# Ultrasonic-based Sensor Fusion Approach to Measure Flow Rate in Partially Filled Pipes

Nuwan Munasinghe, Gavin Paul

*Abstract*—**Flow rate measurement in pipes is essential for many applications. Thus, there have been a variety of flow meters developed that incorporate different technologies. However, a typical limitation in flow meters is that the pipe must be full in order to get an accurate flow reading. In many cases, this is not possible for practical reasons. When the pipe is full, ultrasonic flow meters can calculate the flow rate using known properties of the pipe and fluid, namely the cross-section, propagation path and fluid sound velocity. However, when the pipe is only partially filled, the propagation path is unknown which leads to an inability to calculate the correct flow rate. This paper presents a cost-effective sensor fusion approach to extend the capabilities of transit time ultrasonic flow meters to handle such scenarios. The approach determines the propagation path using capacitance-based level sensing, combined with fluid velocities ascertained via an ultrasonic sensor, leading to a significantly more accurate estimation of flow rates. Experiments in low flow rate situations validated the efficacy of the proposed model, with a 92% reduction of mean error in the lowest water height when compared to a conventional ultrasonic flow meter.**

*Index Terms*—**Sensor fusion, ultrasonic sensing, capacitive sensor, flow rate, transit time, partial pipe, IoT**

## I. Introduction

THE measurement of liquid or slurry flow inside a pipe is important, which has led to the research and development of various flow meters to obtain the flow rate. Measuring the flow rate in a partially filled pipe is challenging because flow meters are generally calibrated based on an assumption that the pipe is full [1]–[3]. When this assumption is violated readings become erroneous. With the increasing prevalence of Industrial Internet of Things (IIoT), maintaining a constant understanding of a device state is essential. In devices through which material flows, such as boilers [4] and water desalination plants [5], measuring flow rate remotely is crucial to understand different operating conditions. This is particularly true in remote or dangerous locations, where direct human intervention is difficult.

Flow meters can be divided into two main categories: intrusive flow meters, in which the transducers are connected in-line with the flow; and non-intrusive flow meters where transducers are mounted externally without obstructing the flow. Examples of non-intrusive flow meters are ultrasonic flow meters, electromagnetic flow meters and optical flow meters, while turbine flow meters and paddle-wheel sensors are classified as intrusive flow meters [6]–[9]. The expected fluid and flow characteristics, such as temperature, pressure, velocity, conductivity, and viscosity, determine the type of flow meter that is most appropriate for a particular application.

Two measurements are required to determine the flow rate within the pipe: flow velocity and the cross-sectional area of the pipe. Transit time ultrasonic flow meters rely on the temporal difference between ultrasonic signals propagated with, and against, the fluid flow [10]. Apart from the inlets and outlets, the cross-sectional area of the flow through a level and uniform-diameter pipe can be assumed to be constant - the inner cross-sectional area of the pipe and the propagation path of sound is known. In filled pipes, the propagation path depends upon the selected method of attaching the transducer to the pipe (i.e. the “W”, “Z”, “V”, “N” methods) [11], which together with the time measurement, can be used by the sensor to internally calculate the flow rate. However, in partially filled pipes, both the propagation path and cross-sectional area are unknown. Thus, determining the flow rate accurately by exclusively using an ultrasonic sensor is infeasible.

This research is motivated by the need to accurately measure the flow rate in partially filled pipes used by the mining industry to transport slurry prior to the separation of minerals from the slurry. In particular, the flow rate of the slurry needs to be constantly monitored and controlled, so as to optimise the Gravity Separation Spirals (GSS), which process the slurry [12]. A mineral-sand and water mixture (i.e. slurry) is fed into the top of the GSS, and the separated minerals emerge from the bottom end. These GSS are shown in Fig. 1. It is important to remotely monitor the GSS operating conditions using low-cost, small Internet of Things (IoT) solutions [12]–[14]. But an outstanding challenge that is observed in the real world is that these pipes are inconsistently filled, and conventional flow meters provide inaccurate readings.

