discuss the choices in designing the sensor, drawing comparisons with existing projects.

2.1 Related work

Earlier work done in DESE, IISc[6] on a similar system to develop a real-time water balance monitoring system at a campus scale is promising. It worked towards developing a similar solution as the one proposed here, but has room for improvement. For instance, the level sensors used in the said project used a level sensing off-the-shelf board that has a one-time programmable microcontroller, due to which its range was limited to an upper bound of 4m, which is sufficient for the tanks on campus, but distribution tanks in cities go up to 8m in depth.

Pipenet[7] is another water monitoring system, but is fairly intrusive as pressure-based level sensors are used, in order to save power.

2.2 Functional concept

2.2.1 Why ultrasonic?

The motivation behind developing ultrasonic level sensors is two fold. Firstly, alternative methods of water level measurement are intrusive, such as using a buoy or using pressure sensors[8] at the base of the tank, which is tedious to install and maintain at a large scale, and additionally
comes with the risk of contamination. Secondly, the easily available ultrasonic sensors in the market are either short on maximum distance[9], or are too expensive, thus giving rise to need for an affordable, easy-to-use ultrasonic water level sensor.

2.2.2 Principle of operation

The functional block diagram of a generic ultrasonic ranging application is shown in figure 2.1. The theory of operation of ultrasonic ranging is well known. Subjects whose dimensions are larger than the wavelength of the impinging sound waves reflect them; the echoes can be picked up by a transducer. If the speed of sound in the medium is known and the time taken for the sound waves to travel the distance from the source to the subject and back to the source is measured, the distance from the source to the subject can be computed accurately[10]. The advantage of going for ultrasound and not audio frequency is that it would make no audible sounds, and consequently, if tuned, be immune to disturbances from audio frequencies.

![Figure 2.1: Block diagram](image)

The ultrasonic frequency selected is 40kHz due to the low cost and ease of availability of 40kHz transducers. Additionally, at lower frequencies we would enter the audio range, and at higher frequencies, the demand on the circuitry, controller and ADCs would go up.
2.2.3 Case study: HC-SR04

The ultrasonic sensor used in the implementation by Vignesh Kudva et al. [6] is the HC-SR04 [9], which has specifications as shown in Table 2.1.

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Parameter</th>
<th>Range</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ranging Distance</td>
<td>2 – 400cm</td>
<td>Resolution 0.3cm</td>
</tr>
<tr>
<td>2</td>
<td>Voltage</td>
<td>+5Vdc</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Current</td>
<td>15mA</td>
<td>Working</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt; 2mA</td>
<td>Quiescent</td>
</tr>
</tbody>
</table>

Table 2.1: Specifications for HC-SR04

As shown in figure 2.2, the HC-SR04 has four pinouts: VCC, GND, TRIG and ECHO. When the TRIG pin is excited with a 10µs pulse, the transmitter emits eight pulses at 40kHz. The onboard signal processing filters the signal received by the receiver and a one-time programmable controller on the HC-SR04 calculates the transit time and sends out logic high on the ECHO pin for a duration proportional to the distance. Half the round-trip distance thus obtained gives the distance from the sensor to the subject.

The drawback of the HC-SR04 is clearly the limitation on the distance of ranging, since our application requires a range up to 8m.

2.2.4 Case study: Electronet Level Transmitter ULT-200

Electronet Level Transmitter ULT-200 is a 2 wire transmitter specially designed for non contact type level measurement. It comes with single transducer which acts as transmitter and receiver.
of ultrasonic waves alternatively. The transducer used in this device are highly directional (beamwidth < 8°) in comparison to transducers used in HC-SR04 which have 30 beamwidth. ULT-200 provides 4-20 mA DC continuous output with local indication through LCD. It supports HART for communication. The measuring range is available from 0.6 to 8 m. It has specifications as shown in Table 2.2.

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Parameter</th>
<th>Range</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ranging Distance</td>
<td>60 – 800cm</td>
<td>Resolution 0.1cm</td>
</tr>
<tr>
<td>2</td>
<td>Voltage</td>
<td>+24Vdc</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Current</td>
<td>20mA</td>
<td>Working</td>
</tr>
</tbody>
</table>

Table 2.2: Specifications for Electronet Level Transmitter ULT-200

It can be concluded from the table 2.2 and the figure 2.3 that ULT-200 is industry standard product in terms of accuracy and industrial design.
2.3 Module study

2.3.1 Transducers

The most basic equivalent circuit model characterizing a piezoelectric ceramic near the resonant frequency is the Butterworth-van Dyke (BVD) Model\cite{11} as shown in Figure 2.4, where $C_0$ represents static capacitance, $R_s$ represents mechanical and acoustic dissipation, $L_s$ represents mass and $C_s$ represents flexibility.

This model works reasonably well near resonant frequency\cite{12}. $C_0$ is not directly related to material constants. It is required in our case for filter applications since represents the electrostatic capacitance of the piezoelectric transducer. $R_s$ models energy dissipation in the transducer. Power consumed across this resistor gets converted into the transmitted acoustic energy with some loss.

![Figure 2.4: Butterworth-van Dyke model for transducer](image)

Another form of the van Dyke model is the so called Easy Model\cite{13} as shown in figure 2.5. The values of the electrical elements in this model can be determined by using the plots for resistance and reactance versus frequency, and impedance and phase versus frequency.

