Development of a Low-Cost Device

To

Monitor Water Quantity and Quality in Water Tanks

By

Zhan Widdison

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Abstract

Water scarcity and quality/contamination is a key issue affecting the current climate of water security particularly with decentralized supply. The solution to this issue was to create a device that can track the water quantity and quality of individual water tanks. This device can enable further data collection and research into regional water security issues and can function as a confirmation for existing research in the impact of decentralised supply on a water network.

The purpose of this thesis was to develop a device that can achieve the monitoring of both these key issues while still being accessible to a broad range of users to aid in water security efforts. To ensure a relevant design, this thesis explores the literature surrounding hyperspectral imaging and more specifically underwater hyperspectral imaging. The thesis also goes into depth with methods used to measure water quantity and level with a focus on non-commercial methods.

Early development focused around using ultrasonic sensors and Sigfox communication to create a device that was being tuned to be a reliable method for water quantity collection. This was assessed in both lab environments and in situ at a local rural property. The device's quality sensor was created based on a hyperspectral point-scanning design and was designed as a separate entity to ensure both devices could function well as individuals.

The result was a functioning water level sensor that can attach to a water tank and returns level readings, with an error of 0.028% in a 25,000L tank, at 1-hour intervals per day for approximately 8 weeks, to a MAFDL server. Additionally, a hyperspectral device was developed that can show different wavelengths but needs extensive calibration to run correctly.

Keywords – Ultrasonic Sensor, Hyperspectral Imaging, Cyanobacteria, Water Tank Sensor, Sigfox, Urban Environment, Rural Environment.

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Chapter 1 - Introduction

Over the past 10 years, New Zealand has entered a state of severe drought five times, according to NIWA. This has led to large water usage restrictions and no easy or an economically feasible way for water tank owners to reliably keep track of water usage throughout the day. Therefore, there is no way to know if the decrease in water for each household is due to actual usage or possibly leaking pipes, with more than 100,000,000 cubic meters of water lost in the 2021 fiscal year due to leakages [1]. This is hard to gauge without constantly monitoring the tanks' water level or installing an expensive pressure/optical sensor. In addition, by not passively knowing the level of water in the tank, it is possible to run out of water and not be able to access potable water until the next water truck is available.

The accessibility of a low-cost water tank sensor would allow continuous data to be gathered around both urban and rural water use. This data would benefit both the user and the wider public as it would enable a proper water budget to be adhered to, and any water losses accounted for if they occur in water tanks. The affordability factor is important as the more users that exist, the better the net for information becomes. It also means that the users can respond to their water needs better and not have to go without water for periods due to overuse or natural depletion.

The quality and quantity of water that a household or business has is an important indicator of water security in a region. Water security is the reliable availability of water in acceptable quality and quantity for the use and development of a society. If the device can be installed in the houses of a region, it can identify regions of poor water quality and identify the potential need for water infrastructure maintenance. During the 2020-2021 period, there was a massive water leak in several new homes in Auckland [1] that could have been mitigated with an option to monitor the water usage and levels in houses. The existing options in the market are either low-quality and don't broadcast the water level or too expensive and would not be feasible for consumers who already have basic manual solutions. This gap in the market lends itself to the development of a new device.

The device being developed will not only be an affordable option to identify the water level, but it will also offer the ability to identify the water quality via a simple hyperspectral device. The multispectral device will focus on identifying algae due to both its potential harm when the cyanobacteria, a common alga that forms, is ingested and the fact that algae only forms when there are external factors like the water's exposure to direct sunlight or a nutrient-rich tank. These factors would both be indicators of poor water quality. The hyperspectral device would be able to identify algae as algae are known to fluoresce easily and can be identified without having contact with the tank water. This is novel as identifying water quality in the potable water for a household could reduce issues with bacteria forming and causing illness. Also, by combining it with a water level sensor, it is possible to deal with issues caused by varying distances to the water changing the response of the fluorescence.

The aim of this masters is to develop a system that can return the level of water in a water tank while also exploring the option of using a multispectral device to identify algae in water.

To meet the aim, the following objectives need to be achieved:

- Develop a device for detecting that is cost-effective and consumer-oriented the water level in a tank.
- Set up wireless communication of the device for remote monitoring.
- Field evaluating the device.
- Use a hyperspectral device to find algal bloom.
- Develop a low-cost multispectral sensor that can find the algal bloom.

However, to start developing the device it is important to get a wholistic view of what is currently used to identify each problem.

Chapter 2 - Literature Review

Water is a key resource in the world, whether it is used as a means of hydration or for hygiene purposes. The fact that clean potable water is necessary for day-to-day life is undisputed. 490,000 people or roughly 181,481 households in a mixture of urban, suburban, and rural environments, with the possibility of multiple tanks per household in more rural environments, use water tanks as the main supply of potable water [2]. The supply to these tanks can be supplied by a few methods namely: rainwater, water supply trucks, and aquifers/groundwater. There are several issues that arise when relying on a water tank such as their limited supply and the possibility of contamination from external elements that affect water quality. This issue of water quality and water quantity is widely documented but solutions to check both in tandem are not.

The water quantity issue requires a detailed look into the current methods used to measure the fullness of the tank. Whereas the water quality issue requires a detailed look into the current methods to assess water quality/potability both in labs and in the field to find any commonalities that can be used.

Water Quantity

Water quantity is currently monitored by myriad techniques ranging from non-contact methods like ultrasonic sensors (US sensors) to contact-inclined methods like capacitance sensors [3]. The wide variance in techniques is due to the nature of evolving technologies and the availability of a commercial version of these devices.

Acquisition Techniques/Devices

Contact Devices

Devices that require contact have several benefits that each section will cover but also suffer more from mechanical fatigue than their non-contact devices. The following is a collection of contact device types that the literature covers.

Float

A float is a basic device that floats on top of the surface of the water and raises or lowers an indicator that highlights the height of water in the tank. As the float is quite basic the literature surrounding it is also quite sparse. However, as the design is quite basic the strengths and weaknesses can easily be found but the evaluation will, unfortunately, be vaguer due to the lack of testing data surrounding it.

Table 1 - Float Breakdown

Advantages	No digital component No risk of corrosion
Disadvantages	Requires line of sight No precision measurement Subject to mechanical failure/fouling
Error	No drift Recording error - parallax/Human

The float is a bare-bones solution that is used for basic water level sensing as it does not offer the precision necessary for a comprehensive water monitoring solution.

Capacitive Sensor

Capacitive sensors that are used in water/liquid level sensing operate by having two electrodes submerged in the liquid and measuring the capacitance of the liquid between the two [3, 4]. This works by using the basic properties of capacitors where a change in the medium/dielectric between two electrodes, the cathode, and the anode, would cause a change in the voltage as per the equation:

$$V = \frac{q}{C} = \frac{qd}{\varepsilon A} \qquad \text{Eq. 1}$$

With Voltage being a result of the relationship of Charge (q), Distance (d), Dielectric Properties (ε), and Area of the Electrodes[5]. In this case q, d and A are all constant when the devices are deployed on location. Therefore, the only impact is the dielectric properties of the medium between the two electrodes. If an assumption is made that no new sediment is introduced to the liquid medium, the fluctuation of the liquid level will cause an increase or decrease in voltage to be observed across the electrodes [4].

Many capacitive sensors that can be seen in the literature calculated the linear relationship between water level and capacitance [3-7]. However, when introduced to a real-life system the measured capacitance differs from the calculated/theoretical capacitance, which is where an additional circuit called a signal conditioning circuit is implemented [3-5, 8].

Further research into the capacitive sensors shows that there are a number of permutations of the basic two-electrode design shown by A. Qurthobi et al [4]. The different permutations alter the main components: a modification by having multiple sets of electrodes with varying lengths to identify the water level with low-cost components [5], Mounting the plates in a tube with one electrode consisting of a PTFE-Insulated wire and with the water acting as the complementary plate [6], Having multiple tubes that exist as capacitive sensors with two electrodes with a gap to allow water and air to act as the dielectric [3, 7, 8], relying on metal tanks to act as the complimentary electrode [3]. While they differ in design philosophies, they are still faithful to the linear relationship between capacitance and water level.

These can be further broken down into the types of electrodes in use by the sensors. More specifically the material and whether it is made from metal or plastic [3].

Table 2 - Capacitive Sensor Material Types

Metal		Plastic	
Pros	Cons	Pros	Cons
Small Linear Expansion	Salt Formations	Flexible	Low Mechanical Strength
High Mechanical Strength	Subject to Electro-Corrosion	Fast/Easy Installation	Resistant to Electro-Corrosion

Capacitive sensors in literature work best when measuring slight changes in liquid level with several papers [4, 6-8] focusing on creating/observing capacitive sensors on distances less than 1m. This allows the sensor to have resolutions of 0.1mm [6] and observe slight changes in capacitance of 0.3nF to 1.110nF which represents the level change of 0m to 0.3m as seen with A Quyurthobi et al [4]. If the resolution were put into perspective for a common 25000L water tank, for this example a Devan 25,000L water tank is used, a change in water level of 1mm would equate to a change of 10L. Therefore, the effective resolution of this method is approximately 1L over the effective range of the device. Although the paper by A Quyurthobi et al focuses on smaller ranges this doesn't mean that the capacitive sensor is limited to just small distances with some being used for distances ranging from 0m to 4m [3].

These capacitive sensors are widely adopted in chemical, oil and gas, water, and waste-water use cases [7] as it allows level measurement regardless of fluid, as long as the dielectric properties are known [8].

However, the operation of the capacitive sensors is not completely without fault. Firstly, when installed in situ the temperature of the environment is not ideal as it is variable across the entire length of the sensor [4]. This variability causes similar issues to vapour, from the liquid mixing in the air, as it changes the dielectric constant across the probes and thus causes the sensor to trigger a false level of liquid [8]. This effect can be limited by checking the system's environment: humidity and temperature. Another issue that researchers faced was when multiple capacitive sensors were placed in close proximity which caused an accidental parasitic capacitive coupling [5, 7]. This can be reduced by the proper positioning of the probes. Another issue linked with improper installation is that the more the electrodes are shifted from their proper orientation, of being parallel, the greater the error in the measurement [3]. This is due to the probes' behaviour as capacitive plates requiring them to be parallel, so the amount of dielectric does not change between the two and thus alter the reading.

Time Domain Reflectometry

Time domain reflectometry (TDR) is a method that is typically used to find the characteristics of electrical lines. The method does this by sending a signal through a transmission line and measuring the time delay between emission and reflection [9]. This signal is affected by the surrounding environment which will cause a change in impedance and hence change the signal's response. A TDR evaluation unit analyses this response change to return where these impedance changes occurred and hence the surrounding environment of the probes.

TDR is a specialised method of water level sensing as the original and more prominent use case is for detecting cable faults, evaluating soil moisture content, and electric circuit testing. This technology was adapted for use in water level measurement as seen by A. Thomsen et al in their paper in the Journal of Hydrology where they repurposed a two-wire soil moisture probe [10]. The probe works by measuring the distance between the probe head and the water level in the tank via the impedance changes. This is similar to the capacitive sensor; however, the TDR operates slightly differently where the key observation isn't the capacitance of the liquid but the interference in the probe caused by the impedance of the air/water [10].

TDR is suitable for identifying small changes in what would be a large-scale environment such as an industrial liquid tank where a change in millimetres would equate to a large volume of water [9] i.e., 13 metres equating to 132.73L per 0.001m. However, due to the nature of TDR and the sensitivity of the equipment it is an expensive option for water level sensing [9] with prices ranging from NZD$4,322.85 to NZD$10,312.14+.

TDR can work well in non-uniform tanks as the probes, typically coaxial cables, can be moulded to follow the shape of the tank. The signal change caused by the bends will not be an issue when measuring liquid levels if the return signal is measured prior to adding water, as this sets a baseline for comparison. TDRs has the benefit of the ability to be mounted on the outside of the tanks given that the tank is non-metallic which allows for easier installation in pre-existing tanks.

Fibre-Optics

Fibre optics is the use of clear fibres to send light from an emitter to a detection module. Typically they are used for high-performance connections in a network of devices [11]. Due to the potential of light to function as a high-speed signal by utilising the modulation of this signal, caused by external factors, it is possible to show the state of the environment. There are two basic archetypes of fibre optic sensors: distributed sensors which are suitable for monitoring seepage and settlement in dams and, punctual optical sensors [12].

A fibre-optics liquid level sensor works by having two sets of waveguides, fibre optic cables, parallel to each other one acts as a receiver and the other an emitter/source. By being submerged in the water it is possible to identify where on the receiver the waves are behaving differently and therefore allows the device to identify the level of the water relative to the known position of the waveguides [13]. Another way the fibre-optics operate is to be coiled around a polyamide pole and submerged in the fluid being measured[14]. This coiling causes macro-bending in the fibres and thus causes a coupling effect between the fibres which changes based on the medium between the turns and lets the level of fluid surrounding it be measured [11, 12, 14].

Fibre optics is a high-performance method of both sending data and identifying the liquid level and retains strong anti-interference properties [11]. However, as it is a high-performance device the cost associated with manufacturing and installation of it is much higher. These manufacturing methods include techniques such as photoengraving cutting and bonding to ensure the fibres behave appropriately when connected to their various demodulators [14]. As the device is capable of operating in large-scale environments the added difficulty of compensating for the changes in temperature across the fluid medium needs to be considered as well [12].

Non-Contact Devices

Pressure sensor

Pressure sensor devices utilise the physical phenomena of pressure to show the level of fluid that is in a container. This has been used throughout the years in devices ranging from early washing machines to chemical storage containers [15-17] to identify the level of fluids in the system at one time.

The basic theory behind the operation of these devices is around the pressure differential between the surrounding atmospheric pressure and the pressure caused due to the weight of the fluid in the system. In the earlier washing machines that had an automatic water level detector, an airtight tube was connected to the machine with a sensing unit. This sensing unit consisted of a diaphragm attached to a switch which would trigger when the diaphragm had deflected due to the pressure differential between the inside of the washing machine and the outside air pressure [17]. However, as technology developed the transition to needing greater precision for some aspects became necessary. This was facilitated by the involvement of piezoresistive strain sensors bonded to the diaphragms [16, 17]. Using a microelectromechanical system (MEMS) sensor allows for a greater level of detail and a better understanding of the actual fluid level and not just a set limit. This is done by observing the piezoresistive sensor relationship between pressure and voltage [16].

Pressure sensors are incredibly useful when a non-electrical method is needed such as in chemical and water treatment industries [15]. This is because several pressure sensors are not in direct contact with the fluid being watched and will not contaminate or cause accidental electrical discharge into the fluid. Another benefit is the strain sensors have high sensitivity, low noise, and are relatively low cost [15] thus the biggest potential point of cost is connecting the sensing unit to the system where the fluid is being measured.

A downfall of pressure sensors is the fatigue experienced over time by the piezoresistive sensor. As the level of the fluid changes the sensitivity of the sensor will also drop and need replacing. Also, as it runs with similar electrical properties as a contact-type capacitive sensor the piezoresistive sensor has similar downfalls. Two of the most prevalent issues that arise are the effects of parasitic capacitance, which will alter the accuracy of the device, and temperature variation. A specific issue that can arise is due to fluid fluctuation called sloshing [16]. This fluid fluctuation causes an artificial increase in pressure which causes discrepancies and makes readings inaccurate.

Ultrasonic Sensor

Ultrasonic (US) sensors are devices that vibrate transducers that propagate sound waves through a medium and detect the return pulse [18, 19]. The device is made of two separate components: the transducer and the demodulation circuit. US sensors act as a non-contact method to identify distances with which the level of a fluid can be identified [20].

US sensors work on the principle that soundwaves travel through a medium and rebound at certain angles. This reflection is then observed, either by the same transducer that made the soundwave or by a secondary transducer with a known position relative to the initial transducer, and the time at which the wave is observed is recorded along with the strength of this return pulse.[18-21]. This relationship is broken down into the basic kinematics equation of $d = V/t$. However, the distance needs to be halved as it would include both the time to travel to the target and back. The velocity is calculated via the speed of sound equation $v=331.4 +0.6T$ (v=speed of sound, T= air temperature) [19].

US sensors are useful due to their simple nature, as they emit and detect with the same mechanism. This means the method for manufacture is simpler than alternate options and therefore the cost of manufacture is lower [20, 21] with a common ultrasonic device, the SR04, costing approximately NZD$8.07. The low cost of manufacture combined with their robust design shows that the US sensor is a simple yet efficient measurement device. Another benefit of the US sensor is the fact it is a non-contact device, this allows it to be used in applications where the contamination of fluids is an issue or where contact with the fluid is a potential hazard such as in fuel or bulk solid level gauging [20]. US sensors are used often in the mechatronics industry with a reoccurring module being the SR05. the SRF05 is a ping ultrasonic sensor module that combines two separate ultrasonic sensor transducers to get a distance. One of the transducers is used solely for transmission and one is used solely for detection [20]. This version of the ultrasonic sensor has a larger form factor but reduces the chance of overlapping signals as the emitter and transmitter are staggered.