Industrial flow meters that utilise electromagnetic principles have already been developed to perform partial flow measurements using capacitance level sensors to determine the water height. The velocity of the flow is determined by the induced current when a conductive liquid flows through a magnetic field. One example is the TIDALFLUX 2000 flow meter [15]. Similar electromagnetic partial flow meters have developed by Toshiba and ABB automation company [16][17]. The main disadvantage of this type of flow meter is that it can only be used with conductive liquids [1][15]. Additionally, the weight of this kind of flow meters are high, and it is impractical to mount it on top of every GSS as an IIoT sensor.

Computer fluid dynamics simulations have been performed for partial flow using 2mm communication pipe [18]. But this

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(a)

(b)

Fig. 1: a) Gravity Separation Spirals (GSS) manufacturing facility. b) GSS bank installed in the field.

approach is inapplicable since adding additional pipe with such small a diameter will clog up with the slurry.

Another type of partial flow meter that has already been developed uses Doppler velocity sensor. In this setup, the sensor transmits an ultrasonic wave along with the flow, and it reflects from the particles travelling in the liquid. Then using the frequency difference, it is possible to calculate the flow velocity. In this method, an ultrasonic depth sensor has been used to measure the flow height inside the pipe. An example of this kind of flow meter is MACE XCi device [19]. The main disadvantage of this type of flow meter is it is required to have an insertion type transducer to measure the flow velocity. Since slurry is used in this specific application, the transducer might clog with deposited material, and then require maintenance. Another Doppler ultrasonic-based partial flow meter called 2150 Area Velocity Flow Module has developed which measure the liquid level using submerged pressure transducer [20]. For open channel partial flow measurements, various flow meters based on different Doppler methods have developed. FLO-DAR is based on Doppler radar velocity measurement [21] and LaserFlow flow meter is based on subsurface laser Doppler [22]. Although different types of commercial and experimental flow meters have been developed, due to various reasons, such as the range of unsupported pipe diameters, the high weight or the restrictive nature of the fluids, an appropriate solution has not been found for use in this specific application. Summary of different partial flow measurements techniques and their limitations are shown in Table I.

Various liquid properties like pressure in a given depth, buoyancy, electrical permittivity, the surface reflection of sound or light can be used as a measure of liquid height. And these properties are used to design various level sensors. Examples include displacer, capacitive probes, floats, and pressure sensors. All these sensors can be divided into two broader categories: contact type and non-contact type. Since there is no physical or chemical reaction with liquid, the non-contact sensors generally have a longer life expectancy [23].

One of the most common non-contact liquid height measurement technologies is the ultrasonic sensor. The main reason for this is such sensors are readily available, easy to install and contactless. However, these sensors are affected by the air temperature fluctuations as well as debris, ripples and floating foam [24]. To measure water levels in streams, ultrasonic sensors mounted inside pipes have been used by submerging the pipe vertically in the stream [25]. Similarly, radar-based level sensing can also be used to measure liquid height [26]. Another surface reflection-based approach uses laser triangulation to measure the liquid height [27].

Liquid height has also been measured using acoustics [28], whereby an acoustic sensor is connected to a small pipe, and the pipe is immersed in the water. Stationary waves are generated between the top of the pipe and the water level, and by analysing the frequency, the water height can be measured.

Image sensors are also used to measure water levels [29]. One limitation is that accuracy is affected by the lighting conditions. Y. Jaehyoung et al. [30] implemented a remote water level detection system based on edge detection.

In this application, the primary requirement of the liquid height measurement in the pipe is that it is not in contact with the liquid and is a long-lasting solution. Capacitance-based measurement is another method of liquid level measurement [31][32]. Bera et al. [33] proposed a capacitance-based level sensing method which can be used to measure conductive or non-conductive liquids in a metallic or non-metallic container. A capacitance-based liquid level sensor for tanks has been developed, with three capacitance sensors to eliminate environmental effects [34]. The main advantage of this method is that it can be used without calibration.

In many cases, a single sensor is unable to measure a particular quantity with the required accuracy or robustness. Sensor fusion is the process of augmenting sensory data from multiple sources to provide a better, more accurate or more reliable estimate than would be possible with individual sources [35][36]. Sensor fusion approaches have been used to combine data from multiple sensors so as to perform remote health monitoring/assessment and fall detection [37]. Sensor fusion has been used to improve the accuracy of the measurements as well. Fusing sensory data from three ultrasonic level meters and other sensors, researchers were able to accurately measure the flow rate in a Venturi channel [38].