![Figure 2.5: Easy model for transducer](image)
2.3. Module study

When the piezoelectric ceramic is mounted with mechanical boundaries, it is considered to be a loaded transducer, and its values for $R_s$, $L_s$ and $C_s$ get changed and exhibit multiple resonant frequencies. To model multiple resonant frequencies in the BVD model, a number of series RLC branches, equal to number to the number of resonant frequencies, have been added in parallel with $C_0$. To accommodate this effect, parallel RLC branches connected across $C_0$ can be considered to be an extension of the BVD model[13]. In characterizing the transducers, RLC values for the various branches have been determined from experimental graphs, and compared with simulated waveforms of the equivalent circuit.

![Figure 2.6: Extended BVD model](image)

2.3.1.1 Deriving components of BVD Model

The procedure to derive the discrete components of the BVD model for a particular transducer are discussed here. Values of various components in the BVD model can be determined from impedance versus frequency curve[14]. At frequencies well above the resonant frequencies, $R_s$, $L_s$ and $C_s$ have negligible influence on the impedance curve, and the impedance equals $C_0$. At series resonant frequency, $L_s$ and $C_s$ cancel each other out, and the impedance equals the parallel combination of $R_s$ and $C_0$. So, $R_s$ can be easily calculated since $C_0$ is known from the impedance versus frequency curve.

The equations for the resonant frequencies are:

Series resonance, $\omega_s = \frac{1}{\sqrt{L_s C_s}}$

Parallel resonance, $\omega_p = \frac{1}{\sqrt{L_s C_{eq}}}$ where $C_{eq} = \frac{C_0 C_s}{C_0 + C_s}$

As there are two unknowns and two equations, L and C values can be found easily. For different pairs of resonant frequencies, different R, L and C values are calculated. In our experiments we found two or three resonant peaks depending on the transducer. At one time only one RLC
branch is considered and others are neglected. As highlighted in [14], this method doesn’t work
when two resonant peaks are very close to each other, because in that case the series resonant
frequency of second peak would be ambiguous. In our low-cost transducers, the peaks lie
around 40 kHz and 52 kHz. We used two different transducers and obtained the following plots
through experiments in the Center for Nano Science and Engineering, IISc.

Figure 2.7: Extended BVD model used to simulate transmitter samples a. A and b. B
2.3. Module study

2.3.1.2 Relation between power and frequency

We now discuss the relation between the frequencies at the troughs obtained in the graphs in the previous subsection and the power transmitted at those frequencies. The impedance curve of the PZT shows two troughs and deals with only the electrical properties of the transducer. Some part of electrical energy dissipated across the resistor gets converted into acoustic waves. It would be wrong to assume from the curves that the power emitted by transducers at their multiple series resonant frequencies are proportional to the power dissipated in their respective branches.

What we demonstrate in this section is that just because there are multiple series resonant frequencies does not necessarily imply that there are multiple frequencies with maximum acoustic power dissipation.
The simulated graphs clearly show that power dissipated in resistors at their respective series frequencies is almost equal. But, if we test the transmitters for the received power by measuring voltage across the receivers, the power curve shows a bell shaped plot around the 40kHz excitation frequency. It can be said that the receivers are optimized for 40kHz and therefore they receive maximum signal strength at this frequency only. The problem, though, with this reasoning, is that when the receivers are characterized using same procedure as that used for the transmitters, it has been found that the receivers also exhibit multiple resonant frequencies.
2.3. Module study

We see clearly in figure 2.10 that the receiver also has two resonant peaks. This curve guarantees that the signal strength received across the receiver should also show some variation, rather than continuous tapering off on both sides of 40kHz like a bell shaped curve, even if it is assumed that the transmitter is emitting same power at both of its resonant frequencies.

It can, therefore, be safely assumed that there is no direct correlation between the electrical characteristic and the power transmitted or received, and that mechanical factors of the transmitter, or the receiver, or both come into picture when it comes to power. The authors speculate that the reason for this effect may be a difference in efficiency of electrical to mechanical energy conversion at different resonant frequencies.

2.3.1.3 Effects of transducer construction

A piezoelectric transducer is basically a two plate capacitor whose plates vibrate when a voltage is applied across it. Since it has mass, it has inertia, which results in finite acceleration. So, sudden changes in voltage across the transducer do not result in a sudden change in the mechanical motion of the plates of the transducer. It can be said that no matter which waveform is applied to the transducer, it generates a sinewave only. Therefore, while exciting the transducer, a sine wave has to be used across the transducer to minimize any sudden voltage.

While simulating and testing with ultrasonic piezoelectric transducers, we found that transduc-
ers take some time to reach peak signal strength. This has been found by measuring signal strength at the receiver, which shows an increasing sine wave whose amplitude gets saturated after a few cycles. The BVD model of transmitter shows this effect in simulation. This effect can be attributed to mechanical nature of the piezoelectric transducer. Vibrations in piezoelectric transducers take some time to build up due to inherent inertia present in any material which possesses mass. Overall, though, this slow rise effect cannot be attributed to solely the transmitter, since the receiver is also a piezoelectric transducer. Therefore, the total rise in signal strength at the receiver is a result of the inherent inertia of both the receiver and transmitter. This effect can also be seen by BVD model simulation. The simulation in figure 2.11 clearly shows that the transmitter takes some cycles to get to its maximum peak.