US sensors suffer from certain drawbacks. For example, as the device relies on the vibrations emitted to be received unmolested any acoustic variation inside the medium causes variations in the returned wave [21]. This variation can lead to an incorrect measurement and contribute to errors when not checked. Adding to this is the effect of humidity and temperature variability in the path of the US sensor. If the distance is large, or the medium is under various environmental effects, the environmental factors impact the speed of sound to cause a variation in the time it takes to return and thus the measured outcome [20, 21]. If the device surrounding the US sensor is poorly shielded there is a chance of electronic noise affecting the return signal. This is due to the ultrasonic sensor converting the physical vibration into an electrical signal which can be affected by the electrical noise [20]. However, these issues can be compensated for by either monitoring the environment [21] or controlling the design of the surrounding electronics. Firstly, by checking the environment for changes in humidity and temperature it is possible to calculate the speed of sound more precisely to allow for the mitigation of this error. Secondly, by controlling the design of the surrounding electronics, and making the device shielded properly, any signal attenuation or interference can be reduced greatly.

Laser

Laser measurement devices are rarely used as they require water to be nearly opaque to experience a return signal. There have been instances of detecting the sea level compared to a ship, however, seawater has intrinsically more minerals in the media which cause a higher level of opaqueness. Therefore, it will only be briefly mentioned as the device exists in literature but does not meet the standards to be used around potable water which tends to not be opaque.

Technique Comparisons

The literature collated shows the benefits and drawbacks of each of the differing techniques. Omitting both lasers and floats due to their inadequacies in the scope of this review. Using this information, it is possible to compare them. However, to compare the devices from the literature effectively it is necessary to find what the methods measure. These can be broken into three categories:

- Distance to the surface of the water from a defined point:
  - Ultrasonic sensor.
- Distance of the water across a known length:
  - Time domain reflectometry.
  - Capacitive Sensor.
  - Fibre optics.
- Weight of the water:
  - Pressure sensor.

Four of the devices use the first two methods in mind with the pressure sensor being the only outlier that estimates the volume of the water via the weight/pressure. This point of difference requires a different approach as there must be an added chamber attached to the tank to measure the pressure differential. Whereas the other methods require a probe to be inserted in the water or a clear line of sight to the surface. This changes the difficulty when installing and performing maintenance on the device in situ. The more inconvenient device is the pressure sensor because it requires adding a separate chamber next to the bottom of the tank. The maintenance includes checking any connecting pipes for leaks and replacing the diaphragm which is used to measure the pressure differential.

The next methods are the devices that measure the height of the water across a known length. This is typically done by inserting a probe that spans the tank. This is slightly better as most options are rigid and can be inserted easily such as the TDR or Capacitive sensors. However, the maintenance needed is increased as the water is in constant contact with the device it is prone to be fouled. The fouling is more specifically due to either build-up of minerals, due to the devices that utilise electrical properties acting as electrodes which split the ionic components from the water and collect them on the probes, or from the condensation due to the vapour.

The final set of devices is mounted above the surface of the water and measured the distance between themselves and the water's surface. By doing this the fouling due to the contact with the water is mitigated but it will still experience condensation which causes issues of build-up on the sensors.

While the different devices each experience differing installation and maintenance issues, they all experience an issue with a difference in temperature gradients i.e. - the change in humidity and temperature over the range being measured. Although each device measures different phenomena, as they are all physical, they are all affected by the temperature gradient. Firstly, the devices that measure distance are affected because the water and air in the tank are not uniform temperatures. This causes a discrepancy with the speed of the beam sent, be it ultrasonic waves or laser, the varied speed of the beam leads to an inconsistent distance that accumulates more error the greater the variance in humidity and temperature. This is like the effect of the devices that use probes to measure the height of the water along a known length. This is shown as having a higher humidity content or temperature will change the electrical properties surrounding the probes, this in turn causes potential differences in the dielectric due to the temperature and humidity changes which are assumed to be distinct and constant, and this difference leads to errors. The effect with the pressure sensor is slightly different as the temperature and humidity rise in an enclosed tank the pressure will rise and will give a false reading as the pressure outside the tank is not increasing at the same rate inside.

From the literature, it is clear some devices are considered more expensive than others with some devices having expensive probes, due to the cost of manufacture, or having an expensive method for decoding the devices’ signal to a usable format, such as a TDR device. This difference in cost for the devices limits their applications. A high-cost TDR device would be suitable for its industrial applications but if it were to be implemented in a small-scale consumer application it would be inappropriate due to the cost of both the rigid probes and TDR sensor totalling more than NZD$10,322+. The opposite on the spectrum would be the

Ultrasonic sensor as the device requires a low-cost transducer attached to a signal decoder totalling more than $8.07+. However, as with any device, there are different iterations that are more expensive and therefore offer greater precision due to the quality of components used. The other devices range in price with fibre optics at an excessive cost due to material and manufacturing methods, approximately NZD$10005.47 and capacitive sensors, approximately NZD$92.39 for a short-range sensor, increasing in price based on the scale of the ranges.

The devices also differ in their capability to measure across distances effectively. Over larger distances, certain devices, such as the non-contact devices lose their strength, as is the case with the ultrasonic sensor, or become deflected, as is the case with the laser. Other devices experience issues with setup over long distances, such as the capacitive sensor which if improperly set up over a distance can start to skew and increase the error as the device must have the two probes parallel. Other devices suffer due to the expense of the probes, such as the fibre optics which has a higher manufacturing cost for the probes. This is the opposite case of the TDR which relies on Coaxial cable as the probes are relatively inexpensive when compared with the device itself and are suited for longer distances due to its original use case being finding faults in powerlines. The opposite extreme case where the device is measuring over a small distance must also be taken into consideration. This is because a small level change in a wide tank could equate to a larger volume change than experienced in a slim tank. This is where high precision techniques such as the Capacitive sensor, which has a linear behaviour in measurements between 0-3m and a precision of 0.1mm, work well. Whereas Ultrasonic sensors suffer at a certain distance from the transducer, with the device unable to work below a certain threshold as rated by the specific device's specifications typically a distance of 0.3m.

Water Quality Via Hyperspectral Imaging

Water quality is a large factor in water security as it is linked directly to the ability to use the water as potable water. In this case, the scope covered solely hyperspectral techniques for the identification of water quality.

Hyperspectral Imaging

Hyperspectral Imaging (HSI) is the practice of taking an intensity image across a spatial plane (XY) and simultaneously recording the spectra (λ) of the points creating a 3d data cube with spatial and spectral data. This is useful as most Objects/ Organisms have certain spectral responses [22] in a wide spectral range. Thus, allowing them to be uniquely identified with confidence. This information cannot be viewed via normal means, such as the naked eye or standard RGB Cameras, as these responses can vary from ultraviolet (UV), 100nm to 400 nm, to near infrared (NIR), 800 nm to 15000nm [23]. Underwater Hyperspectral Imaging (UHI) is a specific method of HSI that detects objects in both fresh and salt water [24-27]. As the medium, the light is traveling through is different there are different issues such as wavelength absorption and scattering, and reduced contrast which affects the overall data cube for analysis [28]. However, using hyperspectral imaging through water is important as the examination of aquatic habitats could lend to early intervention: such as with algal blooms [29-34], especially at the surface level due to its greater exposure to sunlight. This review of HSI will show current techniques for HSI and UHI with a focus on their ability to find Algal blooms and discuss their feasibility for use in a remote passive low-cost underwater hyperspectral imaging system.

Hyperspectral imaging returns a 3d data cube, which highlights the relationship between the spatial data (XY) and the spectral (λ) data. The spatial resolution is a measure of the smallest possible object that can be found by the sensor [35]. This is different from the pixel resolution of the camera as the pixel resolution stays constant, but the spatial resolution is altered by the distance from the target. The further from the object the device is the coarser the spatial resolution becomes. Whereas the spectral resolution is the span of the wavelength which the sensor can detect [36]. Which leads to a higher resolution having a larger precision of spectral wavelength.

The method for imaging changes the complexities involved in the overarching system. It can change the areas the device works in, the spectra the device can analyse, the spatial and spectral resolution of the image, and the density of the data cube.

Hyperspectral Process

The process of HSI can be broken down into 5 stages: Probing, Excitation, Delivery, Filtering, and Detection [37].

Probing

Probing is the method used to help show the specific cell/object being investigated. Probes can be used to further show the cell structure and offer a better contrast while not improving the sensor. This is achieved by introducing fluorescent dyes or nanoparticles (np) which are excited by the beam and fluoresce in a particular way that is known. Another possibility is quantum dots (QD) which are nanoscale crystals that transport electrons and under certain spectra of light, ultraviolet, the crystals fluoresce in a known way. The third choice is surface-enhanced Raman-scattering nanoparticles (SERS NPs) which enhance Raman scattering, which is the way photons interact with objects, this enhances the ability to detect molecules by a factor of 10" [38] which means individual molecules can be detected. These techniques are necessary when performing HSI on molecules with similar responses as it creates a contrast between them. However, in a non-lab environment deploying contrast agents is not suitable especially in mediums such as salt water as they can bond with the various minerals in the water.

Excitation

Excitation is the method used to get a spectral response from the object. This can be either via using a wide-field approach, which excites an entire area, or a scanning-based approach, which excites one point at a time and scans through the spatial region. The more popular method recently is the scanning-based method as it collects all the spectral data simultaneously [23]. For a complete spectrum, the use of white light is best as it elicits a spectral response across a large spectrum. However, it is possible to excite the region with natural sunlight in some cases, such as with organic plant matter that can photosynthesise [29].

Table 3 - Hyperspectral Excitation Sources

Excitation Light Source	Spectral Response	Wide Field/ Scanning Based
White Light Laser (Stellaris 8)	440 – 790 nm	Scanning Based
Xenon Lamp 445-490nm	500-950 nm	Wide Field
Mercury Lamp 330-385nm	500-800 nm	Wide Field
LED Green 545-595nm	400-580nm	Scanning Based
LED Yellow 535-610nm	460-580nm	Scanning Based
LED Red 600-700nm	550-700nm	Scanning Based

Table 3 Highlights the possible light sources used for excitation from existing Literature [22, 39]

Delivery

Delivery is the method used to transfer the light received. This can either be through fibre optics or open space.

Filtering

Filtering is the method used to choose the wavelength for the point of interest. This can be as simple as a prism/grating for spatial dispersion or using filters such as a liquid crystal tuneable filter (LCTF) or an acousto-optic tuneable filter (AOTF) [23]. This method depends heavily on the requirements of the overall acquisition technique and the environment the device works in.

Detection

The type of sensor used to collect the information from the filter is decided based on the level of light available and the wavelengths being measured. For example, a Photomultiplier tube (PMT) works well with very weak light while the conventional photodiode works well with elevated levels of light. However, the PMT's spectral response is lower the larger the wavelength of light.

Acquisition Techniques

All these stages culminate into overarching acquisition techniques with different methods and outcomes.

Snapshot

The Snapshot method records the entire spectra across the entire spatial plane giving a complete 3d data cube. This is commonly used in stellar classification, microscopy, and geology measurements [40]. This is an effective method because it allows the relationship of spectra between the surrounding XY points to be kept and better analysed. Snapshot utilises the wide-field excitation method to excite the entire region this is then delivered through an image mapper and prism array and projected onto a sensor.

Push broom

The push broom method records the entire spectra for a row on the spatial plane and moves across the spatial plane along one of the axes to create a complete 3d data cube. This is commonly used in remote scanning from space and in production lines. This method is used because the object/s of Interest (OOI) is moving while the device stays stationary. This gives a larger precision for the detector as the entire sensor can be used for a smaller area giving a greater spatial resolution as time goes on.

Point-scanning

The point-scanning method takes a point in the spatial plane and records the spectra in an instant and does this over for each point. This is commonly used in satellites where higher resolution is needed such as the Landsat 8. This method works well where the spectra of individual points are of interest and spatial resolution is a concern. The point-scanning method is different from the push broom method in the fact it focuses on a single sensor and allows for a greater resolution. However, this is offset by the fact it takes longer and there are more moving parts. due to the method not recording all possible point’s spectra at the same instant it leads to slight deviations in readings.

Wavelength Scanning

The wavelength scanning method takes a slice of the spatial plane and a section of the spectra. This method uses a wide-field excitation method to stimulate the entire region. the spectra that are reflected are then passed through a filter wheel, So the receiver only processes a narrow band. However due to the time between each band being scanned the OOI can change position or state [23] leading to possible errors in data.

Underwater Operation

UHI generally requires the use of remote sensing [24] as passive observation of an aquatic habitat over long periods of time comes with challenges. For operation, while observing objects in the water a UHI can be used either above the surface of the water or submerged [26]. When it is mounted above water the specular reflection, caused by the surface of the water, needs to be excluded from the dataset to avoid false readings and focus on the desired information.

A main use besides the identification and mapping of underwater environments is the monitoring of water quality [26]. This includes, but is not limited to, phytoplankton, coloured dissolved organic matter (CDOM), and total suspended matter (TSM) which can be used to show the water quality.

Identification of Algae and Plankton

The identification of algal blooms, particularly cyanobacteria, is possible due to their pigment-protein complex " Phycocyanin " [41] which has a broad absorption Feature at ~ 620 nm and can be picked up using a wavelength the range of 615nm-630 nm. However, as stated by Raphael M. Kadela et al [30] it is possible to use the spectral Shape change between 665,681 and 709 to identify the bacteria while being insensitive to atmospheric conditions. This approach was also developed by M. w. Matthews et al[29] who observed the sun-induced chlorophyll fluorescence (SIFC) between 664nm to 885nm and used the maximum peak-height algorithm (MPH) to calculate the dominant peak across these bands. This means it is possible for in situ remote hyperspectral imaging without an extra light source with OOI at the surface of the body of water.

As the desired OOI is situated deeper in the body of water the natural light is either absorbed or scattered and does not elicit a strong response. This means the UHI must rely on artificial excitation [24] to elicit a spectral response with enough intensity for data to be collected at an acceptable standard. This is where light sources such as LED, lasers, and lamps become important to the operation.

Applications for Low-Cost UHI System

In Situ Environment

The environment that is being considered will be in bodies of water in possibly remote locations. Due to this, a remote sensing platform is necessary much like the devices used to observe megafauna [27], algal blooms [26, 29], or mapping seafloors [24]. Although the use of HSI from satellites is possible the spatial resolution is not adequate to identify individual molecules/organisms as the spatial resolution is approximately 3m [42]. This level of spatial resolution would be fine for existing algal blooms; however, the identification of early indicators would not be possible as the OOI, the algae, would be too small to have the spectral response to be solely the algae. This means that it is necessary to use an in situ imaging device like the device developed by Michael Seidel et al [26] that is deployed in the water and operates 0-0.5m from the surface. However, Seidel's device is not a passive remote device, as it does not passively record data and return information periodically, which is an important feature especially in the early identification of potentially harmful algal blooms.

Spectral Response

The natural light intensity of the sun can be enough to stimulate a response from the algal bloom [29]. However, this level of light intensity is not always available or high enough to reach the necessary depth to find algae. This means it would be pertinent to use a separate excitation method. Due to the need for remote passive imaging, the spectral response is not the only condition for the light source. Firstly, the spectral response needs to encapsulate the span of 665-709nm [30] as this allows the identification of the protein complex “Phycocyanin” of cyanobacteria. Secondly, the excitation method needs to be low power, as the device needs to run for weeks at a time with no interaction with an operator. The Red LED nearly meets the criteria of being low-powered and within the spectral response between 665-709nm but only extends to 700nm. However, for an early indicator of possible algae, it could be implemented in an area of low light such as a water tank. As a water tank can typically have little to no exposure to direct sunlight inside the tank itself it would pose a challenge to solely rely on natural light. This would be a similar experience to using UHI in deeper underwater environments, which is proven to work. However, more lighting may be needed.

Acquisition Method

The collection of both the spectral data and the spatial data is the key part of the device. The use of point-scanning and push broom methods, while excellent in satellites and production lines due to the OOI moving about the device, will not work well in the system as the point of view will be static and the OOI will only be oscillating, due to potential waves, and not traveling in a constant direction. There is a possibility for adding moving parts to aid the scanning of the OOI; however, the addition of these mechanisms would increase power consumption and increase the risk of breaking down while in the field and risk losing the passive observation.