In this paper, a methodology is proposed to determine the flow rate in the partially filled pipe using a transit time ultrasonic flow meter (TUF2000M) and a four-channel capacitance sensor (FDC1004). The specific contributions are:

- A method to determine sound propagation patterns inside pipes for different liquid levels.
- Implementation of a capacitance-based level sensor resilient to the environmental and liquid type changes.
- Using sensor fusion to improve the flow rate measurement accuracy compared to conventional flow meters.
- A proof-of-concept system to measure liquid levels in real-time and calculate the correct flow rate.

The remainder of the paper is organised as follows. First, Section II provides a mathematical background and describes the theory behind the work. Section III provides details of the experiments followed by analysis and discussion of the results, and finally, Section IV concludes the paper.

## II. Methodology

This section sequentially presents the theory. Firstly an explanation of how transit time flow meters work is provided, then the second section contains a description of how the

TABLE I: Comparative summary of partial flow measurement methods

| Technology | Examples | Accuracy (Error) | Limitations |
| --- | --- | --- | --- |
| Electromagnetic | TIDALFLUX 2000 [15]<br>Toshiba LF502 [16]<br>ABB FXP4000[17] | 1% full scale [15]<br>2% full scale [16]<br>3-5% of rate [17] | Only work with conductive liquids, Does not support small pipe diameters (70-100mm) required (⌀189mm [15], 150mm [16] and 212mm [17]), Heavy (40kg [15], 8kg [16] and 29kg [17]) |
| Velocity (Doppler ultrasonic), Depth (Ultrasonic) | MACE XCi [19] | 0.2-1% Full scale | Heavy (5kg), Insertion type transducer will clog |
| Velocity (Doppler ultrasonic), Depth (Submerged pressure transducer) | Teledyne ISCO 2150 [20] | 2% of reading | Submerged transducer will clog |
| Velocity (Doppler radar), Depth (Ultrasonic) | FLO-DAR AV Sensor [21] | 5% of reading | Heavy (4.8kg), Only works for open channel |
| Velocity (Doppler laser), Depth (Ultrasonic) | LaserFlow [22] | 0.5% of reading | Heavy (8.7kg), Only works for open channel |
| Using U-shaped communication pipe [18] | No commercial product | 2% of reading | The 2mm communication pipe will clog |

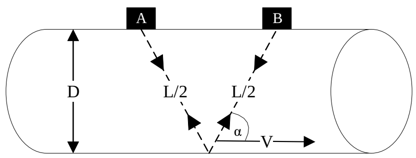



Fig. 2: V-method sound propagation pattern in a full pipe.

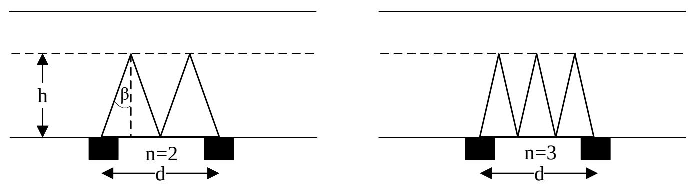



Fig. 3: Possible propagation patterns from the V-method in a partial pipe.

propagation path is determined with different water levels. The third section presents the implementation design of capacitance-based sensors to determine the water height, and the final section describes how water level, propagation path, and transit times from a flow meter can be used to calculate the correct flow rate in partially filled pipes.

### A. The Principle of Transit Time Flow Meters

Ultrasonic flow meters do not have any moving parts or cause any pressure drop when the flow is measured. Those are significant advantages when compared with some other flow meters like vortex, turbine, or orifice [39].

In these flow meters, piezoelectric transducers are used to transmit and receive acoustic pulses. Transducers can be mounted in different ways like the V-method, Z-method, W-method, and N-method [11]. In this research, the V-method, where both transducers are attached on the same side along the same line was chosen. In the V-method, when the pipe is partially filled, transducers can identify sound waves that are bounced back from the water surface as shown in Fig. 3. Additionally, the V-method is suitable for the size of the pipe that is being used in the proposed application where pipes have an inner diameter ranging from 15mm to 200mm [11].