Figure 2.11: Simulated rise time of transducer voltage

Experimentally, we obtain very similar results, as shown in figure 2.12.

Figure 2.12: Experimental Rise time of transducer voltage
2.3. Module study

2.3.1.4 Maximising power

To maximize the signal strength received at the receiver, the voltage across the transducer can be increased. But increasing the voltage beyond a certain point does not improve the received signal strength a lot. We find that in our transducers, this voltage is around 30V. Increasing the number of pulses transmitted, on the other hand, significantly improves the received signal strength after voltage has been increased. To pick up signals at distances more than 5m, we require many more cycles as received signal strength degrades rapidly.

![Figure 2.13: Experimental results for number of cycles](image)

In figure 2.13, the first image shows received signal for transmission of 5 cycles at 10V. The second image is for 5 cycles at 20V, and the third is for 30 cycles at 20V. We can see by comparing the first two images that increasing the voltage across the transmitter does not significantly increase the received energy. On the other hand, we can see from the latter two images that increasing the number of cycles, keeping the voltage applied to the transmitter constant, increases the received energy significantly.

The problem with more number of cycles is that ranging accuracy decreases significantly with the number of cycles, as shall be discussed in subsequent chapters. The received signal takes the shape of an amplitude modulated signal with a carrier sine wave of frequency 40kHz, and a message that resembles a half sinusoid whose length and amplitude are related to the number of cycles of excitation and the voltage across the transducer. In ranging calculations, it has been assumed that the end of transmission phase is equivalent to the maximum amplitude point in the received signal. This assumption can be verified with the simulation of the transducer.
2.3.1.5 Cross pick-up due to coupling

As we can see in figure 2.14, due to coupling between the transmitter and receiver which are placed next to each other, the receiver picks up a signal even as the transmission is in progress. This problem is aggravated at large distances, as high gain of the amplifier amplifies the cross pickup too. To mitigate this problem, we introduce the concept of 'adaptive ignore' in our algorithm, which ignores some portion of the received signal depending on the gain setting.

![Experimental results for cross pickup between transmitter and receiver](image)

Figure 2.14: Experimental results for cross pickup between transmitter and receiver

2.3.2 Measuring time of flight

The final leg of the ultrasonic level sensor development is to accurately measure the time of flight of the sound waves to determine the water level. The challenges here are picking up attenuated echoes that have amplitudes close to the noise floor. This can be achieved in two stages: first, by amplifying the signal at circuit level, and second, by implementing robust algorithms to identify the echo of interest. Once this echo is identified, obtaining the distance is just a matter of multiplying the time of flight and speed of sound. Another challenge is determining the sampling rate and resolution of the ADCs. This is governed by a number of factors, including, but not limited to the desired accuracy, the computational prowess and memory on the controller and the frequency to be picked up in the signal.

The amplitude of the received signal by the ultrasonic microphone is too low to be interpreted directly. An amplifier is needed, but if the gain is high, the amplifier will saturate if the reflecting surface is close to the transmitter, and if the gain is low, the amplifier will not amplify the
signal above the noise if the reflecting surface is too far. A low noise preamplifier (LNP) will be used to reduce input noise voltage and input current noise to exceptionally low levels.

### 2.3.2.1 Algorithms

A sample output of the received signal is shown in figure 2.15. Ten pulses of a square wave of peak magnitude 20V at 40kHz were transmitted at t=0, which is not shown here, and reflected off a surface close to 4m away in the Anechoic Chamber in Department of Electrical Communication Engineering, IISc. The echo was received by the receiving transducer and the waveform shown in figure was obtained at the output of a simple fixed gain amplifier. It is important to note that the peak right after t=0s is due to pickup from the transmitter directly by the receiver, as explained in section 2.3.1.5 and can be ignored.

![Figure 2.15: Sample received waveform. X-axis: Time(s), Y-axis: Voltage(V)](image)

If we observe the plot after t=0.05s, we see that the signal and noise have not much difference in magnitudes. In this particular case, though, the echo of interest is the visible peak at around 24ms. Therefore, the simplest method would be to simply take the peak to imply the echo of interest. This may not necessarily be true in a real world scenario as noise might cause peaks at uninteresting times.

A second approach would be to set a threshold, and use a comparator to monitor the duration the signal goes above the threshold for. In this case, the duration for which the signal goes above the threshold the longest can be understood as being the echo of interest. Although this
method would work fine in most cases, we need to ascertain if it is robust for operation in tanks.

A third approach would be to use correlation to determine the echo of interest. Implementing this would mean cross correlating the received signal with that transmitted. An important question to answer here is which signal do we use as the correlation vector? The square wave that is transmitted (figure 2.16a) or a reference received signal[15] (such as an idealised echo)(figure 2.16b)? Or can we use the envelope of the signal which requires much lower ADC sampling rates, and consequently much simpler correlation?

One way to improve the correlation accuracy is by transmitted a coded signal and correlating with this coded signal. We shall see in the next chapter that using an envelope of the signal with a coded signal gives the best results for minimum computational overhead.

2.4 Industrial design

The housing for the sensors is both ergonomic and aesthetic. Given the modular nature of the design, the deployment essentially consists of three parts:

1. The level sensor is housed in a small box connected by wire to the main box. This is fastened to the bottom of the lid of the tank so that operation is possible even with the lid closed, and maintenance is easy. The box is sealed to make it IP-65 so that operation is not hindered even if the tank overflows, and to ensure water doesn’t get in contact with the circuitry enclosed.