The use of snapshot and wavelength scanning is possible as they are both widefield excitation methods. This means the device does not need to move to scan the region and therefore there are no added moving parts in the excitation of the region. When comparing the two methods of getting a notable point, the wavelength method can use a smaller detection array. This is due to the way snapshot and wavelength scanning filtering fundamentally works. wavelength scanning filtering uses a wheel filter that lets only a certain band of light pass through to the sensor/detector. Thus, the number of sensors needed to collect data for a certain spatial resolution is related to the number of pixels. However, the snapshot method requires a method for image mapping that splits the spectral response into pixels and prisms that split up the light into differing bands.

This filtering method is more complex, but it gets the entire data cube faster than going by each band. The speed of collection can be an issue if the region changes too rapidly, and the different bands are not from the correct position in the spatial plane.

Conclusion

From the literature covering the use of hyperspectral devices, their possible use in underwater environments, and their method of operation it is possible to find which methods are applicable for use in a low-cost hyperspectral device for use in remote locations capturing OOI in water. Combining this information with the differing methods for finding water levels it is possible to begin developing the baseline device to succeed in creating a device to detect the water quantity and quality of a water tank remotely.

Chapter 3 - Software & Electronics

The first version of the device separated the water quality and water quantity devices to allow for easier evaluation of how the devices worked. This chapter will focus on the software and electronic aspects of the water quantity device.

Measurement Design

Measuring Device

A key part of the water tank Sensor is the measurement of the water level. By looking through the literature on water level measurement it was possible to find six different means of measurement.

- Pressure Sensors
- Encoders/Floats
- Ultrasonic
- TDR
- Capacitive Sensors
- Fibre-Optics

By looking into the background of each, as seen in the literature review, it was possible to find the shortcomings and collate a table to compare.

Table 4 - Sensor Type Comparison

Method	Encoders/Floats	Fibre Optics	Capacitive Sensors
Advantages	• Simple • Non-Electronic	• High resolution • High measuring range	• Precise • Extensively researched • Used widely in water and wastewater
Liabilities	• Non-Digital	• Expensive • Requires strong anti-interference • Requires contact	• Requires meticulous design/installation • Requires contact • Prone to mineral build-up/electro corrosion

Table 5 - Sensor Type Comparison Cont.

Method	Pressure Sensors	TDR	Ultrasonic
Advantages	• Scalable • Digital or Analogue • Non-Conductive	• Accurate • Long Range • Reliable	• Non-Contact • Low Cost • Compact • Medium Range (up to 30m)
Liabilities	• Installation	• Expensive • Heavily Electronics Based	• Has a non-zero Minimum Range • Requires calm surface for reflections

Using the above tables, Table 4 and Table 5, it’s possible to immediately eliminate the float as it requires both contacts and is non-digital. These are both issues as contact with the water can bring issues of the device being fouled or contaminating the water while the analogue nature means extra infrastructure is additionally needed for a conversion.

As the device is intended to be a low-cost device, the expensive devices such as the TDR and Fibre Optics sensors were removed at once. Although they both can cover a broad range at high resolution their overall cost causes them to not be fit for purpose.

Pressure sensors are the next set of sensors which, while an excellent choice for new tanks, require modifications to existing tanks to work. This is to ensure the pressure is correctly captured the device must be attached to the bottom of the tank which increases in difficulty when the tank is filled/in use. Therefore, the pressure sensor was disregarded as a possibility for the overall device.

The capacitive sensor was likewise disregarded due to its reliance on the meticulous installation of the probes that allow it to run. As an incorrect installation causes the capacitive plates to not be parallel and add significant error which, when compounded with the error that the environmental temperature applies to every choice, is enough to mitigate the precision offered by the sensor type. This combined with the mineral build-up on the electrodes in potable water causes the sensor to not be a suitable choice.

The US sensor can run into issues with extremely turbulent surfaces as the sensor requires ultrasonic waves to reflect off the surface to the device and waves are likely to either dampen or disrupt this process. This occurs when the water tank is being filled as water is being poured in and disrupting the surface. It is also hampered by the fact the minimum distance it can read is non-zero. However, both limiting factors can be mitigated. The non-zero closest distance is not an issue when the sensor is mounted above overflow pipes as the water will never cross into the non-measurable region. The turbulent surfaces only exist in non-stationary tanks or when a shock occurs to the tank, these measurements can be ignored given earlier and future measurements when the system is stable.

Therefore, the measuring device that was selected was the US sensor. The sensor is also low-cost and non-contact which improves upon the shortcomings of other potential options from the literature. Although the US sensor can have low precision and an error of 0.7 mm

Operation

To get a better grasp on the challenges that arose from using the US sensor it is necessary to understand how the device fundamentally works:

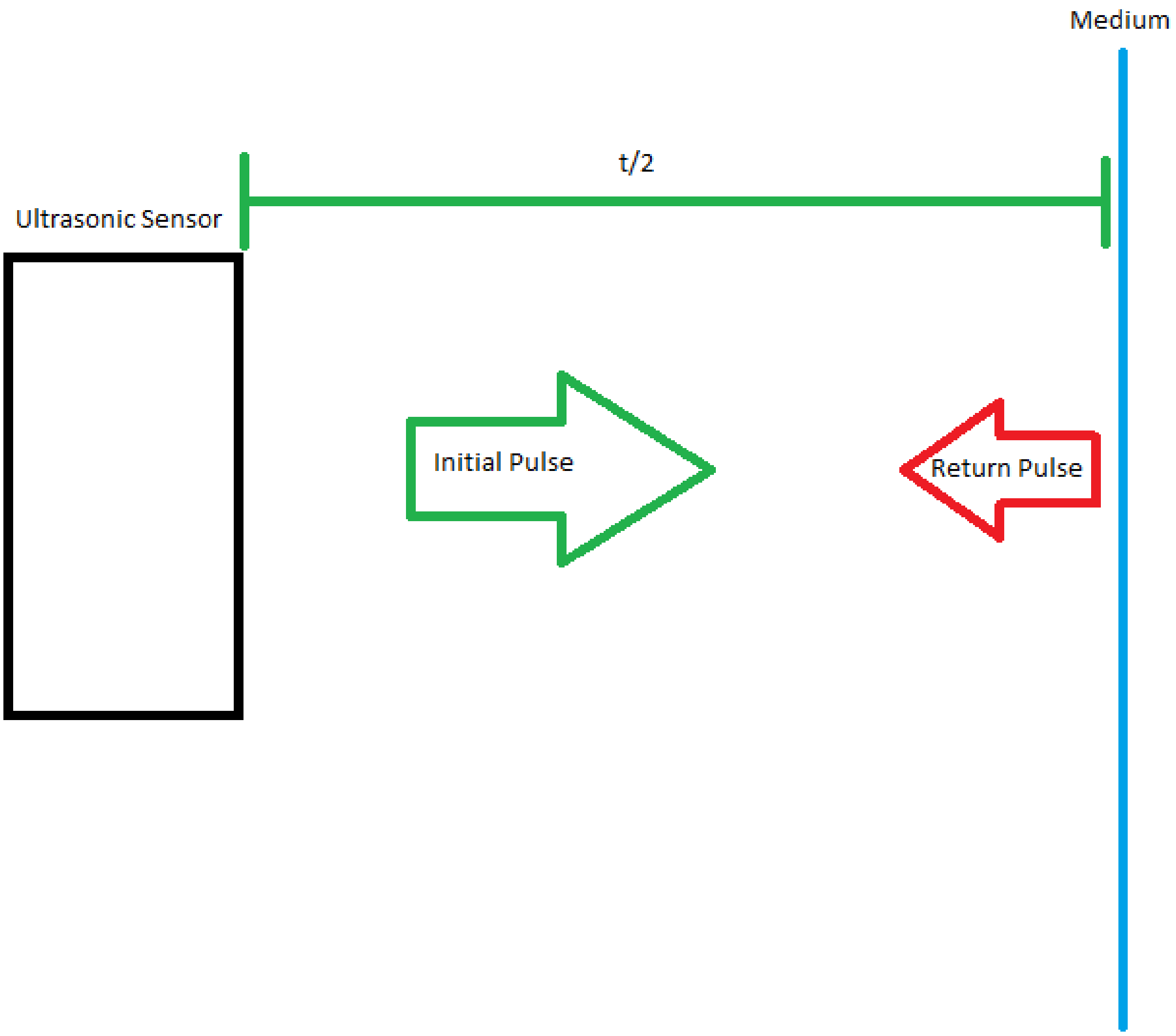


Figure 1 - Ultrasonic Sensor - Basic Operation

The ultrasonic sensor operates by the intermittent vibrating of a transducer at a frequency of 39.4KHz. The pulse created by this vibration bounces off the different surfaces and returns to the transducer which excites it to identify a return signal. The time difference between a pulse and the return signal is processed given the speed of sound (input calculation) as can be seen in Figure 1. This calculation is processed via the onboard chip pga460 and returns the distance.

This reflection is affected by the environment and medium in a few ways that need to be taken into consideration:

- Medium that the wave is reflected off.
- Medium that the wave is travelling through.
    - Temperature
    - Humidity

Firstly, as the medium it is reflected off will be limited to water and no other mediums this was less of a concern. The only two potential issues that can arise are the surface being too turbulent or not parallel with the sensor. As the device relies on the waves being reflected the sensor having the water at an angle could reduce the efficacy of the device. However, due to the sedentary nature of a water tank, it was decided that a turbulent surface would be an edge case that would occur if there was a sudden intake of a large amount of water, like when rain is entering the tank or water is being pumped into the tank, or the tank itself was unexpectedly shaken enough to cause large waves. Thus, these edge cases would offer a weaker-than-expected response and can be ignored, and another reading can be taken to confirm if the earlier reading were constant, or an outlier caused by turbulent water.

The thermal properties of the environment inside the tank are another issue. This is an issue due to the propagation of the waves through the air with a variable temperature gradient. This causes the speed of the wave to change based on the conditions outside and inside the tank. This means that the measured length would fluctuate based on the time of day or weather. This interference is harder to mitigate as the inside of the tank is not one uniform temperature and without a complete array of temperature and moisture sensors inside the tank there is not a readily available way to check this change. What can be done in the long term is to collect data of expected measurement vs actual and combine it with environmental data to reduce the error caused by the properties of the system fluctuating. However, this is out of the scope of the research so it will be only highlighted and not explored.

Power

The device was designed with the consideration that it would be used as a consumer good. The device also needed to run in isolated areas which shaped the power options considerably.

The use of mains was disregarded due to the accessibility to it would be limited for different use cases. This led the design to be limited to battery power and due to the power consumption of all the components being above 300mA when in operation it limited to lower profile battery options. The device required a minimum of 6.5V consistently to run properly due to the ultrasonic sensor unit power requirements. The device will also be in a constant state of discharge, due to the quiescent current consumption of the device, which means batteries that perform poorly with constant discharge between periods of recharge cannot be used.

A possibility would be a solar panel, however, the mix of a higher operational voltage with a standard operating current means the size of the solar power would excessively increase the footprint of the device and increase the overall cost. The device would also not be useful in areas where water tanks are covered or regions with little amounts of direct sunlight. Therefore, it would be a good added attachment, but the base model would most likely use basic batteries without added recharging attachments.

As the device is intended to be left isolated and not require interaction for prolonged periods of time, power sources such as lithium batteries which cannot be drained below a certain amount are not suitable. There are also limited places to recycle lithium batteries. Couple that with the availability for consumers to easily buy these batteries affordably and it makes a lithium-ion battery non-desirable.

The final choice becomes which alkaline battery is most suitable, given the other options will not meet the requirements of affordability, accessibility, operability, and size profile. The issue with using cell batteries, while they are widely available, is the differing options commercially available either offer the voltage and not the capacity, such is the case with the 9V Alkaline which has 550mAh of capacity, or capacity and not much voltage, as is the case with the AA battery which is 1.5V with a capacity of 2500mAh. The middle ground of the two battery types, the AAA battery, is the same voltage as the AA but half the capacity and a smaller form factor. Ideally, the 9V would suit the best, due to the battery's voltage and smaller form factor over 6 AA/AAA, but the abysmal battery capacity cannot meet the power requirements of daily activation over a period longer than 2 years. The AAA behaves in a similar fashion and the jump up in form between 6 AAA and 6 AA is not too significant to choose the AAs.

Therefore, due to their acceptable battery capacity, discharge, and voltage the selected power supply was a battery pack of 6 AA.

Communication

Communication was a key issue as the device had to be able to update the user wirelessly in both rural and urban environments. The specifications for the device were as follows:

- Urban Operability
    - I. Multiple devices in proximity
    - II. Device operable in areas with surrounding buildings
- Rural Operability
    - III. Able to work in areas without services.

Allowing for both environments offer different challenges that run counter to them. The first urban operability specification is an issue that is an edge case in rural environments due to population density. However, creating a device that is location agnostic will mean some edge cases in the different environments can be automatically catered to and distinctions do not need to be made. This would not be the case if a device specialised for either the urban or the rural environments was created. This also allows easier long-term maintenance as the communication all occur on the same network and all the infrastructure and issues can be responded to quickly. To enable multiple devices to work in proximity without substantial amounts of interference it is necessary to avoid saturated communications mediums such as radio and WIFI. This is because the more devices that are communicating on these bandwidths the more interference the devices cause and slow down the entire network for other devices as well. This means a low-data network, generally used for IoT, is necessary. These options include networks such as Sigfox, Zigbee, and LoRa. There are differences between the options, but they all offer an excellent alternative to standard messaging networks and will solve the issue of multiple devices sending messages in proximity.

The second specification for the urban environment is the ability to work surrounded by buildings. This is a challenge that affects communication methods that require a line of sight between the transmitter and receiver or where the waves are unable to travel through certain mediums. This can be illustrated with WIFI as the 2.4GHz band can travel through walls easier due to its higher power and longer wavelength while the 5GHz band has a higher data transmission but it has a lower range due to its lower power. This difference in behaviour over one type of communication mirrors the behaviour of other communication methods. Where a higher frequency device will struggle to have a signal pass through surrounding materials. Therefore, a relatively low-frequency device, in the order of Megahertz, is necessary to have the power to send data over long distances and through obstacles while supporting an acceptable data rate. Which removes short-range communication such as WIFI.

The first specification for rural environments is to be able to work in areas without service. These areas are quite common where mobile coverage is not available which limits devices that connect to the internet via mobile networks such as 2degrees and Spark. Options for long-range low-power communication can perform worse in these areas as some networks i.e. – Zigbee and LoRa require a base station to connect to the wider network and these are not available unless placed by the user or an open-source member of the network. However, Sigfox, a low-power communication network uses designated operators to place coverage, rather than rely on open-source gateways. This means the coverage is increasing to cover both urban and rural environments. The communication network is expanding and as the device goes across the land rather than to a satellite the weather conditions have less of an impact. The antenna profile is also smaller compared to a radio which is larger due to the difference in frequencies.

From the different specifications, it was possible to show that using WIFI as the sole communication method would be insufficient and not suitable for use in most environments. However, long-distance methods such as radio would not be suitable due to the potential for interference between devices and existing infrastructure. Leaving the only possibility being an IoT network such as LoRa, Zigbee, or Sigfox. Due to the nature of the network coverage offered by each network provider Sigfox was selected as the network that the device would utilise.

Processor

As the device needed to function as a communication device and run as a low-powered system, the ESP8266 chip was selected. This chip was a low-cost choice that included WIFI accessibility and extensive documentation on its operation. The WIFI accessibility, while not necessary as specified previously while selecting the communication method, allows the device an easy and accessible way to set up the device without having to add a physical user interface.

Improvements

During the testing of the original device several errors occurred with both the software and the electronics these errors required various changes and improvements as the real-world testing introduced novel issues.

Ultrasonic Sensor Issues

The ultrasonic sensor experienced most of the issues that appeared.