In Fig. 2, A and B are the transducers, $D$ is the inner diameter of the pipe, $L$ is the total travel distance, $V$ is the velocity of the flow, and $\alpha$ is the angle between the sound wave and the flow velocity.

Consider $t_{up}$ as the propagation time of sound waves in an upstream direction and $t_{down}$ is the time for the downstream direction. When there is no flow, the difference between these two values are zero and when there is a flow, the travel time of the sound waves is affected by the flow velocity. Given that $C$ is the speed of sound in the liquid, the transit times in each direction can be calculated as,

$$t_{up} = L \ / \ (C - V\cos(\alpha)) \tag{1}$$

$$t_{down} = L \ / \ (C + V\cos(\alpha)) \tag{2}$$

$$V = \frac{L}{2\cos(\alpha)}\left(\frac{1}{t_{down}} - \frac{1}{t_{up}}\right) \tag{3}$$

$$\dot{Q} = AV \tag{4}$$

The speed of sound is constant for a given liquid at a given temperature, hence, (1) and (2) can be combined and it is possible to derive the equation (3) [40]. Since the pipe is full, the cross-sectional area, $A$ is known, and the flow rate can be calculated by using the equation (4).

### B. Determining the Propagation Path

From the (3), it is clear that to calculate the velocity of the flow, it is necessary to know the value of $L$, which is the distance ultrasonic waves must travel. When the pipe is full, this distance is known. Commercial flow meters are generally configured by entering the pipe diameter, pipe thickness, pipe material, and the liquid type, so it can calculate the recommended distance between transducers. Then the transducers are mounted according to that recommended configuration. However, when the pipe contains different liquid heights, this reflection pattern is unknown and different propagation patterns can occur such as those depicted in Fig. 3. In Fig. 3, $n$ is the number of peaks that can occur, and the horizontal dashed line is the liquid level, $d$ is the distance between transducers and $n$ is in the set of positive integers ($n \in Z^{+}$).

This propagation path can be determined numerically, and the goal is to find a pattern which contains an angle of incidence close to the angle of incidence when the pipe is full. By calculating the angle of incidence, $\beta$, then both $L$, and the travel time, $t$ can be calculated for different $n$ values.

$$\beta = tan^{-1}(d \ / \ 2nh) \quad (5)$$

$$L = 2nh \ / \ \cos(\beta) \quad (6)$$

$$t = L \ / \ c \quad (7)$$

It is possible to identify the propagation pattern by following the steps below.

1) Calculate $\beta$ for a full pipe using (5) where $n = 1$ and $h$ is equal to the inner diameter of the pipe.
2) For different liquid heights, $h$, change $n$ and calculate $\beta$.
3) For each liquid height, identify the $n$ which gives the least deviation for a calculated $\beta$ and a full pipe $\beta$.
4) $n$ gives the propagation pattern in that specific height.
5) Then $n$ is used to calculate the travel distance with (6) and the liquid velocity using (3).

The above steps can be run programmatically, and a comparison with the experimental results will be discussed in the results section.

### C. Measuring Liquid Height in Pipes

Once the liquid height is known, it is possible to determine the propagation pattern and eventually, the flow velocity. The height is required to calculate the flow cross-sectional area, which is required to determine the flow rate as per (4).

In this application, the slurry density and properties can change over time, and the height measurement should be independent of the liquid, and hence a capacitive height sensing technique has been selected. However, moisture in the air can significantly affect capacitance and when using different types of liquids; a single sensor would require calibration. Thus, a three-electrode design is proposed where measurements are independent of the air, liquid, and the dielectric constants of the container. Fig. 4 shows the arrangement of the three electrodes: the liquid electrode, the level electrode and the environmental electrode.

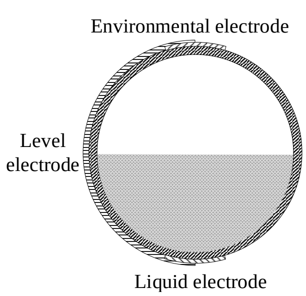



Fig. 4: Electrode placement around the pipe.