2. The main box, which is shaped as a 3-sided rounded-edged prism, such that every side of the prism is occupied by either the microcontroller, or the battery bank, or the power
module. An antenna to improve communication is extended out from the top. This box is water-tight and dust-tight to allow for deployments on tanks in remote areas with no protection from rain and other climatic forces.

For prototyping, the box is manufactured in a rapid prototyping machine, but for large scale deployment we use plastic.

2.5 Target scope

The target deployments for the solution include is to intrument all the tanks in the IISc campus to visualise the usage and usage patterns in a small scale real-time environment, having deployments on ground level reservoirs (GLR) and overhead tanks (OHT). This can serve as a proof of concept for deployment at town and city scale.
Chapter 3

Design

This chapter goes through the design of the hardware and software of the sensor in detail.

3.1 Module partitioning

We divide our work into the following modules for the purpose of this chapter:

1. Hardware
   (a) Transmitter
   (b) Receiver

2. Software
   (a) Algorithm
   (b) Implementation

3. Industrial design

3.2 Hardware design

3.2.1 Transmitter

A block diagram of the transmitter circuit is shown below.
3.2. Hardware design

3.2.1.1 Excitation

The driver circuit chosen for the transmitter is a push-pull output driver (Totem Pole Output). Switch S1 supplies current and builds up the voltage and switch S2 takes current and removes the charge build up. These are switched alternatively at a time interval equal to the time period of the ultrasound signal (40kHz).

Using a matching circuit[16] solves two problems. Firstly, it increases the voltage across the transducer at resonant frequency. Secondly, it converts 40kHz square wave into a 40kHz sinewave. The reason for using the sine wave for excitation has been explained in the next
3.2. Hardware design

3.2.1.2 Matching circuit

An LC matching circuit[17] has been used for matching the transducer and switching network. Referring to figure 3.3, X1 and X2 are the matching components of the LC circuit. This has been chosen for its simplicity in terms of number of components. A potential error at this stage is that we may wrongly assume that we can use an equivalent Π type network, considering \( C_0 \) as one of its components, and keeping the component count same. However, the problem with this assumption is that this model is valid only near resonant frequencies and the value of the capacitor will not remain constant.

![Figure 3.3: Matching circuit](image)

X1 and X2 can be derived through some simple network transformations assuming that source has impedance of 50 Ohm. The applicable equations for obtaining the matching impedances are:

\[
X_a = \frac{-(R_s^2 + X_s^2)}{QR_s + X_s} \quad \text{and} \quad X_b = QR_L - X_L
\]

where Q is defined by:

\[
Q = \pm \sqrt{\frac{R_s[1+(X_s/R_L)^2]}{R_L}} - 1
\]

where \( R_s \): Source resistance

\( X_s \): Source reactance
3.2. Hardware design

Referring to figure 2.4, \( R_L \) and \( X_L \) are the equivalent series resistance and reactance (figure 3.4) of the circuit at the series resonance frequency where \( L_s \) and \( C_s \) effectively cancel each other.

### 3.2.1.3 Complete transmitter circuit

Concluding from the discussions in the subsections above, we obtain the final circuit for the transmitter as below:

![Figure 3.5: Circuit diagram of transmitter](image)

3.2.2 Receiver

The block diagram of the receiver is shown below.

![Figure 3.6: Block diagram of receiver](image)
3.2.2.1 Amplifier

The heart of the receiver is the Texas Instruments’ chip VCA2615. It is a voltage controlled amplifier (VCA) consisting of a Low–Noise Preamplifier (LNP) and a Voltage Gain Amplifier (VGA). This combination, along with few other features, makes this well suited for ultrasonic ranging applications.

The LNP gain can be programmed to one of four settings: 3dB, 12dB, 18dB or 22 dB; while maintaining excellent noise immunity and signal handling characteristics. It also has provision to program input impedance to match with the receiver impedance. This active termination allows the user to closely match the LNP to a given source impedance.

The VGA follows linear-in-dB response, and its gain can be varied over a 52dB range with a 0.2V to 2.5V control voltage, $V_{CNTL}$, controlled by a digital potentiometer. It provides an internal clipping function where an externally applied voltage controlled by digital potentiometer sets desired clipping level. The next chapter describes the schematic and ICs used to exploit this chip.

![Figure 3.7: Block diagram of VCA 2615](image)

3.2.2.2 Envelope detection

Amplified output signal from the VCA is differentially signal, but the on-chip ADC on the MSP432 that we are using is single channel. So, we convert this differential signal to a single ended output as shown in figure 3.8. We use the TI’s quad op-amp, OPA 4228, for this circuit for its low noise characteristics.
This signal ended output is then sent to a passive RC filter, which can also be considered as AM demodulator. This RC filter performs two functions. One, it extracts the envelope of the received signal, and two, it acts as a low-pass filter. An active filter with high roll-off is not required as the sampling frequency we have selected is 200kSamples/s, and envelope of received signal has very low frequency spectrum, much less than 40 kHz. Aliasing is prominent only when spectrum of the signal lies beyond 100 kHz which is not the case here.