Harmonic Frequencies

A large issue while developing the sensor was the existence of harmonics that appeared when measuring the height of the water in the tank:

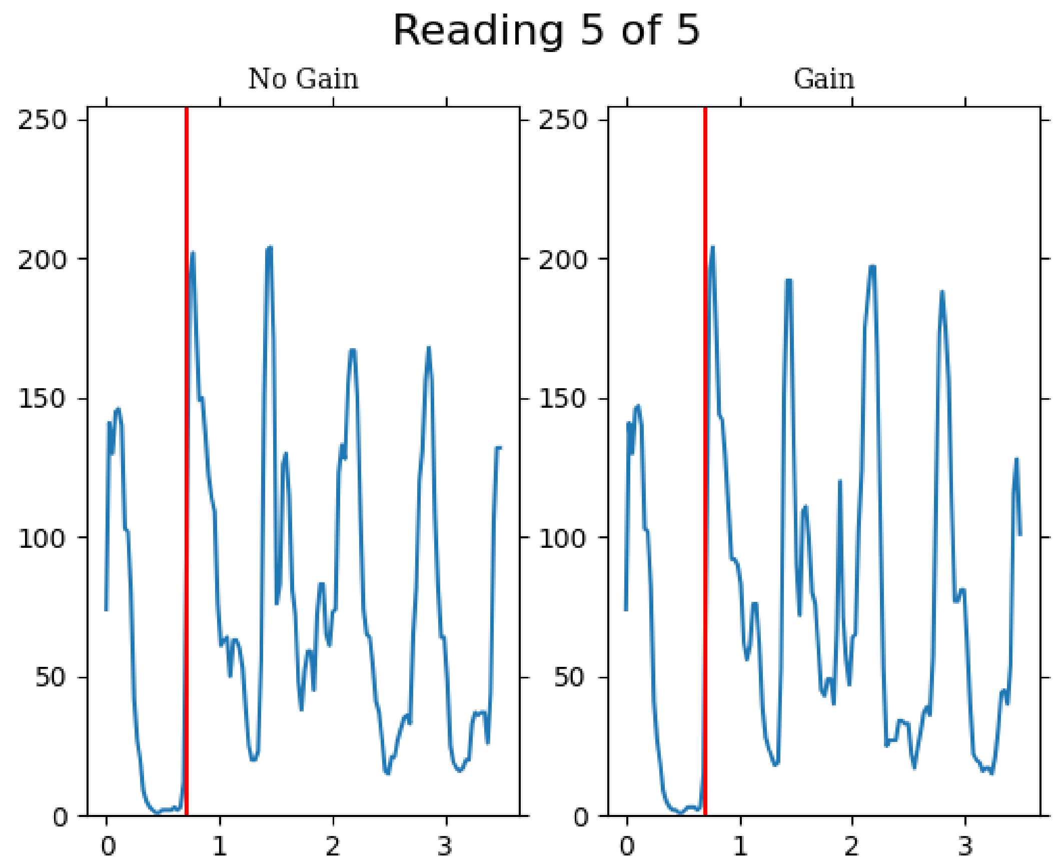


Figure 2 - Ultrasonic Sensor Data from water tank

Figure 2 shows the data collected from the water tank in a snapshot (note the left and right show measurements taken at two separate times). As this was taken from inside a water tank with no other possible medium to reflect off, bar the wall which can be discounted as the reflection from a perpendicular wall would not give a strong enough response, thus it is assumed that the remaining peaks are harmonic resonance.

This harmonic resonance does not have a significant impact on large distances as the harmonic resonance would not be strong enough to be identified as an object. However, when the water is closer the harmonics have more strength and can appear larger than the actual first response due to being potentially amplified by the environment. This leads to issues where the returned reading is further away than it is by a significant amount.

This was considered a software issue because the ability to completely remove harmonic resonance would increase the overall complexity of the design and increase design costs to the point a shift to a different sensor would be right. Therefore, software was used to find possible harmonics and remove them from the set of possible measurements.

The code that was used can be viewed in the appendix, the following will breakdown the reasoning behind the algorithm used here:

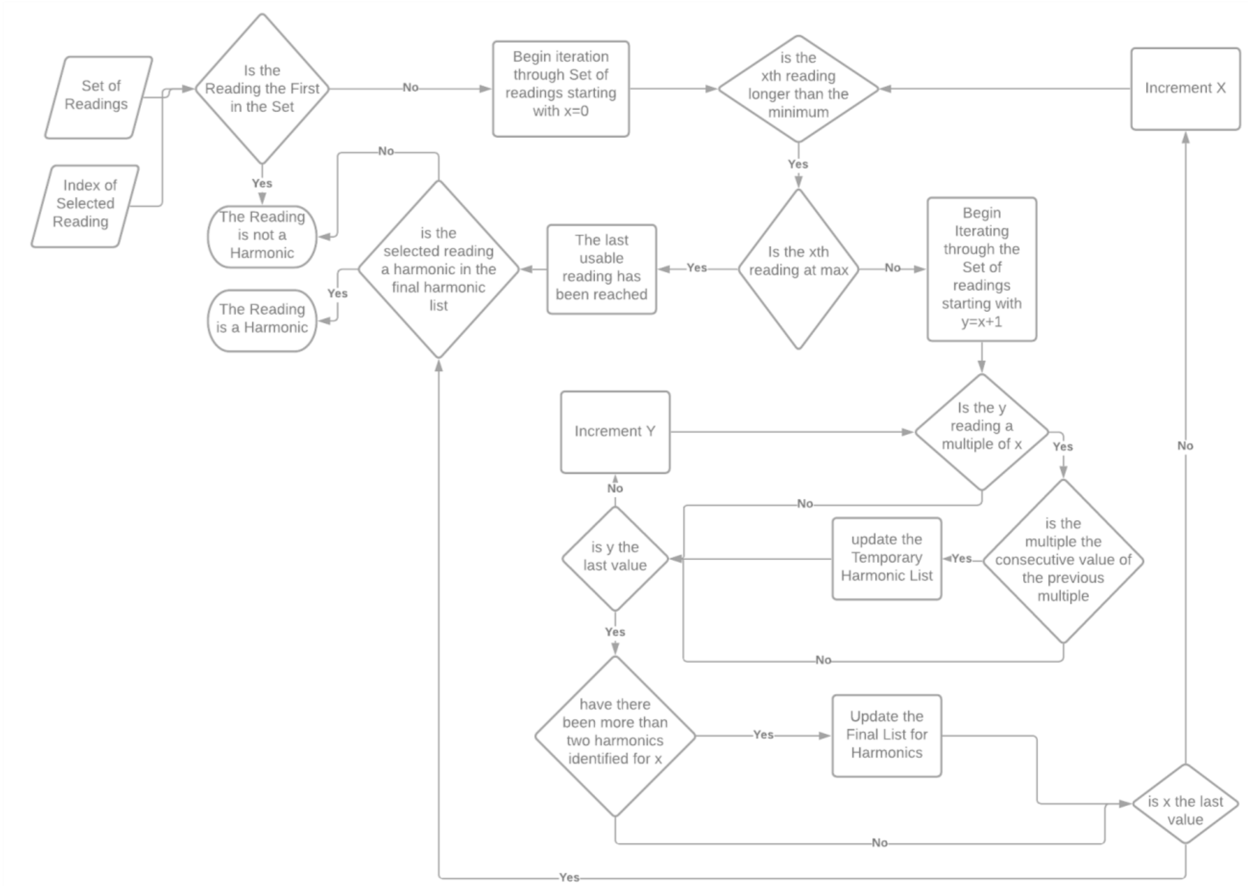


Figure 3 – Harmonic Removal Algorithm

The overall algorithm is relatively simple as seen in Figure 3 and can be broken down into three steps:

The first stage checks if the reading is the first in the set. This is because, as the first reading in the set, it has no preceding values it is highly unlikely that it is a harmonic, so the rest of the algorithm is unnecessary. Therefore, the algorithm exits with it letting the software know that the reading of interest is not a harmonic.

Failing that it continues to the second stage where the readings inside the set are compared with each other to find if they are factors of each other and therefore possible harmonics. However, a smaller reading being a factor of a longer reading does not implicitly mean that the longer reading is a harmonic. For there to be confidence that the longer reading is a harmonic there must be consecutive factors in the set of measurements. For example:

Table 6 - Harmonic Algorithm Example

Reading no.	1	2	3	4	5	6	7	8
Reading	0.21	0.5m	0.7m	0.8m	1.0m	1.5m	1.6m	2.5m
Harmonic	0	1	0	0	2	3	0	0

In this example the first value being compared is the second reading. After having found the second reading as having multiple harmonics one at 5 and 6 but the reading at 8 with the value of 2.5m is not included. This is because there is no reading at 2.0m that would show that the 2.5m is related to the original 0.5m reading.

Once the harmonic for the reading is confirmed, the algorithm checks to see if there are two or more harmonics related to the first reading. In the case of this example, there are exactly two harmonics. With this information, the overall list of harmonics is updated, and the algorithm will iterate through the remaining values.

Table 7 - Harmonic Algorithm Example Continued

Reading no.	1	2	3	4	5	6	7	8
Reading	0.21	0.5m	0.7m	0.8m	1.0m	1.5m	1.6m	2.5m
Harmonic	0	1	0	1	2	3	2	0

Once the final harmonic list is complete the algorithm goes into the third and final stage where the harmonic list is queried for the specific reading and checked whether the specific value is a harmonic. This would be any value that does not have a 1 or a 0 under it. These values have been identified as a harmonic and can be discounted when showing the actual distance to the water.

Pulse Rest Time

During early testing, the device appeared to have some form of noise that altered which was the most prominent peak. This only occurred in readings after the first set. A possible cause of the noise was the time in between pulses was not enough for the entire system to return to a zero state.

This lack of settling time for the transducer meant that the previous pulses to identify the height of the water were affecting the future pulses and readings. This issue was alleviated by adding greater times between each reading so that the device performed like the diagnostics program, which was used to display the waveforms of the transducer.

Reading Consistency

During testing, there would be cases where intermittent noise would cause a false positive at a different distance than expected. For example, if the water level were at 0.7m from the device the intermittent noise would appear and boost a measurement at 1.5m like what was seen in Figure 2. This could have been due to other issues but to ensure that the final output to the device was not due to intermittent noise the memory on the chip was used.

This was utilised by accessing the Real Time Clock (RTC) memory of the ESP8266 and writing to it the measurement that is sent out. By doing this it allows the ability for comparison; To see if the earlier readings are similar in the distance (±0.3m) to the current reading being taken. Incorporating this checking of memory to ensure no unintended spike in the received data.

However, solely having a gate for anomalous readings led to errors when there were massive fluctuations in the water tank i.e. - the water tank leaked/ a tap was left on. The original check to see if the value were similar would not allow for the identification of these extreme events. This was remedied by allowing the algorithm to ignore the need for the new measurements to be like earlier measurements. If a valid reading could not be made three times the memory is wiped, and the next valid reading is sent out. This way the valid reading would be consistent with earlier readings when possible but not be stuck when there was a larger-than-expected change.

Noise

As the ultrasonic sensor relies on emitting and absorbing vibrations to work, anything that would: vibrate, dampen vibrations, resonate, or amplify vibrations would cause unwanted tampering to the received signal. A minor example is shown in the figures below; the example shows where the Ultrasonic Sensor has been physically decoupled from the board in Figure 4 and when it has been attached directly to the board in Figure 5.

As can be seen, the coupled sensor has clear differences from the decoupled version. Firstly, the first pulse is split into two distinct peaks showing that either a new object has appeared or that the pulse has changed. As both instances were recorded with the same system, and no new objects were introduced, the extra spikes are most likely due to the physical connection of the Ultrasonic Sensor.

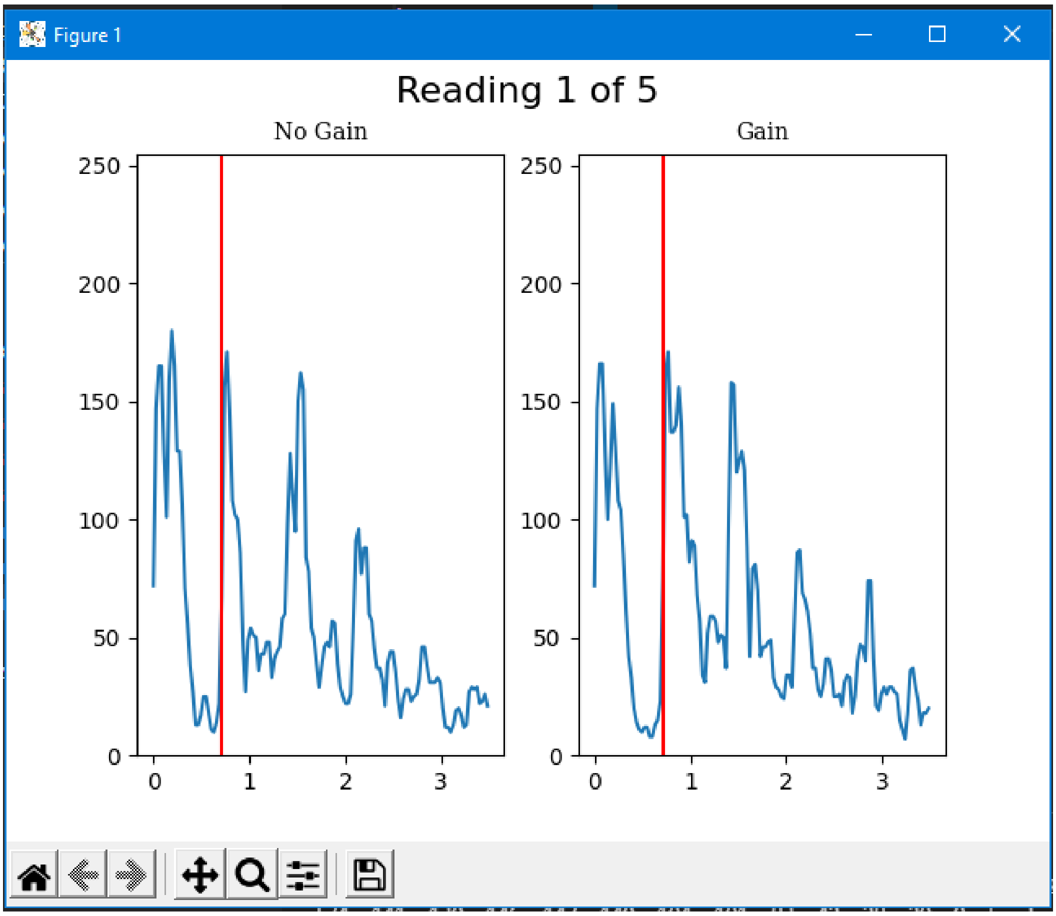


Figure 4 - Ultrasonic Reading of 0.72m wall - Decoupled US Sensor

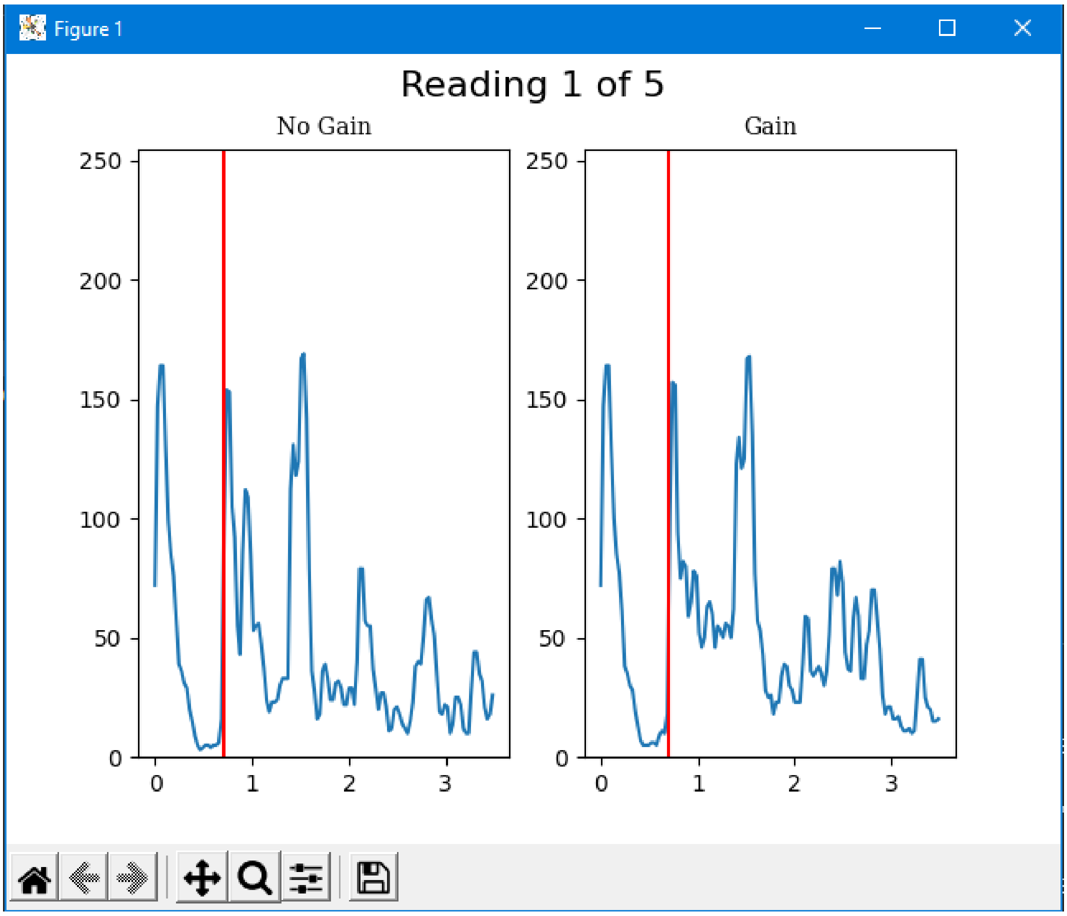


Figure 5 - Ultrasonic Reading of 0.72m Wall - Coupled US Sensor

This was a larger problem when using the first design of the chassis there was a greater effect on the first pulse that caused the value to be at max for a period. However, this issue was easily solved by putting a form of insulation between the transducer and the board. Also, the method for holding the transducer in place was changed to limit as much contact with the transducer as possible to decouple it.