From [41] the liquid level height can be determined as,

$$Level = h_{ref} \frac{C_{Lev} - C_{Lev}(0)}{C_{RL} - C_{RE}} \quad (8)$$

where, $h_{ref}$ is the height in the desired units of the pipe, $C_{Lev}$ is the current capacitance in the level electrode, $C_{Lev}(0)$ is the capacitance of the level electrode when empty, $C_{RL}$ is the capacitance of the liquid electrode, and $C_{RE}$ is the capacitance of the environmental electrode.

This method has been used in this research to determine the liquid level in the pipe. Then, using the liquid level, it is possible to determine the propagation pattern as per the previous section. Additionally, by using (9), it is possible to calculate the cross-sectional area of the liquid.

$$A = \frac{D^2}{4} \cos^{-1}\left(\frac{D-2h}{D}\right) - \left(\frac{D-2h}{2}\right)\sqrt{Dh - h^2} \quad (9)$$

where, $A$ is the cross-sectional area of the liquid, $D$ is the inner diameter of the pipe, and $h$ is the liquid height.

### D. Determining Correct Flow Rate

By determining the liquid height using the capacitance-based method, the flow velocity can be calculated indirectly, and the cross-sectional area can be directly measured non-intrusively. The proposed sensor fusion design is shown in Fig. 5. This real-time data can be used to determine the flow rate of the pipe. This process is illustrated in Fig. 6.

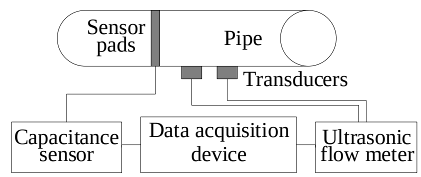



Fig. 5: Proposed sensor fusion design.

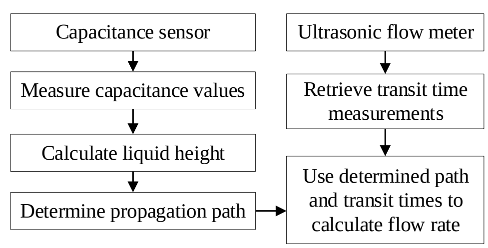



Fig. 6: Flow of determining the correct flow rate.

## III. Experiment Results and Discussion

This section presents the results of the experiments. Firstly, the overall experimental rig setup is introduced. Secondly, it describes results for identifying the ultrasonic propagation pattern with different water levels. Thirdly, the results of capacitance-based level sensing are presented, and finally, the results of flow rate measurement are presented for when the pipe is partially full.

### A. Experimental Rig Setup

A test rig has been developed as shown in Fig. 7c, which includes a 4m-long pipe and a pump to pump water into the pipe. The transducers of a TUF-2000M ultrasonic flow meter (shown in Fig. 7d) are connected to the pipe. This flow meter supports Modbus protocol [11] and a computer is connected to the flow meter, and real-time data is read using a python program. The details of the rig setup, including


(a) (b) (c) (d) (e)

Fig. 7: (a) Multiple layers of flexible PCB. (b) Flexible PCB after manufacturing. (c) Flow rate testing rig. (d) Ultrasonic flow meter. (e) Capacitance sensor testing with water level.

dimensions, are shown in Fig. 8. Transducers are mounted using cable ties and the flexible PCBs are mounted using tape. Transducer mounting locations are decided according to the manufacturer specifications by considering the water inlet and outlet locations. The flow meter setup software determined the transducer distance, ($d_1$) by entering pipe diameter, thickness, pipe material, liquid type and transducer mounting method (V-method). The transducer location, relative to the capacitance electrodes ($d_2$), was a convenient location near the transducers.

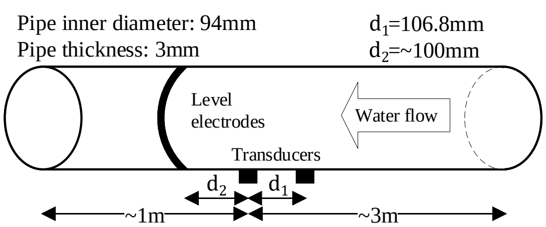



Fig. 8: Rig setup details.