RC values are calculated using the following formula:

$$\frac{1}{\pi \times f \times B} > RC \gg \frac{1}{\omega_c}$$
3.3 Software design

3.3.1 Algorithm

The knobs in our hands for implementing a robust measurement algorithm are:

1. Length and pattern of transmitted pulses
2. Gain of VCA2615 by controlling $V_{CNTL}$

3. Ignore period in the data

Our primary aim is to get to the best accuracy in measurement of distance between the sensor and the water surface. To this end we control the aforementioned knobs in ways described below. As was discussed in the previous chapter, the number of pulses sent out and the encoded pattern in the transmission can help distinguish the signal from noise.

As was described in section 2.3.1, the inertia of the piezoelectric transducer causes some latency in the build-up of the signal that is transmitted and received. When the number of pulses transmitted are too low, the signal gets attenuated and cannot be picked up reliably by the receiver circuit. On the other hand, if the number of pulses are too high, the accuracy of measurement is affected adversely. This can be seen from some simple numbers. Let us assume one were sending out 100 pulses. At 40kHz, this would translate to 2.5ms, which at 340m/s as the speed of sound, yields $s = \frac{(340 \times 2.5 \times 10^{-3})}{2} = 0.425m$. This means that the transmitted signal, and by extension the received signal, would be as long as the equivalent of 0.2m and could potentially lower the accuracy of the sensor.

Similarly, if the gain of the amplifier is too low, reflections off the water surface are not picked up if the distance is too large. Conversely, if the gain is too high and the distance too small, the sound would reflect off the water surface and the tank surface multiple times and lead to erroneous readings. Therefore we require an algorithm to set the correct gain depending on the level of water in the tank.

The ignore period in the data serves a trivial purpose. We observed in section 2.3.1 that since the transmitter and receiver are placed adjacent to each other, there is some coupling between the two that causes the receiver to pick up some signal while the transmission is in progress. With increased gain, this coupling is also amplified. The ignore period is used to ignore this coupling in the initial samples, and is increased at higher gains.

3.3.1.1 Length and pattern

We first define a nomenclature for lengths and patterns for ease of discussion. We define any pattern of transmission by two numbers, $(x \ y)$, where $x$ denotes the multiplier for each element of $y$, and $y$ is a string of numbers which denote a pattern. To understand this, consider a pattern $(1\ 525)$ shown in figure 3.10(a). This is constituted of $5 \times 1 = 5$ pulses of transmission, followed by $2 \times 1 = 2$ pulses of no transmission and again by $5 \times 1 = 5$ pulses of transmission. Similarly, we
show a pattern (2 321) in figure 3.10(b).

We experimented with a number of patterns for transmission and performed correlation on them. Two patterns that we mention here are (x 434) and 5-bit Barker codes (x 311)[18]. A reasonable measure of the potency of these patterns is their autocorrelation output. Since our ADCs sample the envelope of the received signal, the correlation vector is taken as a vector that is 1 at all times when signal is being transmitted and -1 when transmission is paused.

Figure 3.11(a) shows the autocorrelation for vector (x 434). This vector has sharp tapering off from the central peak, but suffers from additional sidelobe peaks, which are a source for error after correlating.

We then tried using Barker codes. Barker codes or Barker sequences are a finite sequence of N values with the ideal autocorrelation property, such that the off-peak (non-cyclic) autocorrelation coefficients are as small as possible. Barker codes come in many lengths, from 5 to 13 bits.
As we can see in figure 3.11(b), the 5-bit Barker code has a very sharp peak and gives desired accuracy when used in our application. We therefore use the 5-bit Barker code for transmission.

### 3.3.1.2 Gain and ignore

Depending on the distance, we adjust the gain of the VCA and number of pulses transmitted. We also control the ignore distance, as explained in section 2.3.1.5. The ignore distance limits the minimum distance can be measured by the transducer, and is therefore lowered when the gain is low and increased at high gain. Table 3.1 shows the values of gain, pulses transmitted and ignore distance for different distances that is used as a look-up table by the controller. The table uses $V_{CNTL}$ as a measure of gain (see section 3.2.2.1). The number of pulses can be interpreted as: If +1+1+1-1+1 is the pattern, 4 pulses are transmitted.

<table>
<thead>
<tr>
<th>Distance (cm)</th>
<th>Gain ($V_{CNTL}$)</th>
<th>Pulses</th>
<th>Ignore (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>0.8</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>120</td>
<td>1.0</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>200</td>
<td>1.2</td>
<td>16</td>
<td>10</td>
</tr>
<tr>
<td>300</td>
<td>1.5</td>
<td>16</td>
<td>60</td>
</tr>
<tr>
<td>400</td>
<td>1.6</td>
<td>16</td>
<td>60</td>
</tr>
<tr>
<td>500</td>
<td>1.7</td>
<td>16</td>
<td>60</td>
</tr>
<tr>
<td>600</td>
<td>1.9</td>
<td>24</td>
<td>60</td>
</tr>
<tr>
<td>700</td>
<td>2.1</td>
<td>24</td>
<td>60</td>
</tr>
<tr>
<td>800</td>
<td>2.2</td>
<td>24</td>
<td>60</td>
</tr>
<tr>
<td>900</td>
<td>2.4</td>
<td>24</td>
<td>60</td>
</tr>
<tr>
<td>1000</td>
<td>2.6</td>
<td>40</td>
<td>60</td>
</tr>
</tbody>
</table>

Table 3.1: Gain, pulses and ignore versus distance

### 3.3.2 Sequence of operations

#### 3.3.2.1 System operation

Figure 3.12 shows the flowchart for top-level operation of the sensor. Upon reset, the MSP432 initialise all the requisite peripherals: ADC, timer, GPIO, UART and I2C. After initialisation, interrupts are enabled and the microcontroller goes to sleep. Upon receiving wake-up signal, which can either be from RTC or received on UART or GPIO, the controller enables power to
the sensor board. A measurement is taken and communicated to the radio module, after which power is disabled to the sensor board and the controller goes back to low-power sleep mode.