Communication Issues

During field testing of the prototype, there were issues where the device would not send a message. The first consideration was that the device had experienced software issues and was not reaching the point where it could send out a message.

This was checked via rapid-fire testing of the algorithm in the lab with varying distances to trigger a failure state. This ended up with the device finding areas where the software was caught in a loop thus activating the watchdog timer. This was easily remedied by finding the holes in the logic of the code and either changing the conditions in the loops or removing the feature as it was not necessary to meet the objectives.

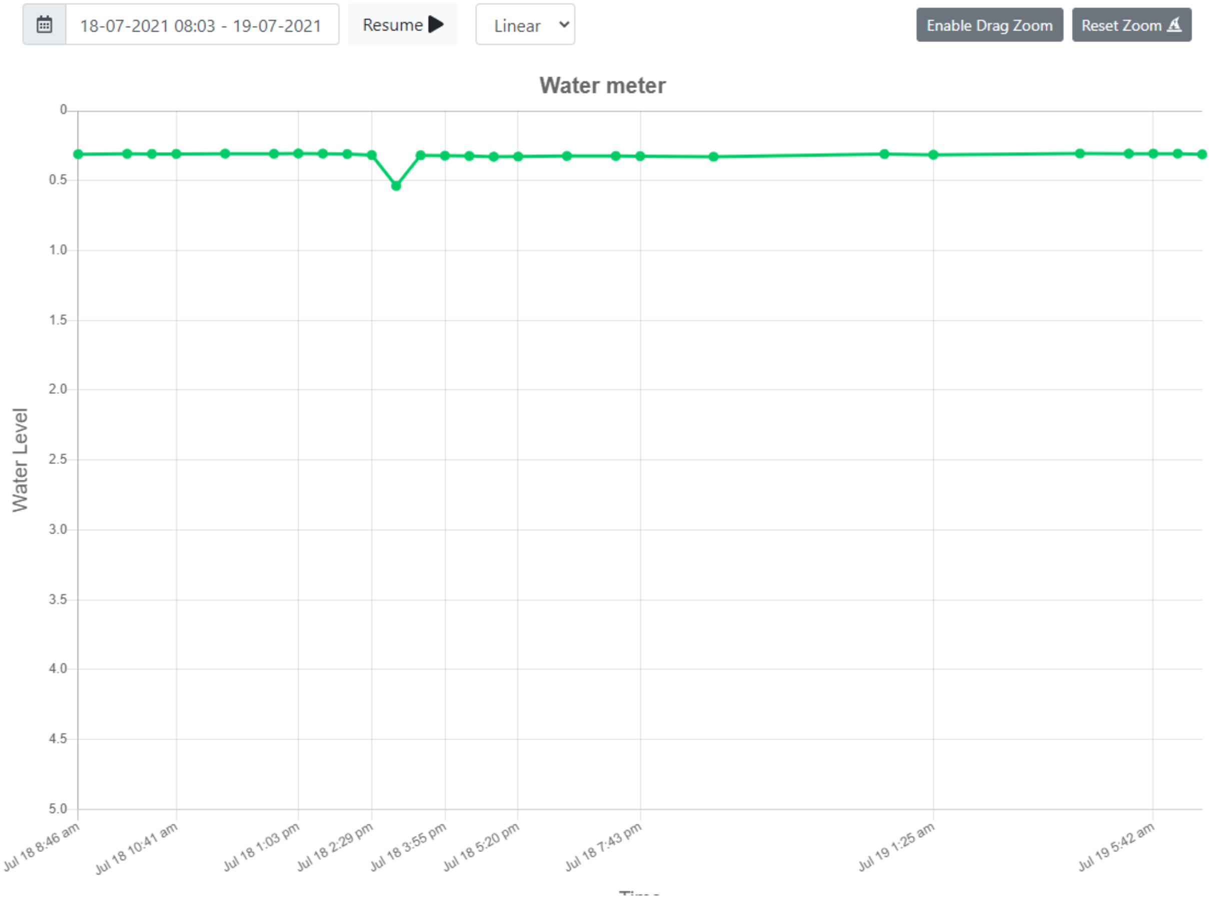
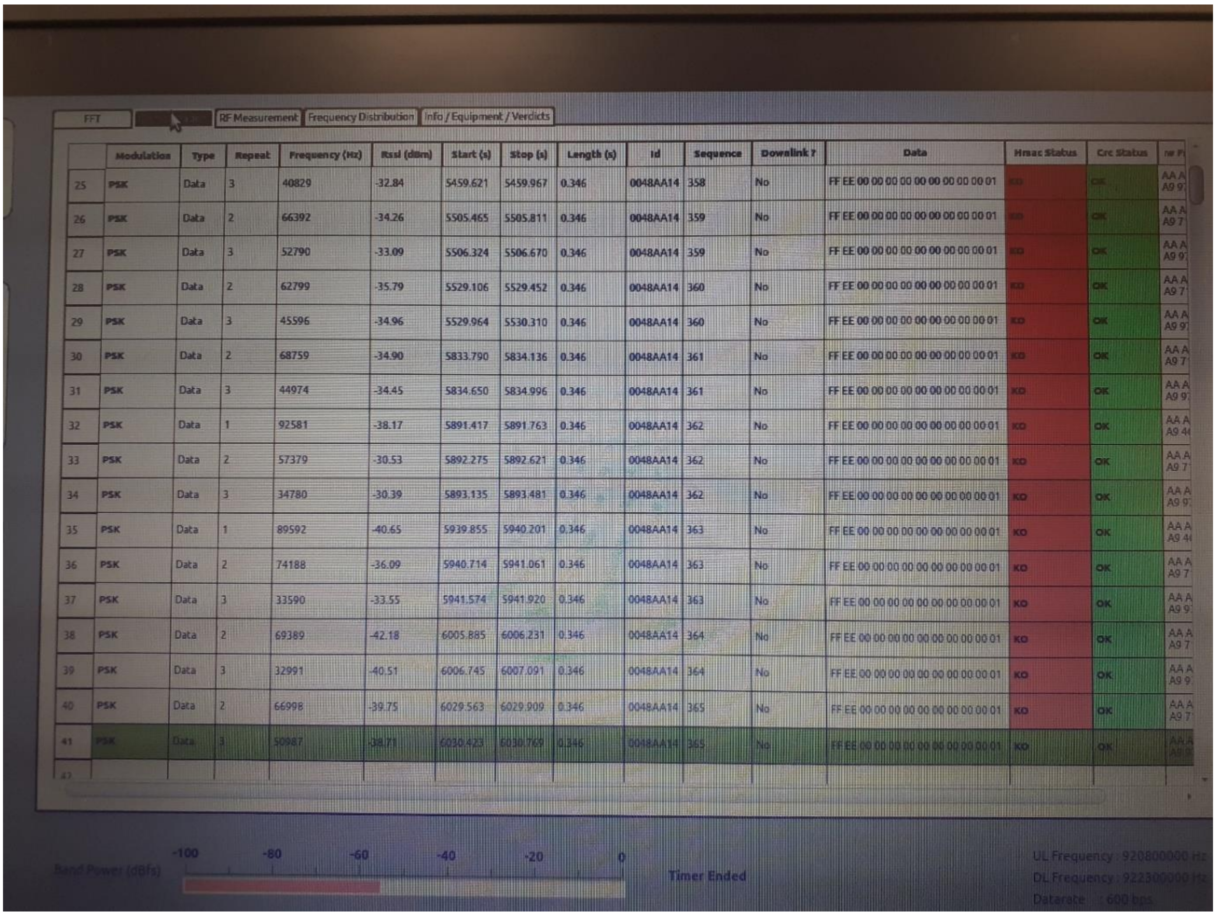


Figure 6 - Received Data Graph showing gaps.

While this fixed the issue temporarily the overall problem was not solved. There were still transmission gaps where data should have been. This led to an investigation into the radiation pattern of the antenna being used.

According to the datasheet, the antenna being used was based on the radiation pattern and had a torus shape with holes along the centre axis of the PCB. This meant that the terrestrial coverage was significantly hampered by this configuration. This was confirmed via testing with a Sigfox analyser that allowed for the device's transmission strength to be evaluated in different orientations as seen in Figure 7.



	Modulation	Type	Repeat	Frequency (Hz)	Rssi (dBm)	Start (s)	Stop (s)	Length (s)	Id	Sequence	Downlink ?	Data	Hmac Status	Crc Status	Nw F
25	PSK	Data	3	40829	-32.84	5459.621	5459.967	0.346	0048AA14	358	No	FF EE 00 00 00 00 00 00 00 00 00 01	KO	OK	AA A A9 9
26	PSK	Data	2	66392	-34.26	5505.465	5505.811	0.346	0048AA14	359	No	FF EE 00 00 00 00 00 00 00 00 00 01	KO	OK	AA A A9 7
27	PSK	Data	3	52790	-33.09	5506.324	5506.670	0.346	0048AA14	359	No	FF EE 00 00 00 00 00 00 00 00 00 01	KO	OK	AA A A9 9
28	PSK	Data	2	62799	-35.79	5529.106	5529.452	0.346	0048AA14	360	No	FF EE 00 00 00 00 00 00 00 00 00 01	KO	OK	AA A A9 7
29	PSK	Data	3	45596	-34.96	5529.964	5530.310	0.346	0048AA14	360	No	FF EE 00 00 00 00 00 00 00 00 00 01	KO	OK	AA A A9 9
30	PSK	Data	2	68759	-34.90	5833.790	5834.136	0.346	0048AA14	361	No	FF EE 00 00 00 00 00 00 00 00 00 01	KO	OK	AA A A9 7
31	PSK	Data	3	44974	-34.45	5834.650	5834.996	0.346	0048AA14	361	No	FF EE 00 00 00 00 00 00 00 00 00 01	KO	OK	AA A A9 9
32	PSK	Data	1	92581	-38.17	5891.417	5891.763	0.346	0048AA14	362	No	FF EE 00 00 00 00 00 00 00 00 00 01	KO	OK	AA A A9 4
33	PSK	Data	2	57379	-30.53	5892.275	5892.621	0.346	0048AA14	362	No	FF EE 00 00 00 00 00 00 00 00 00 01	KO	OK	AA A A9 7
34	PSK	Data	3	34780	-30.39	5893.135	5893.481	0.346	0048AA14	362	No	FF EE 00 00 00 00 00 00 00 00 00 01	KO	OK	AA A A9 9
35	PSK	Data	1	89592	-40.65	5939.855	5940.201	0.346	0048AA14	363	No	FF EE 00 00 00 00 00 00 00 00 00 01	KO	OK	AA A A9 4
36	PSK	Data	2	74188	-36.09	5940.714	5941.061	0.346	0048AA14	363	No	FF EE 00 00 00 00 00 00 00 00 00 01	KO	OK	AA A A9 7
37	PSK	Data	3	33590	-33.55	5941.574	5941.920	0.346	0048AA14	363	No	FF EE 00 00 00 00 00 00 00 00 00 01	KO	OK	AA A A9 9
38	PSK	Data	2	69389	-42.18	6005.885	6006.231	0.346	0048AA14	364	No	FF EE 00 00 00 00 00 00 00 00 00 01	KO	OK	AA A A9 7
39	PSK	Data	3	32991	-40.51	6006.745	6007.091	0.346	0048AA14	364	No	FF EE 00 00 00 00 00 00 00 00 00 01	KO	OK	AA A A9 9
40	PSK	Data	2	66998	-39.75	6029.563	6029.909	0.346	0048AA14	365	No	FF EE 00 00 00 00 00 00 00 00 00 01	KO	OK	AA A A9 7
41	PSK	Data	3	50987	-38.71	6030.423	6030.769	0.346	0048AA14	365	No	FF EE 00 00 00 00 00 00 00 00 00 01	KO	OK	AA A A9 9

Figure 7 - Sigfox Analyser Log from Monitoring Device

Therefore, the device had to be rotated perpendicular to its central axis as can be seen in and this led to a performance increase in signal strength for terrestrial coverage. The importance of the terrestrial coverage is that the Sigfox network is a terrestrial network so the priority for signal strength is across rather than upwards. Therefore, by changing the orientation the stability of the messaging system was improved thus leading to further tests that have effectively no missed messages. There are occasionally dropped messages, but these only occurred during weather events which could have impeded the transmission strength.

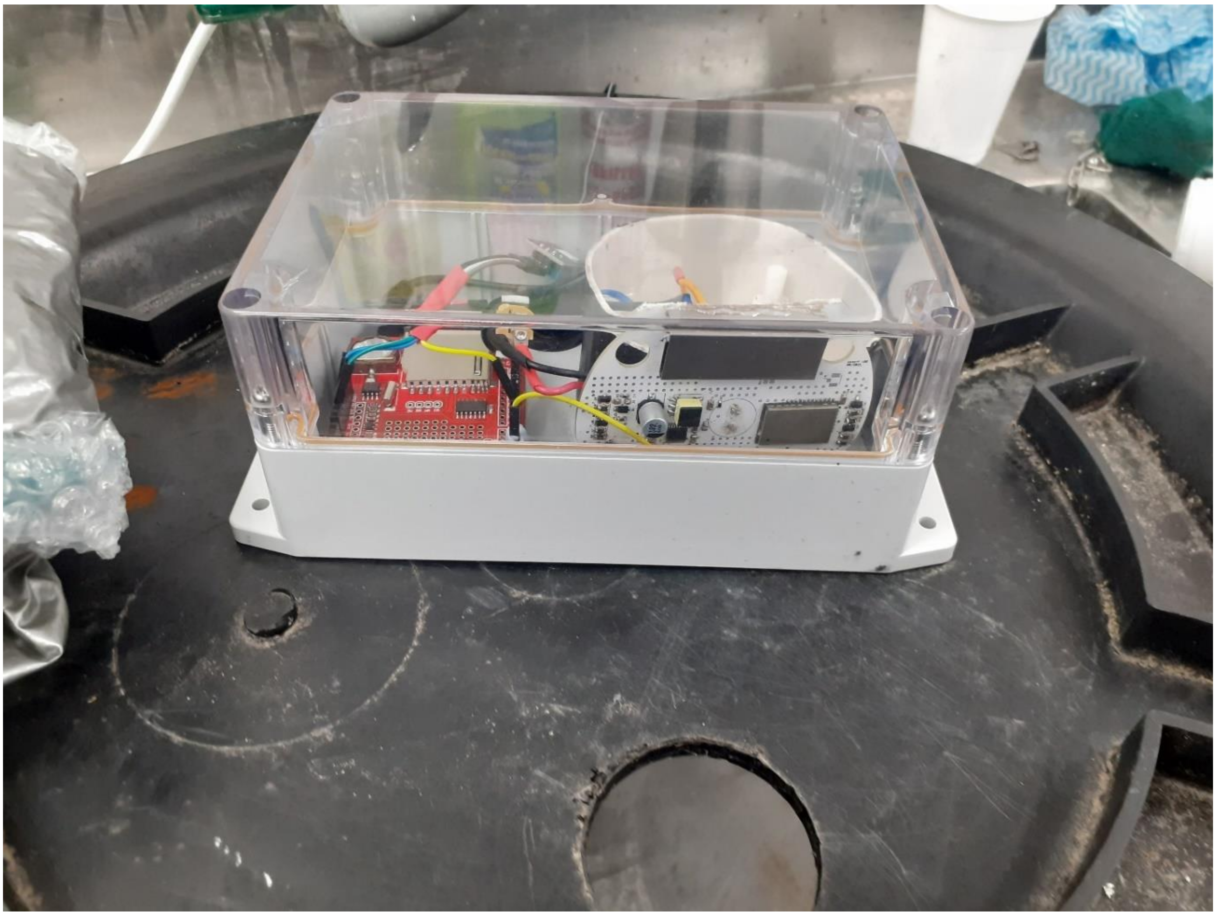


Figure 8 - PCB Vertical Configuration with extra logging equipment

Orientation

The change to the orientation of the board led to the redesign of the PCB. The redesign removed the wires connecting the device to the transducer and soldered it directly to the board, allowing for a decoupling medium between the board and the sensor, as well as changing from a circular shape to a long rectangular one as can be seen in Figure 9. This was to allow the transducer placement to remain the same and limit the number of changes needed to be made to the chassis profile.