### B. Identification of the Ultrasonic Propagation Pattern

The TUF-2000M transit time flow meter is used in this experiment. An acrylic pipe with a 100mm outer diameter and a thickness of 3mm is used. As per the previous section, in the first step the propagation pattern is identified to calculate the $\beta$ for a full pipe according to (5), so $\beta_{rad} = 0.51$ ($d = 106.8mm,\ n = 1,\ h = 94mm$).

Since the transducers and the transducer distance do not change with different water levels, the transducer will always transmit sound at this angle. Therefore, the actual propagation pattern, which will occur in the pipe at different water levels, should have a $\beta$ value that is similar to that of the full pipe. Furthermore, by calculating different $\Delta\beta$ values for different propagation patterns, it is possible to accurately predict the actual propagation pattern that occurs at that height. This leads to a calculation of the correct flow rate.

TABLE II: $\Delta\beta$ values for different $n$ and $h$

| Propagation Pattern | Water Height (mm) | | | | | |
|---|---|---|---|---|---|---|
| | *40* | *45* | *50* | *55* | *60* | *65* |
| 1 | 0.420 | 0.362 | 0.310 | 0.263 | 0.219 | 0.180 |
| **2** | **0.080** | **0.027** | **-0.017** | **-0.055** | **-0.088** | **-0.117** |
| 3 | -0.088 | -0.130 | -0.165 | -0.194 | -0.219 | -0.240 |
| 4 | -0.185 | -0.219 | -0.246 | -0.269 | -0.288 | -0.305 |

Table II shows the difference between angles as per step 2 in subsection II-B, which described how the propagation path is determined. The lowest deviation is highlighted in bold text. According to this calculated result, the propagation pattern is $n = 2$ for these water levels. In order to verify this result, the travel time is also calculated using (7) (Refer Table III) and compared with the measured travel time using an ultrasonic flow meter for the different water heights.

TABLE III: Calculated travel time (µs) for different $n$ and $h$

| Propagation Pattern | Water Height (mm) | | | | | |
|---|---|---|---|---|---|---|
| | *40* | *45* | *50* | *55* | *60* | *65* |
| 1 | 90.1 | 94.3 | 98.8 | 103.5 | 108.5 | 113.6 |
| 2 | 129.9 | 141.4 | 153.1 | 165.2 | 177.4 | 189.9 |
| 3 | 177.4 | 196.1 | 215.1 | 234.3 | 253.7 | 273.2 |
| 4 | 227.9 | 253.7 | 279.7 | 305.9 | 332.2 | 358.6 |

Table III lists the calculated travel time according to (7), and Fig. 9 illustrates the calculated results and measured results using an ultrasonic flow meter. From Fig. 9, it is clear that the measured travel time is slightly higher than the identified reflection pattern, which is $n = 2$. This is due to the thickness of the pipe (3mm) and the thickness of the transducers (18.9mm). The additional time for these distances is 10.245 µs. This error has been compensated for in the graph in Fig. 9. It can be seen that when this error is compensated for, the calculated and predicted pattern matches the measured travel time using the ultrasonic flow meter.