Figure 3.12: Flowchart: Sensor operation

Figure 3.13: Flowchart: Measurement
3.3. Software design

3.3.2 Measurement

Figure 3.13 shows the flowchart of how readings are taken, and how the controller expects the water level to not change more than 40cm in one minute. If the change exceeds 40cm, the sensor is reinitialised (section 3.14).

3.3.2.3 Initialisation sequence

When the first reading is to be taken, or when the change in distance between successive readings is too drastic, the sensor goes through an initialisation sequence to measure the distance. For a normal measurement, the sensor takes the reading once, or in some cases twice. The one-time initialisation sequence takes between 5 and 11 (or more in exceptional cases) to measure the distance. The reason for this latency is that during initialisation, the previous value of distance is unknown/incorrect. Therefore, the sensor does not know the correct value of gain and pulses to be set for the measurement.
Figure 3.14: Flowchart: Initialisation Sequence
3.4 **Industrial design**

The industrial design of the sensor enclosure is discussed in this chapter, in accordance with the constraints discussed in section 2.4.

The enclosure is mounted on the tank as shown in figure 3.15. The design is such that the controller board sits outside the tank in the 3-sided prism, as shown. The batteries, communication chip and power board can also be housed in the same box.

The ultrasonic sensor is placed in the smaller box inside the tank. The design of this box is such that it always aligns itself perpendicular to the water surface under the influence of gravity. Two cavities are provided at the bottom of the box for the transducers to face the water. The ultrasonic sensor board is placed inside the box and connected to the controller with a 3-wire power cable and a standard 14-wire ribbon connector. The design of the clamp is such that the wires can pass through without hindering the closing of the lid of the tank.

![Figure 3.16: Level sensor mounting](image)

Figure 3.16: Level sensor mounting
Figure 3.15: Sensor mounted on tank
3.4. Industrial design
Chapter 4

Engineering and fabrication

4.1 Hardware

4.1.1 Board Design

The sensor board is designed and fabricated. During design, the following issues were mitigated:

1. The MSP432 operates at 3.3V, whereas the VCA2615 operates at 5V. This is resolved by using a 4-channel level translator, TI TXS0104. The advantage of this IC is that it can translate open-drain signals as well, which is required for I2C level translation.

2. The gain of the VCA2615 is controlled by varying the voltage to the $V_{CNTL}$ pin. This is achieved by using a 100k digital potentiometer, TI TLP0102.

3. We provided a standard 14-pin ribbon connector from the sensor board to the controller board, which includes the control pins for the various ICs on the sensor board, the TX signal for transmitting the desired pulse pattern at 40kHz, and an analog signal, shielded by GND and VCC lines, to the ADC on the controller.

The circuit was designed with all the ICs and connectors were provided for the transducers to fit on to the sensor board. The reasoning is that the transducers can be replaced easily without changing the sensor board.
4.1. Layout

Figure 4.1: Board Layout a. Top layer b. Bottom layer

4.1.3 Final board

Figure 4.2: Fabricated Board a. Top layer b. Bottom layer

Figure 4.3: Assembled board
4.1.4 PCB Details

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Board Dimensions</td>
<td>40mm × 60mm</td>
</tr>
<tr>
<td>Component Size</td>
<td>0603</td>
</tr>
<tr>
<td>IC Packages</td>
<td>48-TQFP, 14-SOIC, 14-TSSOP</td>
</tr>
<tr>
<td>Layers</td>
<td>2</td>
</tr>
<tr>
<td>Track width</td>
<td>12mils</td>
</tr>
<tr>
<td>Via drill diameter</td>
<td>16mils</td>
</tr>
<tr>
<td>Board thickness</td>
<td>1.6mm</td>
</tr>
<tr>
<td>Copper thickness</td>
<td>35µm</td>
</tr>
<tr>
<td>Finishing</td>
<td>HASL</td>
</tr>
</tbody>
</table>

Table 4.1: PCB Details

4.1.5 Bill of Materials

<table>
<thead>
<tr>
<th>Component</th>
<th>Quantity</th>
<th>Rate (INR)</th>
<th>Cost (INR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VCA2615</td>
<td>1</td>
<td>850</td>
<td>850</td>
</tr>
<tr>
<td>TXS0104</td>
<td>1</td>
<td>110</td>
<td>110</td>
</tr>
<tr>
<td>TPL0102</td>
<td>1</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>OPA4228</td>
<td>1</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>Pair of transducers</td>
<td>1</td>
<td>85</td>
<td>85</td>
</tr>
<tr>
<td>Total capacitors</td>
<td>12</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>Total resistors</td>
<td>11</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>MMBT4401</td>
<td>3</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>MMBT4403</td>
<td>1</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>660µH inductor</td>
<td>1</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Jumpers and connectors</td>
<td>-</td>
<td>-</td>
<td>20</td>
</tr>
<tr>
<td>Board manufacture</td>
<td>1</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
<td>1807</td>
</tr>
</tbody>
</table>

Table 4.2: PCB Details
4.2 Software

The TI MSP432P401R microcontroller[19] is used and development done on the LaunchPad board. Code Composer Studio is used for programming in C, and an on-board TI XDS110 is used for debugging. A GUI is designed in Python2 that communicates with the controller over UART for testing the sensor.