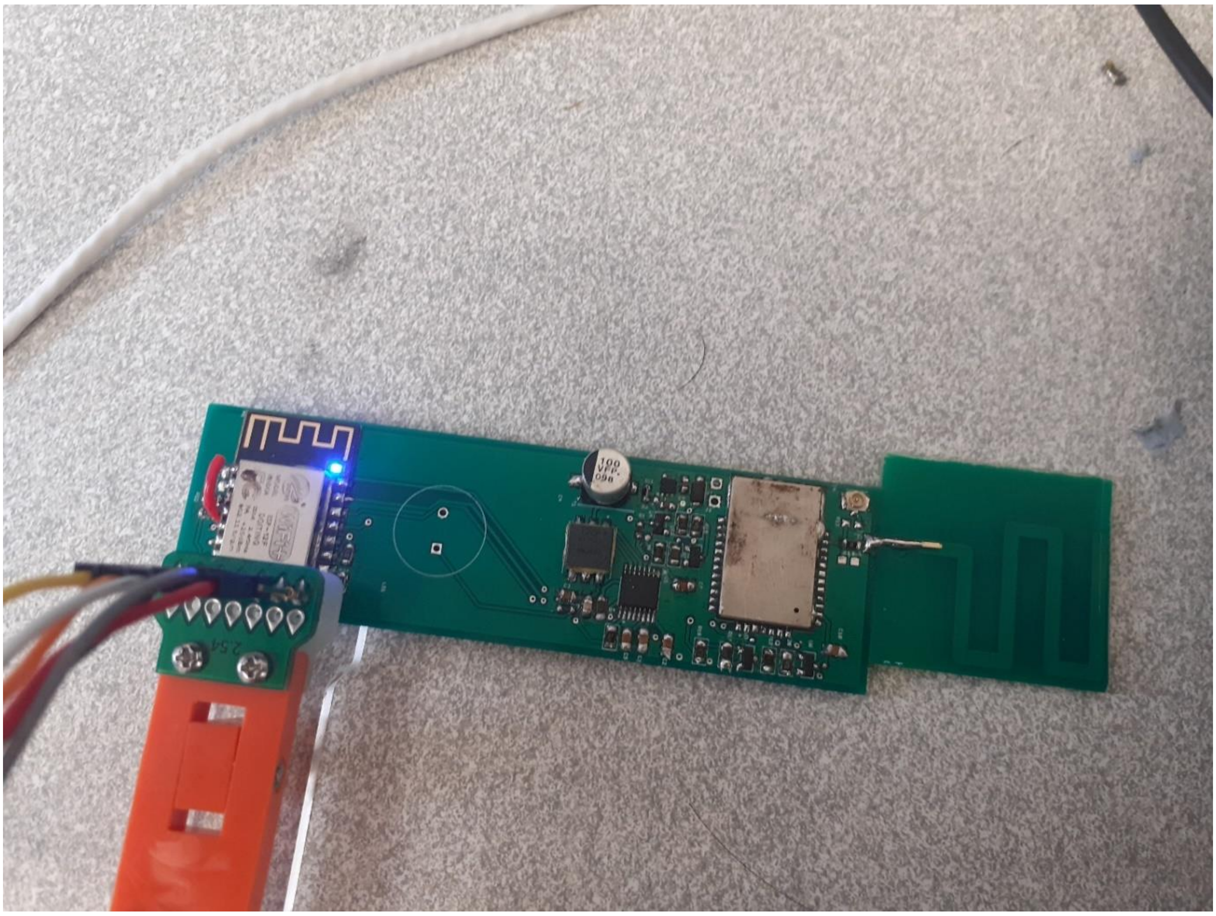


Figure 9 - PCB with Testing Antenna and Equipment

This new PCB design switched from a stamp antenna to a meandering monopole antenna as the necessary space for the stamp antenna was not readily available.

Software & Electronic Design

Software

The software can be broken down into four components:

- Initialisation
- Communication
- Data Acquisition
- Data Processing

Initialisation

The initialisation of the software can be further broken down into blocks.

The first block sets up the serial communication within the device. This links up the CPU with the PGA460/US sensor chip and the Sigfox module/communication chip.

The following block, which was added after the improvements were made, accesses and verifies the RTC memory. This memory holds earlier readings, if any exist, and readings are saved to local memory for easy access later in the software.

Data Acquisition

The data acquisition starts by initialising the PGA460 to the predefined settings that were identified to work effectively during testing as shown in Figure 10, Figure 11, and Figure 12.

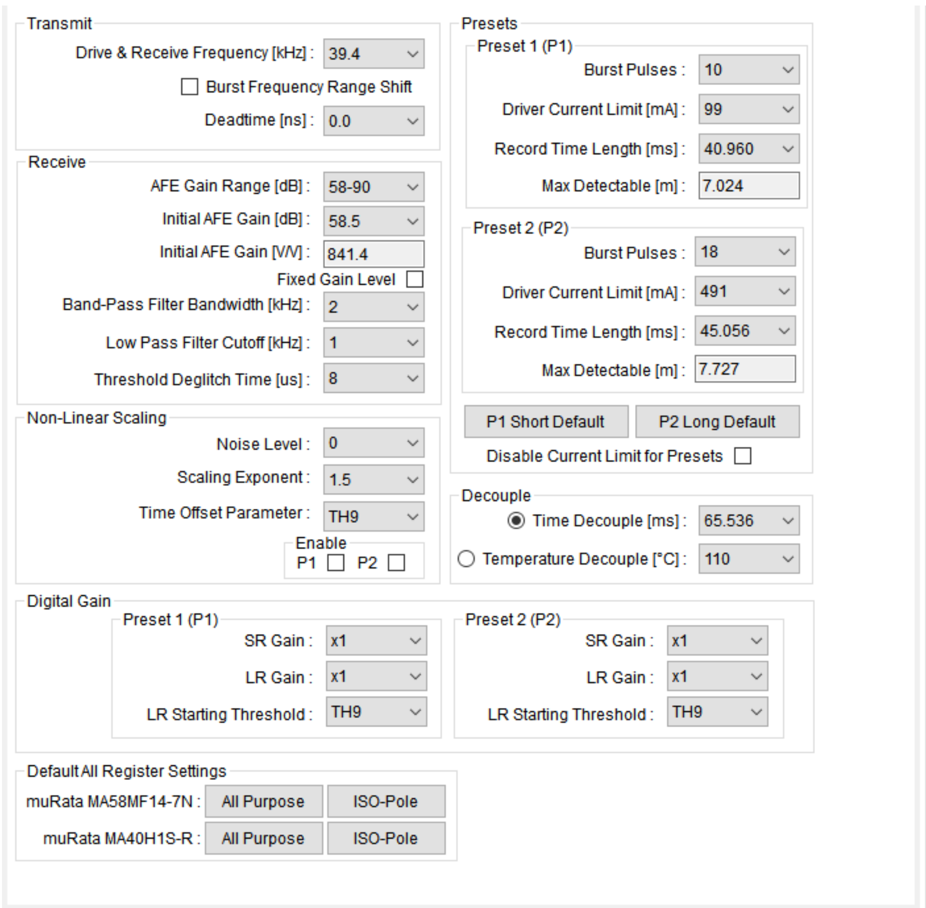


Figure 10 - Ultrasonic Sensor Settings/Parameters

The key features in Figure 10 that have a significant impact on the operation and performance of the US sensor were the following:

Frequency choice is important as it is dependent on the capabilities of the transducer being used and the amount of power available to drive the signal. This is due to the higher frequency requiring more power to drive the signal than a lower frequency with the same level of signal strength. Therefore, selecting a slightly lower frequency of 39.4kHz with a 40kHz rated transducer was a method of reducing overall system power consumption while keeping performance.

Gain controls control how much the received signal is initially boosted by, in this case, 58.5 dB, and the range that the time-variant gain can be within, which is 58-90 dB.

The next important setting is the built-in bandpass and low pass filter options which allow the device to remove excess noise when tuned correctly.

The final setting controls the pre-set which controls the signal which is sent and received by the transducer. Firstly, the number of pulses per reading allows the device to control the sample rate to find a measurement. If there are too many pulses per reading, they begin to overlap which causes false readings and noise due to there not being enough settling time. The more pulses per reading also affect how strong the response that is received. Combining that with the driver current limit, which controls how much power is supplied to the transducer, allows control over the strength of the first transmission of the transducer while keeping control over the power consumption. Having a strong signal is good, however, too strong a signal inside an enclosed tank causes unnecessary echoes and saturates the return signal which causes the duration of peaks to be elongated and increases the error when reading measurements. Therefore, a set of ten pulses limited to 99mA was selected.

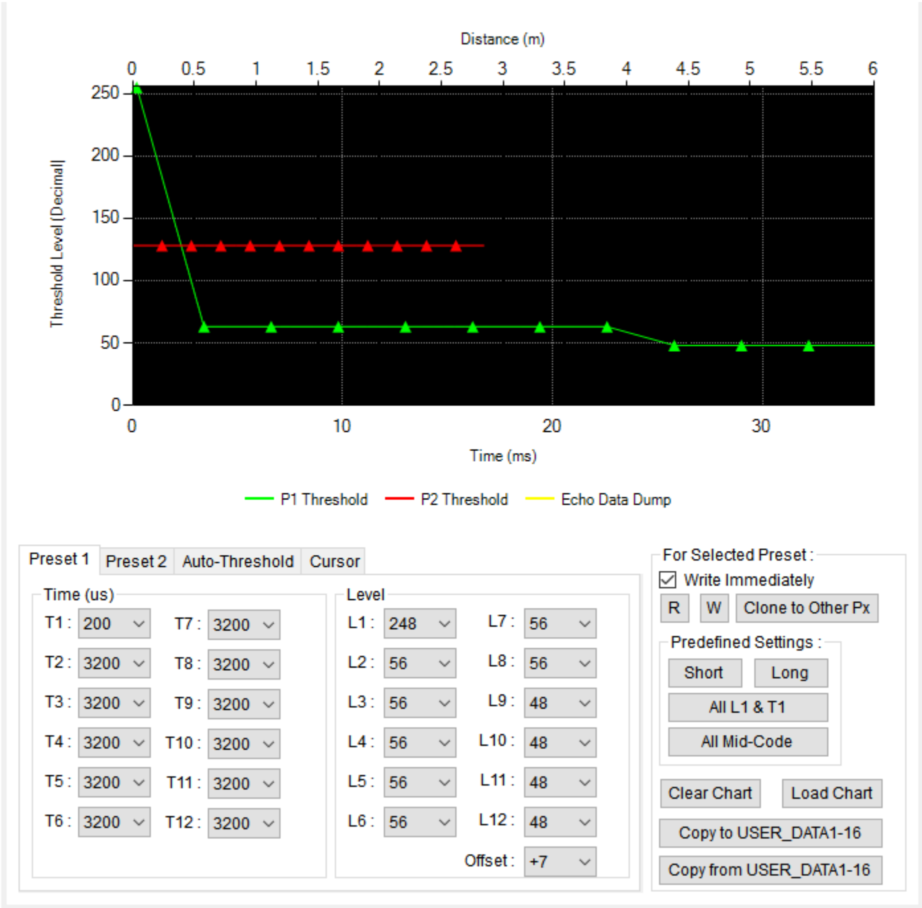


Figure 11 - Ultrasonic Sensor Thresholds

Figure 11 shows the thresholds that were set for the device. These thresholds dictate what signal strength is needed for the reading to be accepted as an actual reading and not disregarded as noise. The threshold is max at the beginning to avoid issues where the device experiences interference on the transducer and causes a false zero reading. The threshold decreases after a period of waiting for the return pulse to ensure a weaker response, due to power loss over greater distances, is taken into consideration.

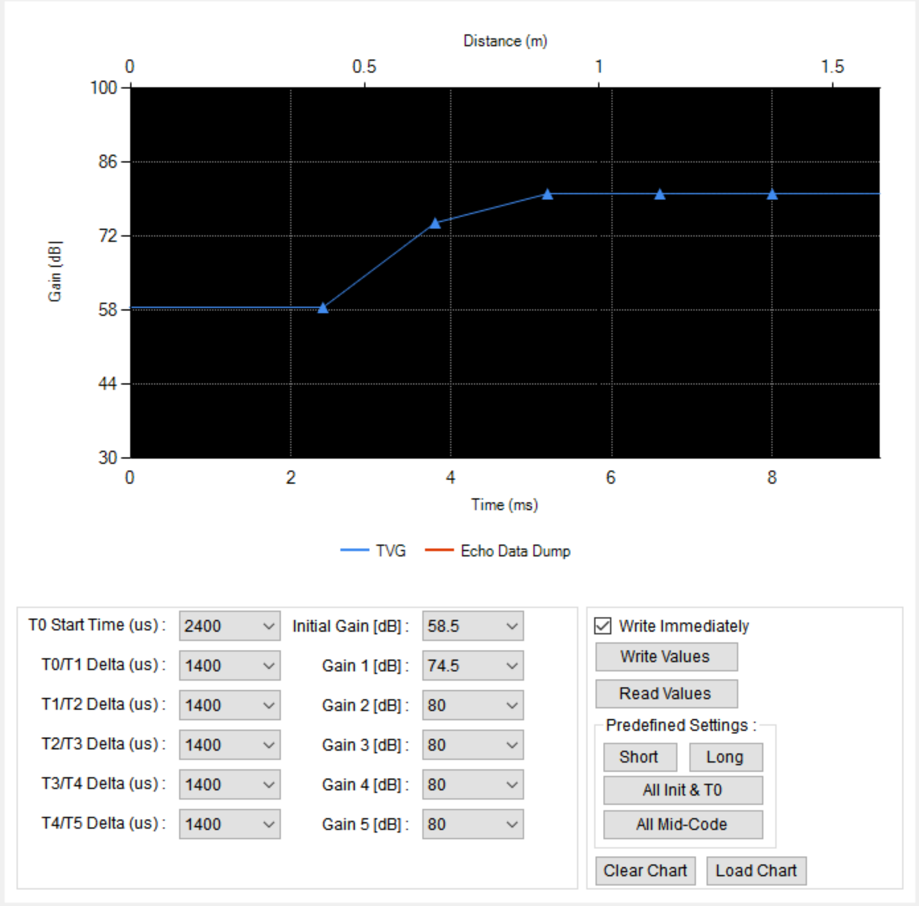


Figure 12 - Ultrasonic Sensor Time Variant Gain

Figure 12 shows the gain that is applied to the received signal with 58.5 being the initial gain, as set in Figure 10. The gain increases over time to match the natural weakening of the return signal. The gain does not increase linearly to avoid instances where a reflection is boosted over the actual detected object.

After this initialisation, the device activates the Ultrasonic Sensor and takes five sets of readings between 75ms and 200ms each reading. This is to make sure the settling times between each set do not affect the results and that any echoes between readings have dissipated. These readings are then stored for use in the data processing section.

Data Processing

Once the data is acquired the system begins to process it via the algorithm in Figure 3 to remove any harmonics that exist. The system then checks for the most consistent and strongest reading that reoccurs in multiple sets. This is to reduce the possibility of a false reading due to a spike in noise. This value is then compared with existing measurements to see if the value is a possible continuation of the last set of measurements. If the reading is not continuous it will try to make new measurements. If it fails a set number of times, it will accept the next practical measurement.

Communication

Finally, once the device has a reading selected it takes that and converts it into a Sigfox-compatible string and sends it, and then puts itself into a deep sleep.

Electronics

The electronics in the device can be broken into four categories: Ultrasonic Sensor, Communications, Processing, and general electronics. The first three are the essentials to perform the data collection, processing, and communication, respectively. While the last category is dedicated to controlling current and regulating the power supply.