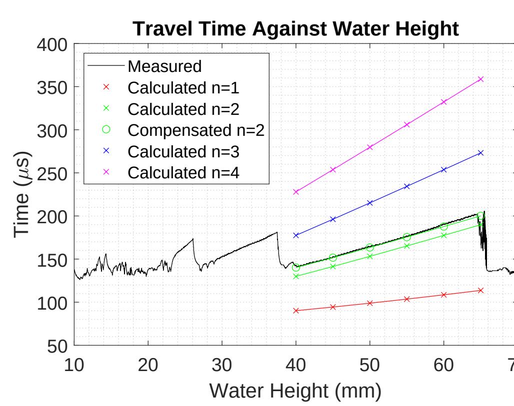
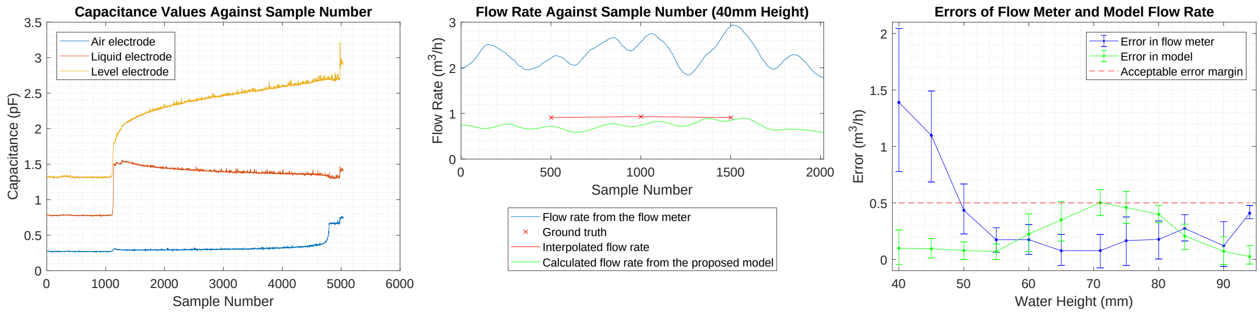



Fig. 9: Measured and calculated times for values of $n$ and $h$.




(a) (b) (c)

Fig. 10: (a) Raw capacitance values of three electrodes. (b) Flow rates at 40mm water height. (c) Errors in both the flow meter readings and the calculated model.

### C. Capacitance-based Liquid Level Measurement

A three-channel capacitance sensor is required to calculate the liquid level, which is connected to liquid, level, and environmental electrodes. A Texas Instrument FDC1004 4-channel capacitance sensor has been used for this purpose. This sensor is a high-resolution, 4-channel capacitance-to-digital converter with a full range of $\pm$15pF. This sensor also can handle up to 100pF sensor offset capacitance [41].

When measuring capacitance in the real-world, there can be interference from the environment. Therefore, the measuring electrodes should be adequately shielded. Since these electrodes should be wrapped around the pipe with shielding, a flexible Printed Circuit Board (PCB) with four layers was developed. The Out-of-Phase technique has been used to mitigate parasitic capacitance. In this technique, the potential of the liquid is kept at a constant value during the excitation phase by using a differential capacitive measurement [42]. The sensor layout used according to this method is depicted in Fig. 11, and there are three channels and two shield terminals.

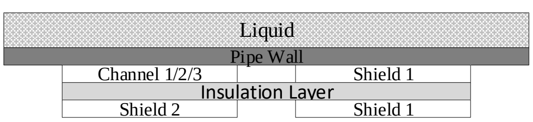



Fig. 11: Sensor layout: Out-of-Phase technique.

The top and bottom layers in the designed PCB are flexible insulation layers, and it has pads to solder on to. The middle layers contain electrodes and shields as shown in Fig. 7a. The figure also shows how the middle layer 1 contains channels and shield 1, While middle layer 2 contains shield 2.

Fig. 7b shows the top and bottom sides of the flexible PCB after manufacturing. On the left PCB (i.e. top side), the three electrodes in the middle layers are visible. The long electrode is the level electrode, and the shorter ones are used as environmental or liquid electrodes. The right PCB (i.e. bottom side) shows the shielding, which is also in the middle layer.

Fig. 7e shows how the level sensing method has been tested. The PCB was connected around the pipe and the pipe was filled with water. The capacitance values and water height are then measured continuously. The measured raw capacitance values are shown in Fig. 10a. The capacitance value from the level electrode shows an increasing trend while the other electrode values stay at a near-constant value after water filling begins. The sudden jump in the liquid and level electrode capacitance values, around sample number 1000, occurred when water filling started. Similarly, there is a spike when the pipe became full at around sample number 5000.

By using these raw capacitance values and (8), it was possible to calculate the water height. Fig. 12 shows the calculated height compared with the ground truth. In order to reduce noise and outliers, a moving average with a window size of 100 has been used. The ratio values from (8) can be normalised to be between 0 and 1 (i.e. empty and full). These results show that this method can be successfully used to estimate the water height in pipes with a maximum error around 10mm.