4.2.1 Clock System

The MSP432 provides for multiple clock sources and distributions, and can operate up to 48MHz. For our application, the clock frequencies are governed primarily by the frequency required to operate the ADC at 200 kilo-samples per second. We require around 100 clock cycles for each 14-bit ADC conversion, including overheads, sampling period and conversion period. Assuming 120 clock cycles, we obtain the frequency for operation as $200k \times 120 = 24\text{MHz}$. MCLK is the master clock that is given to the core, and SMCLK is the sub-system master clock which is kept ON for peripherals to interrupt during low power modes. We set both these clocks to 24MHz using DCOCLK, which is the internal digitally controlled oscillator (DCO) with programmable frequencies.

4.2.2 General Purpose IOs

General purpose IOs are configured for digital outputs to the sensor and power boards. These include enable signals for the power supply and ICs on the sensor board, transmit signal for exciting the transducer and on-board LED. These GPIOs are programmed to maintain proper timing between enabling ICs and taking readings.

4.2.3 Timers

The MSP432 has four 16-bit timers/counters. We use two of these timers, one for transmitting 40kHz, and another for setting sampling rate of the ADC.
4.2.3.1 Transmitting 40kHz

TA0 is used for the transmission as shown in figure 4.4. The timer is triggered by SMCLK and divided by 8. Therefore, \( \text{timer}\_\text{clock} = \frac{24\,\text{MHz}}{8} = 3\,\text{MHz} \). TA0R starts counting from 0 on every tick of timer\_clock. To obtain pulses at 40kHz, TA0R must trigger at 80kHz and toggle the switching signal. The interrupt trigger is set to \( \frac{3\,\text{MHz}}{80\,\text{kHz}} = 37.5 = 37 \text{ timer}\_\text{clock cycles} \). Therefore, an interrupt is programmed such that every time it is serviced, the switching signal is toggled. The timer is enabled and disabled according to the pattern to be sent.

```c
/*ISR for transmitting at 40kHz. Ncyc is a global variable storing number of cycles. Pin P4.4 is the switching pin. */

#define toggleTX () P4OUT ^= BIT4
#define unsetTX () P4OUT &= ~BIT4

void TimerA0_0IsrHandler(void) {
    TA0CCTL0 &= ~CCIFG;
    if (Ncyc--)
        if (txr==1)
            toggleTX();
        else
            unsetTX();
    else {
        unsetTX();
        TA0CCR0 = 0;
    }
}
```

![Figure 4.4: Timer A0 for transmitting 40kHz pulses](image)
4.2. Software

4.2.3.2 Setting ADC sampling rate

Figure 4.5 shows the setup for sampling the ADC at 200ksps. SMCLK is selected directly as the timer clock, i.e. 24MHz. We do not use interrupts to trigger the ADC. Instead, we directly connect the internal signal from TA1 output to the ADC sampling input. TA1 is programmed to be a 200kHz square wave with 50% duty cycle. To do this, the timer is set to up-counting mode, with outmode as set-reset, which means that every time TA1R equals TA1CCR0, it is set, and every time it equals TA1CCR1, it is reset. Setting TA1CCR0 to \( \frac{24MHz}{200k} = 120 \) sets the frequency to 200kHz, and setting TA1CCR1 to 120/2 sets the duty cycle to 50%.

```c
/* Code snippet for setting Timer A1 to 200kHz*/
TA1CCTL1 = OUTMOD_3; // CCR1 reset/set
TA1CCR0 = 120; // PWM Period
TA1CCR1 = 60; // CCR1 PWM duty cycle
TA1CTL = TASSEL_SMCLK | MC_UP | TACLR; // SMCLK, up mode, clear TAR
```

Figure 4.5: Timer A1 for setting sampling rate

4.2.4 ADC

The MSP432’s 14-bit ADC is used for sampling the received signal. It is configured to be triggered by the internal signal from Timer A1, such that the it samples during the positive period of the signal (60 clock cycles), and the remaining period is used for conversion. Once the conversion is complete, the ADC interrupt is called and the reading is stored to the heap. Once all the data for 68ms is saved, TA1 is disabled and ADC triggering halts.

```c
NVIC_ISER0 = 1 << ((INT_ADC14 – 16) & 31); // Enable ADC interrupt in NVIC module
```
4.2. Software

ADC14CTL0 = ADC14SHS_3 | ADC14SSEL_2_SMLCK | ADC14CONSEQ_2 \ \ | ADC14ON;
// Sampling input from timer TA1CCR1,
// Sampling time equal to
// ON time of timer out, SMCLK,
// Continuous sampling on single channel,
// ADC14 on

ADC14CTL1 = ADC14RES_3 | ADC14PWRMD_0;
// 14−bit conversion results,
// regular power mode (since 14 bit)

ADC14MCTL0 |= ADC14INCH_14;
// A14 ADC input select; Vref=AVCC
ADC14IER0 |= ADC14IE0;
// Enable ADC conv complete interrupt

4.2.5 UART and I2C

UART is configured for debugging and testing the sensor by communicating with an interface.
I2C is configured for controlling the digital potentiometers on the sensor board for setting the gain.