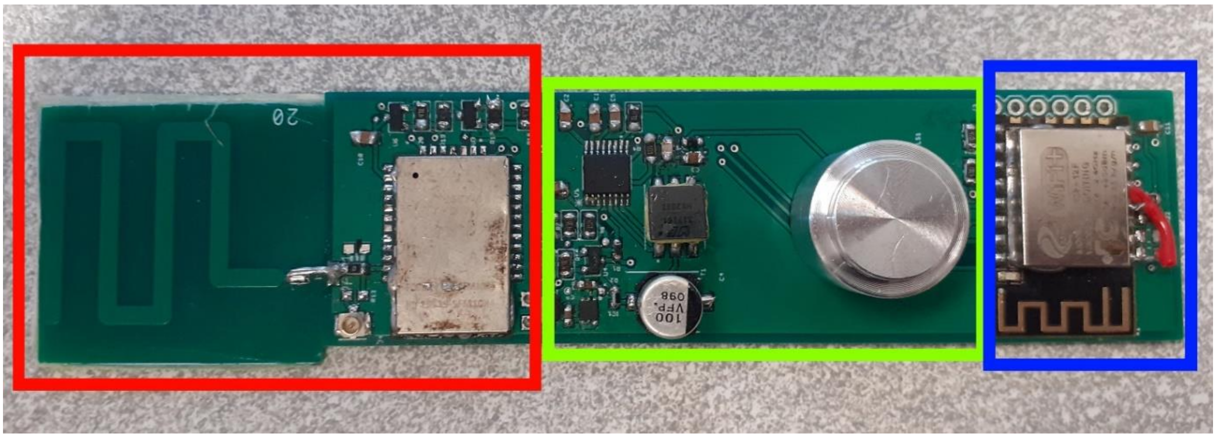


Figure 13 - Assembled PCB (Left – Antenna and Comms), (Middle – Ultrasonic Sensor), (Right – Processor)

The board is compact to ensure a small profile device, with space around the transducer to allow for the necessary decoupling. The meandering pole antenna is designed based on the Texas Instruments specifications for antennas between 868MHz and 955MHz and was chosen over the stamp antenna due to the orientation issue and to reduce the number of unnecessary components. To keep communication lines as short as possible, to avoid interference, the Sigfox module is found next to the antenna as shown in the left box in Figure 13. This section also holds the high-side switch which allows the processor to shut off virtually all current to the communications module when not in use. This is done to drop the quiescent current, the passive current that is constantly being used, as much as possible to increase the longevity of the device. The next section holds the ultrasonic sensor, namely the PGA460 module, and the transducer. The space around the transducer is necessary due to the way it is decoupled in the device with a connector holding the transducer in place in the chassis. The right-most section is the processing chip ESP8266 which is placed as far away from the Sigfox Antenna to reduce the interactions the antennas have with each other.

Chapter 2- Physical Chassis

The firmware while an integral part was not the only component to undergo testing. It was expected but with insufficient waterproofing with the prototypes, which were made with PLA plastic, there was major corrosion on the batteries in the first testing in October 2021. This was due to the structure of the 3D printed body allowing water and condensation into the interior of the device as the relative humidity changed between the two areas.

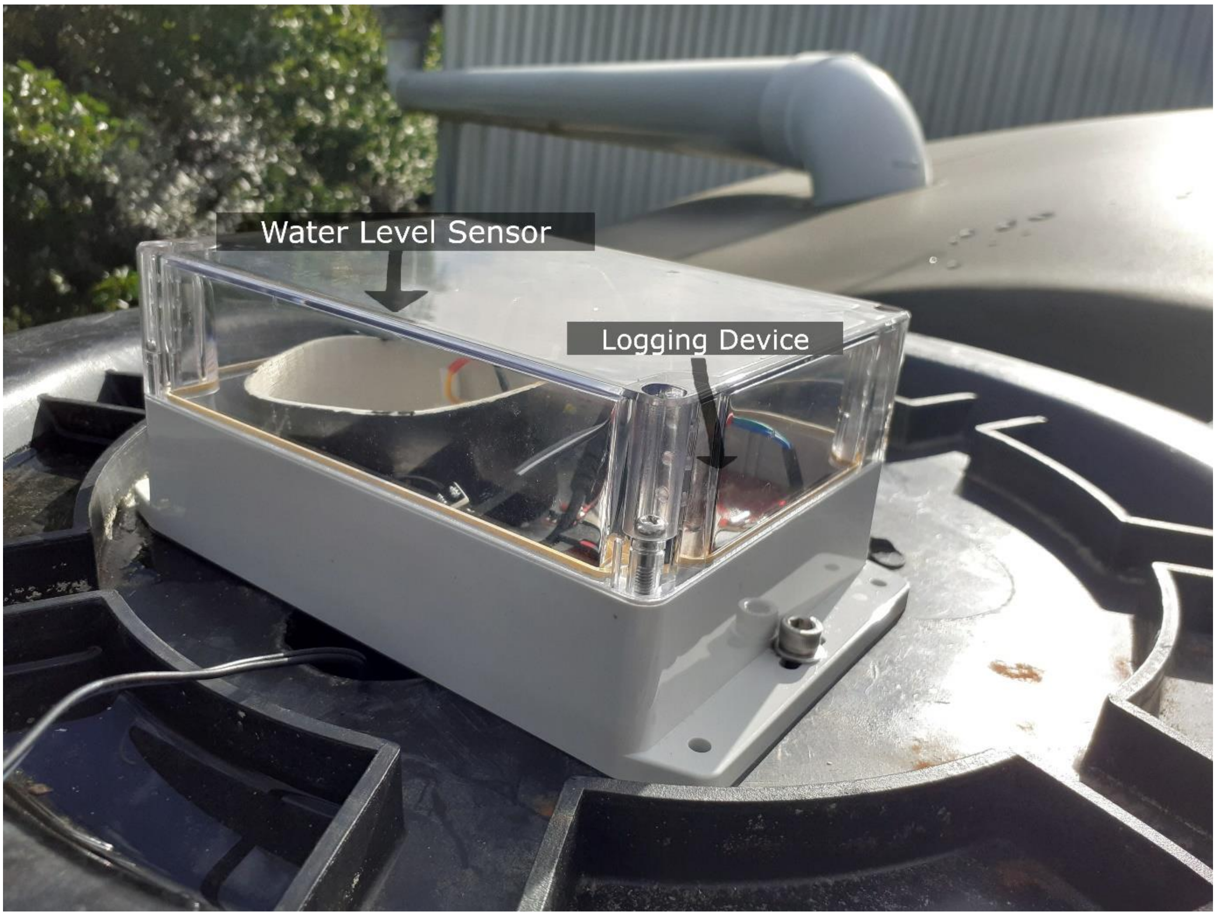


Figure 14 - Logging Device in Situ

This corrosion that had been attributed to the condensation that had formed inside the device was not the sole cause. During a later outdoor test, the device was placed in a logging device placed in the same location as seen in Figure 14. During the summer period the temperatures reached +30℃ outside of the logger but, as was later discovered when a temperature sensor was added, the temperature often exceeded 60℃ inside the device. As the operating temperature of AA batteries is 21℃ at nominal humidity this massive increase in temperature, worsened by the increase in humidity, led to the batteries reaching their limits and beginning to leak/corrode. There is evidence to support this claim of temperature damaging the batteries over the condensation as there were two devices deployed in the same location. One was more thermally isolated but both experienced condensations build up in the device. However, while the more thermally isolated device had a significant amount of water inside there was significantly less corrosion when compared to the device in the logging case.

This led to the review of the specifications of the device and to what degree it needs to be UV, heat-resistant, and water-resistant.

Physical Design

Figure 15 - Initial Prototype Chassis

The original design of the chassis was effectively two components:

- Electronics case - which holds the batteries and PCB.
- Transducer tube - which holds the transducer.

When the device is installed, the electronics case is situated on the outside of the water tank while the transducer tube is inserted into a hole in the lid of the water tank. This led to an interesting phenomenon where the device is experiencing two relatively different sets of environmental conditions. With the transducer tube, the part is constantly in an environment with condensation and humidity that fluctuates based on external temperatures and the level of water. Whereas the outside is directly exposed to the elements.

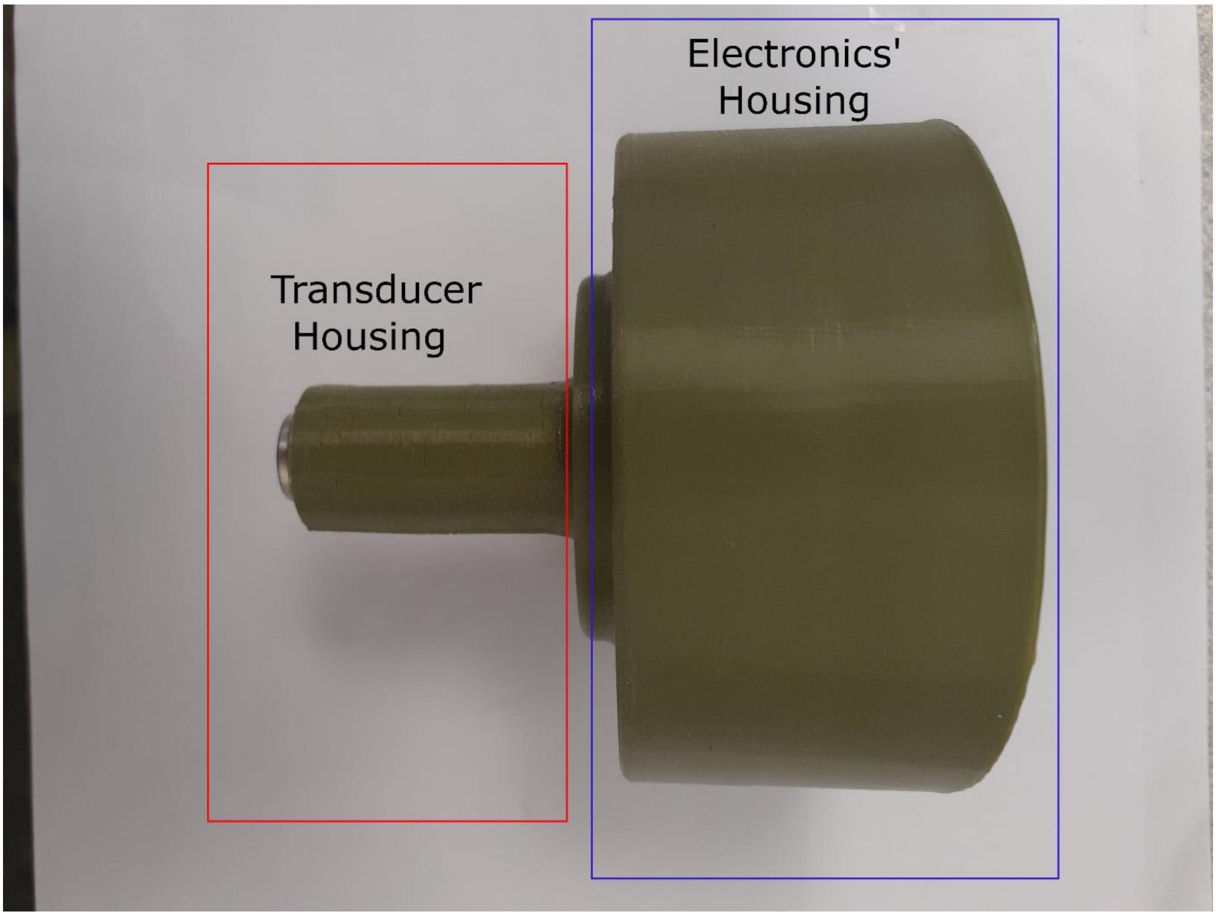


Figure 16 - Testing Prototype

Electronics Case

The electronics case was originally designed to match the cylindrical shape of the water tank. The size and volume were made to fit the circular PCB and battery pack. The lid was designed with the addition of O-rings to try and create a seal on the device to reduce the ingress of water and dust which would affect the operation of the device long term.

To allow for testing in the field rapidly and improvements to be implemented easily during development injection moulding or rotational moulding was not suitable. This was due to the monetary and time cost associated with making small runs via using these moulding techniques. Specifically, the cost surrounding the creation of new tooling each time a change was needed. The cost aspect was also the reason that machining the case was not possible. Therefore, the only remaining possibility for manufacturing the casing to specification was using 3D printers. This allowed for a quick turn-around of improvements while keeping enough structural integrity to allow in-situ testing.

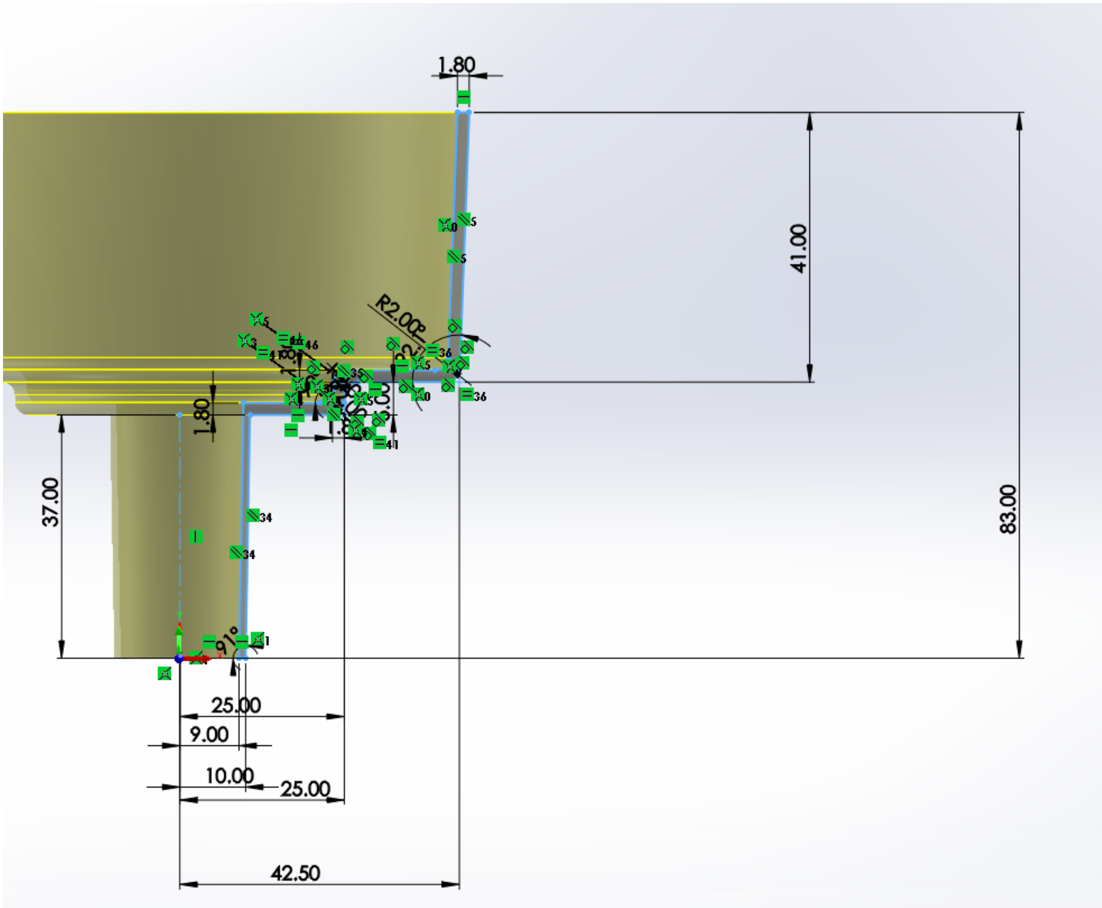


Figure 17 – Solidworks cross-section of housing (in mm)

The casing was designed in Solid Works, the cross-section of which can be seen in Figure 17, and printed in the MAFDL 3D printing lab as it was readily available. The printing material selected was ABS which is a common 3D printing material and readily available in the lab.

Transducer Tube

The other part of the housing that needed extra care was the mounting system for the transducer. The original design consisted of press-fitting a transducer into a tube with a lip to prevent the transducer from slipping past the desired point. This allowed the transducer to be in a fixed location while being disconnected from the PCB.

Improvements

During the field testing of the device, the physical design's flaws were made clear and aided in the refinement of the overall design.

Condensation

One of these issues was the introduction of condensation to the testing environment. As the metallic transducer face was parallel to the water the temperature and humidity changes caused condensation to form on the transducer's surface. While minimal condensation did not affect the overall performance of the device whenever condensation reach a significant enough amount to cause a dome of water to form over the face there were issues where the pulses were dampened significantly. This dampening of the pulses leads to instances where no return signal is given as the condensation has essentially absorbed the sound waves.

This was confirmed to affect the device by applying water to the transducer's face and trying to get a reading that matched the expected reading in both an upwards and downward configuration. Both directions showed a lack of a first pulse and response signals when water was present.

By seeing the lack of pulses and responses it was decided to look at existing ultrasonic devices and how they overcame the condensation issue.

Devices like Siemen's liquid level sensors have a hydrophobic spray applied and are tilted to help water running off the face and not letting the water accumulate to the point that it has a significant impact. Another way of avoiding this problem was taken by Flowline with their level sensor. The method involved mounting the transducer vertically so that the water does not bead enough to cause disruption and reflecting off a 45° wall to keep the wave detecting the surface below the device.