### D. Accurate Flow Rate Calculations

Since the water height can be determined robustly from the method above, the propagation pattern can also be identified. This is because the mapping between propagation patterns and different water levels are pre-calculated for a given pipe using the method described in Section II.

An experiment was conducted at different water levels, such that for each water level, the actual flow meter readings from the flow meter (blue line in Fig. 10b) are measured. The calculated flow rates (green line in Fig. 10b) are also calculated according to the proposed model and compared to the actual

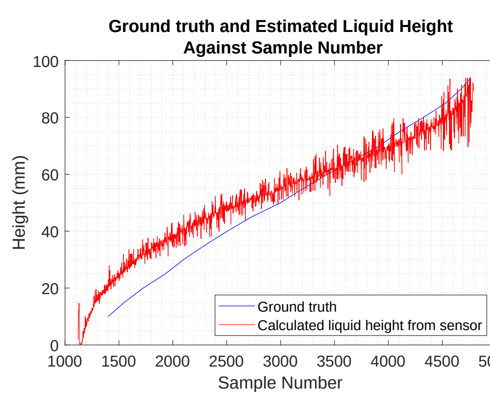



Fig. 12: Estimated liquid height and ground truth.

flow meter readings. The ground truth of the flow rate is measured by collecting the water during a certain amount of time and weighing it to get the volume of the water. This water collection and weighing has been done several times during the experiment (red "x"s in Fig. 10b) and interpolated to get the intermediate values (red line in Fig. 10b).

The test results for different water levels are summarised in Fig. 10c. This graph depicts errors compared to the ground truth. The top and bottom whiskers represent $q_3+w\times(q_3-q_1)$ and $q_1-w\times(q_3-q_1)$ where $q_1$ and $q_3$ are the $25^{\text{th}}$ and $75^{\text{th}}$ percentile and $w=1$. The middle value in whiskers represents the mean error value. The error bars show that the flow meter performs poorly when the flow is low. Also, there is a broader distribution in errors in flow meter at low levels compared to the model. In this application, the error needs to be less than $0.5\text{m}^3$/h. When the water level is at 40mm, the mean error from the flow meter is around $1.4\text{m}^3$/h while the calculated model gives a less than $0.1\text{m}^3$/h error, which is an around 92% error reduction. For practical reasons and limitations with the pump, it was not possible to generate a flow with less than 40mm height.

It is evident from the experimental results that the ultrasonic flow meter performs poorly when the water level is low. On the other hand, the proposed model performs within the accepted error margin when the water level is low. It is notable that there is a slightly higher error rate in the proposed model for water heights between 60mm and 80mm. However, the model error mean value is less than the maximum acceptable error ($0.5\text{m}^3$/h). In order to minimise the error rate, it is possible to switch between model-based and flow meter-based flow measurement when the liquid level is within certain predefined liquid height ranges. In this case, it would be possible to reduce the average error to $0.2\text{m}^3$/h for all water levels.

## IV. Conclusion

This paper has presented an inexpensive, easily extensible sensor fusion solution to improve the accuracy of transit time ultrasonic flow meters when there is a partial flow. Measuring the flow rate in a partially filled pipe in a non-intrusive manner is challenging. Commonly used transit time ultrasonic flow meters fail to provide readings with adequate error margin when the pipe is partially filled, and this error increases with lower water levels. This paper proposed a new method of extending transit time flow meters to give more accurate readings by measuring the water level of the pipe using an inexpensive, yet robust, capacitance-based level sensor. The paper also proposed a method to determine different ultrasound reflections patterns which occur inside the pipe with different water levels and has experimentally proven its accuracy in several different scenarios. Using the proposed equations and reflection pattern, it was possible to accurately calculate the flow rate even when the pipe is partially filled. An experiment was carried out to test this method, and it proved that this approach drastically reduces the error (i.e. from $1.4\text{m}^3$/h to $0.5\text{m}^3$/h)) when the water levels are low. Future work is to make the presented method more general and robust by investigating different mediums being pumped through the various pipe types at different gradients.

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