4.2.6 Correlation

The function used for correlation is given below. In the (x 311) notation, cycles in the code
represents x, and pattern[] is a vector that contains {1,1,3}, i.e. 311 in reverse. nPat is the
number of elements in the pattern vector. data[] is a 32-bit integer 1-D array that stores the
readings from the ADC, and also the output after correlation.

#define BANK 13600 // Number of elements in data[]

void correlate(void) {
    uint16_t i, l;
As we can see, the operation is made up of only additions and subtractions, with no multiplication. This helps reduce the computation time of the correlated output.

4.2.7 User Interface

A user interface is designed in Python2 with Tkinter for graphics and Matplotlib for plotting. It communicates over serial with the controller and sensor, and provides a console to test the sensor for various conditions. It also has the ability to plot the data that is stored by the controller after sampling the received signal, with and without correlation. It also has a feature to plot histograms to test the accuracy of the sensor. A screenshot of the interface is shown in figure 4.6.
4.3  Industrial Design

The design discussed in section 3.4 is implemented in rapid prototyping, with the clamp fabricated in stainless steel.
4.3. Industrial Design

Figure 4.8: Clamping mechanism

Figure 4.9: Bottom view; transducers are shown
Chapter 5

Concluding remarks

5.1 Results

To test the accuracy of our sensor, we plot histograms of the measurements for known distances. We give priority to consistency in reading over correctness in value, because our test setup was prone to 3-4cm error in absolute distance measurement, but the setup was undisturbed during testing.

The methodology for these tests are as follows: the sensors were set up in a corridor and a large aluminium board was used as the reflector. The distance between the sensor and the board was fixed and held constant for the course of an experiment. Fifty readings were taken at every 60cm and histograms were plotted at each distance.

Figure 5.1: Histogram for short distances a. 180cm b. 240cm
5.1. Results

Finally, all the histograms were merged into a single scatter plot as shown in figure 5.3. The blue spots in this graph indicate the concentration of readings in an area. Clearly, accuracy is better at shorter distances. We conclude that our sensor has an accuracy within $\pm 1.5\%$ of full scale, with improved accuracy at shorter distances.

We can see erroneous readings at 600cm and 660cm in figure 5.3. These are caused due to some reflective surfaces present around 6m in our test setup, which were interfering with the echo signal. Such reflectors are not present in water tanks.

Further experiments was done at the IISc Swimming Pool to test the reflections off the surface of water. We found that our sensors performed as desired with the same accuracy as that observed with the aluminium board.
Experiments have been performed to compare our sensor to the industry grade sensor ULT-200 currently being used by civil engineering department, IISc. Experiment setup was exactly same as that used to test our sensor. The sensor gives readings on LCD mounted on it after taking into account the height of the tank and the placement of the sensor on the tank. Some calibration was done and difference in consecutive readings was tabulated in 5.1 to check the accuracy and precision of sensor as actual distances were 60 cm. Readings were taken every 60cm. Readings were very consistent, and seldom varied more than 1cm for a particular distance, though there were exceptions where it varied up to 2cm with no change in actual distance.

<table>
<thead>
<tr>
<th>Actual Distance</th>
<th>Measured Height</th>
<th>Delta</th>
<th>Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>730</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>180</td>
<td>665.6</td>
<td>64.4</td>
<td>0.3</td>
</tr>
<tr>
<td>240</td>
<td>595.3</td>
<td>70.3</td>
<td>0.5</td>
</tr>
<tr>
<td>300</td>
<td>526.2</td>
<td>69.1</td>
<td>0.5</td>
</tr>
<tr>
<td>360</td>
<td>459.4</td>
<td>66.8</td>
<td>0.5</td>
</tr>
<tr>
<td>420</td>
<td>392.4</td>
<td>67</td>
<td>1.5</td>
</tr>
<tr>
<td>480</td>
<td>322.8</td>
<td>69.6</td>
<td>1.5</td>
</tr>
<tr>
<td>540</td>
<td>255.5</td>
<td>67.3</td>
<td>2.0</td>
</tr>
<tr>
<td>600</td>
<td>188.4</td>
<td>67.1</td>
<td>1.0</td>
</tr>
<tr>
<td>660</td>
<td>121</td>
<td>67.4</td>
<td>1.0</td>
</tr>
<tr>
<td>720</td>
<td>49.9</td>
<td>71.1</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Table 5.1: Experimental Results of ULT-200

The results seem alarming when comparing the overall actual delta (720-120=600) to the overall measured delta (730-49.9=680.1). In other terms, it can be said that ULT-200 transmitter is quite precise compared to our sensors but not very accurate at long ranges.

5.2 Suggestions for next gen

1. More directional transducers can be used to get better accuracy in measuring distances.
2. Improved algorithms to detect and ignore false peaks completely, and to reduce computation time.
3. The system has been over-designed, and components can be replaced with cheaper alternatives to reduce cost.
These sensors can be installed across tanks in the campus for monitoring the water balance, and running analytics. Once these sensors prove their reliability on a campus scale, their deployment can be much more widespread, at all levels in the water distribution network.

Although the primary purpose of these sensors is to measure water level in tanks, they can also be used in other short-ranging applications.
Bibliography