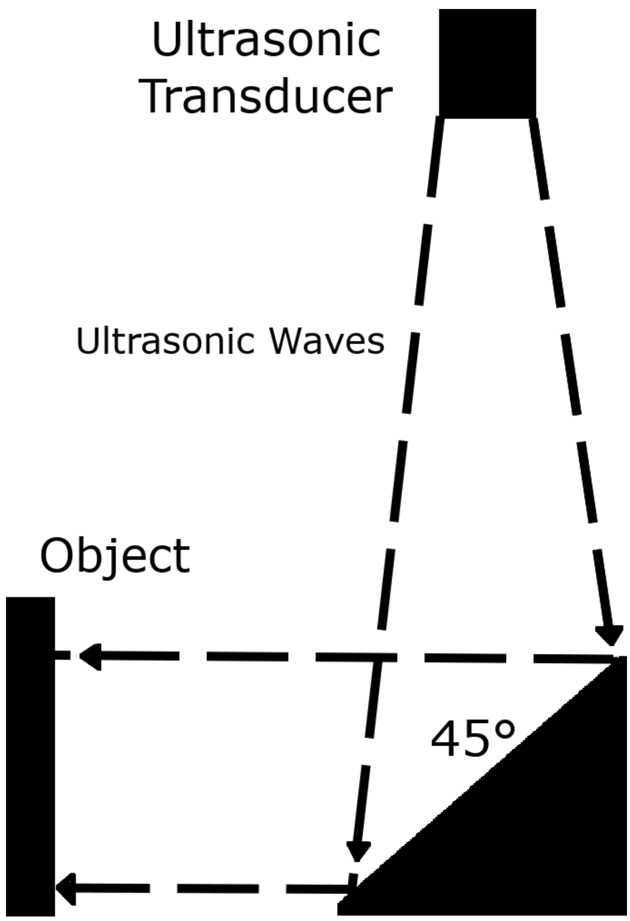


Figure 18 - Principle Behind Christos M. Koukovinis Patent

The Siemen's method of tilting the device to allow runoff works well in industrial tanks due to their size and shape. However, on average household water tanks fluctuate in size between 1,000L to 30,000L [43] the tank is not as large, so the wave has a higher chance of reflecting off the wall at lower water levels. Therefore, it was decided to use a similar method to the Flowline device which appears to be based on a patent from 1986 by Christos M. Koukovinis for an Ultrasonic Distance Sensor [44]. The patent highlights a device that reflects the ultrasonic waves perpendicular to the transducer as seen in Figure 18. Installing a transducer horizontally so that it bounces off a reflective surface and towards the water in the tank allows the water to run off the vertical surface before the water beads to a significant amount. It also has the added benefit of being parallel to the water, so the response is stronger than if it was at an angle.

To implement this new method of mounting the ultrasonic sensor it was necessary to try both a curved and flat surface. This is due to the original patent being a rectangular device while the design of this device was round. This made it necessary to see if the device required a flat wall, like in the patent, or a curved wall which would focus the return signal to the transducer and offset any power loss caused by reflecting the waves off the wall.

Two sets of connectors were printed out of PLA to attach to the existing device. This allowed a test to be done where all the electronic components remained the same and only the end effector was changed. Thus, limiting the number of variables that could affect the performance of the device.

During operation, the number of pulses was adjusted to see the minimum strength signal compared to the nominal strength response.

Table 8 - New Transducer Connector - Curved vs Flat

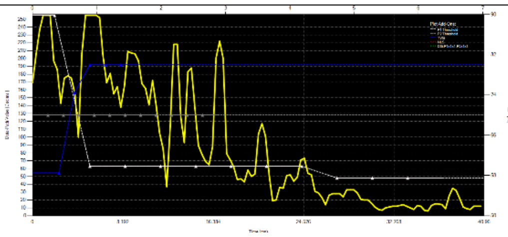
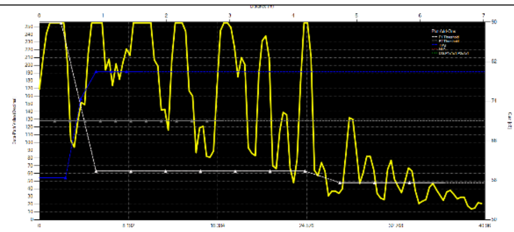
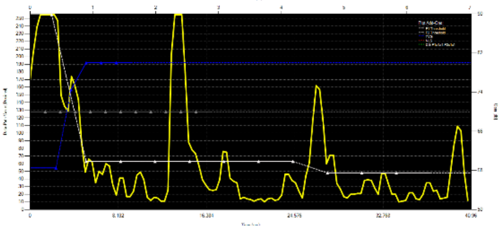
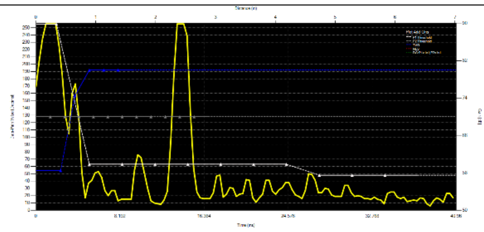
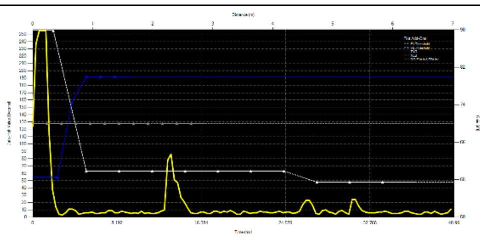
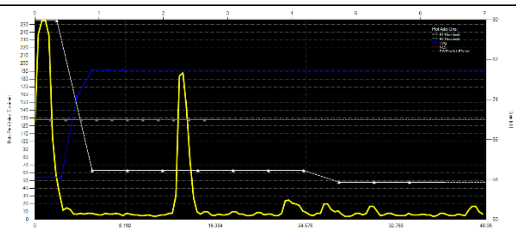
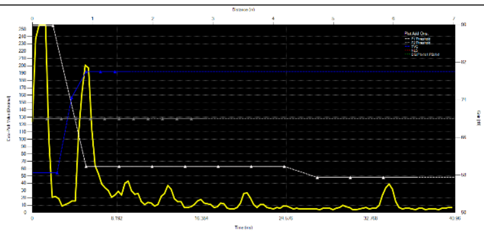
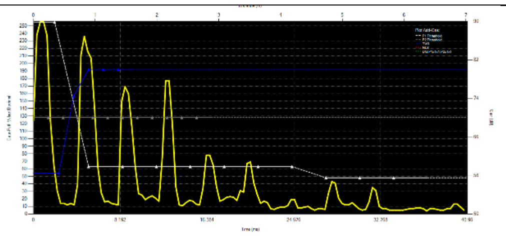
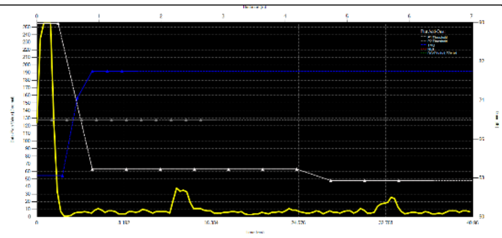
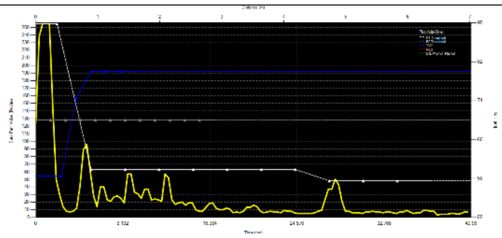
Distance	Type of Wall	
	Flat	Curved
0.7m (15 pulses)		
2.2m (15 pulses)		
2.2m (1 pulse)		
0.7m (1 pulse)		

Table 9 - Old Transducer Connector

Distance	Type of Wall
	No Connector
2.2m (1 pulse)	
0.7m (1 pulse)	

To make sense of these graphs it is necessary to breakdown the legend:

- The white line denotes the threshold for finding peaks.
- The blue line denotes the Time Varying Gain (TVG) being applied to the measurements.
- The yellow line denotes the Response Signal as Strength vs Time.
- The grey line can be ignored.

After collating the data from the device in three configurations at two set distances, as seen in Table 8 and Table 9, it was possible to note key factors.

Firstly, by noting the readings when the pulses are at their minimum, it is possible to find the base performance of the device. This is because by controlling the number of pulses the strength of the response is altered, with more pulses increasing the response trending towards saturation as can be seen in the first pulse which clips at 255 values. By seeing the measurement at 2.2m the device shows the strongest response with a curved reflector and an acceptable response with a flat reflector. However, the default configuration performed below acceptable standards - in this case below the threshold for the identification of peaks. This was consistent with the closer measurement at 0.7m. This led to the conclusion that the design did not just influence removing condensation but also acts as a method for focusing the soundwaves.

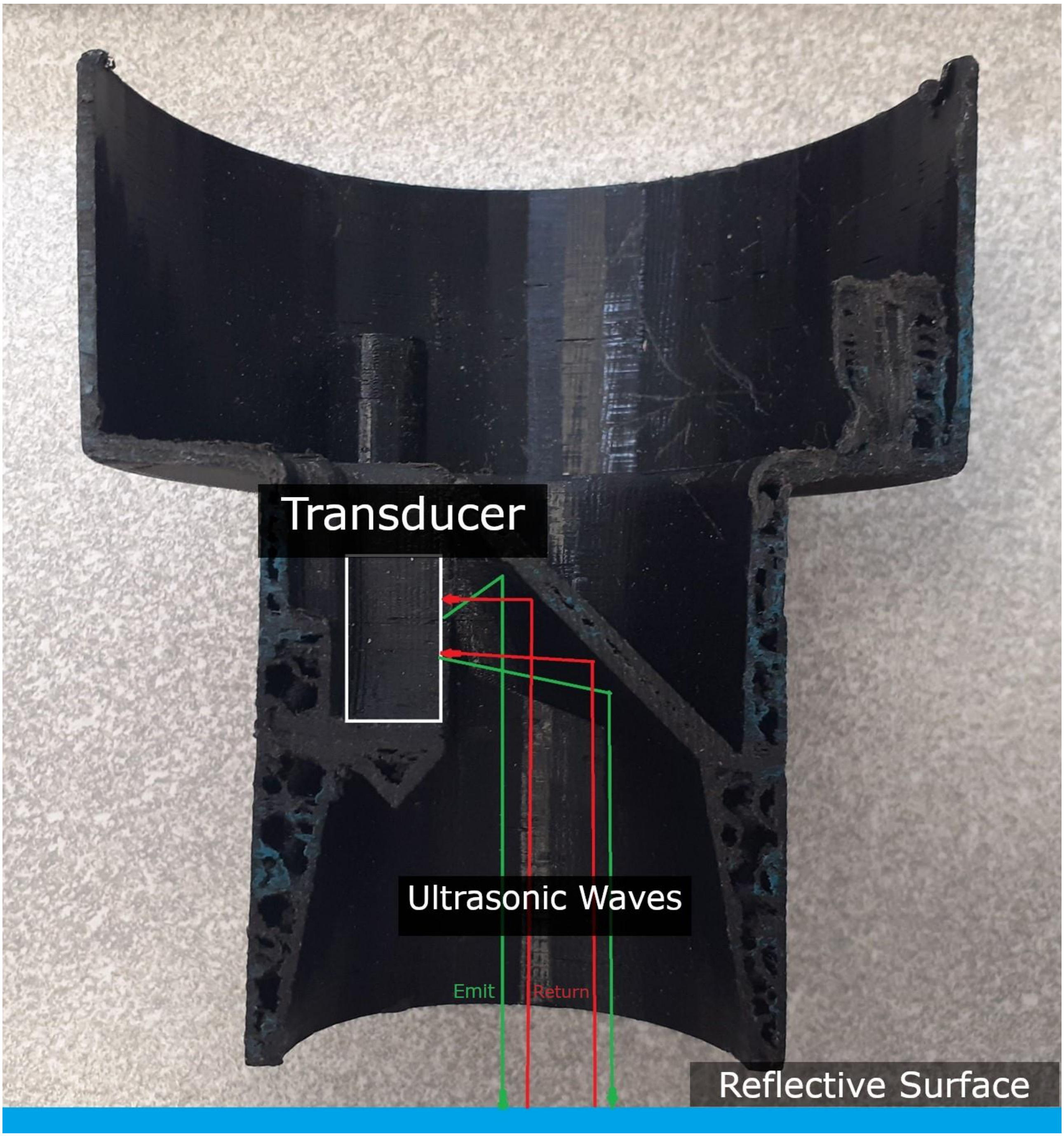


Figure 19 - Cross-section of Chassis

The device goes from emitting in a hemispherical pattern to switching to a more focused cone. This can be used to explain the dramatic performance difference between the original configuration and the updated configuration. However, there is an increase in echoes that appear with the curved surface compared to the flat. This could be due to the curved surface further focusing the response. This can be proven in Figure 19 where the reflected waves are focused due to the concave shape of the wall. These echoes were problems that the software was able to mitigate as was mentioned in Chapter 1.

After applying these changes and redeploying the issue of the water beading was removed and there was the added benefit of having a stronger response.

Angle

Figure 20 - 3D printed Angles

When the device was running, the pitch of the roof of the water tank was raised as a potential issue. When installed in the water tank the device may not be parallel to the water. This could be due to either the pitch of the roof or even the pitch of the water tank itself. The issue was the potential for the response to be inaccurate as the device's response was not from an exactly parallel surface.

This was assessed by creating 3d prints of varying angles that would simulate the different pitches in a controlled environment as seen in Figure 20.

Table 10 - Tank Roof Pitch Test

Set Distance (m)	Measured Distance (m)	Angle (°)
0.65	0.707	0
0.65	0.711	5
0.65	0.717	10
0.65	0.726	15
0.65	0.738	20
2.24	2.240	0
2.24	2.230	5
2.24	2.230	10
2.24	2.240	15
2.24	NaN*	20

*- *The device did not find a distance due to the prototypes code filtering it out as noise - when seen via the Onboard chip there was a clear peak*

From the above data, at closer distances, the angle has a marked effect with the distance varying by 0.021m at 20°. With all the measured distances being at a distance 0.05m more than the set distance. However, this increase in distance is due to the design of the chassis where the transducer must reflect off the curved wall and then toward the surface. This means this increase can be safely ignored.

The effect this has on the longer distances, there is no discernible difference. This is most likely due to the way that the wave propagates and spreads out further from the transducer it is. As this is the standard behaviour of a wave.

Waterproofing

During testing, the device was shown to have issues with condensation forming inside the device. This was due to the nature of 3D printing the device where the layers allow the condensation to permeate through the walls which can be seen with the condensation on the batteries in Figure 21. As it was not economically feasible to create an injection mould for the prototype a plastic spray was used instead, namely plasti-dip, as can be seen in Figure 22. This allowed for greater protection from condensation and combining this with a silicon seal on the inside improved the water resistance significantly.

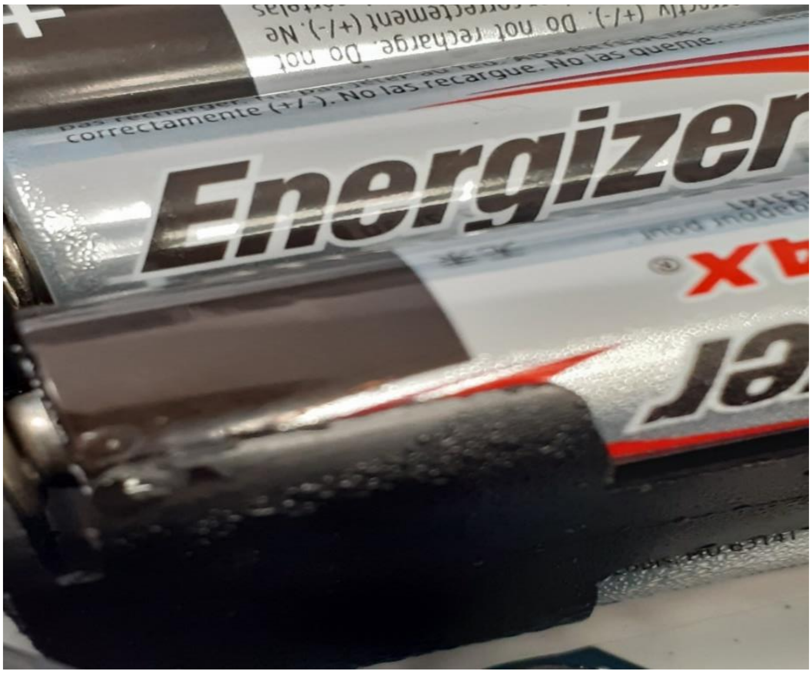


Figure 21 - Condensation on Batteries due to LOW IP rating of original case

Figure 22 - Plasti-Dipped Water Tank Sensor

The effect of water was minor during short tests of 2-3 weeks. This was made clear when one of the test units was not correctly insulated and was partially filled with water but continued to work.

Heat

Whilst the environmental effects of water do not actively hamper the device's operation, the sun is a major concern. This was made clear when, during the operation of one of the prototypes, the batteries leaked when the housing experienced exposure to direct sunlight on +28°C days. The event happened during a +28°C Day and was repeated on another day when the device was installed in a plastic box for data logging purposes.

Both these days had unusually elevated temperatures, for the region, of 28°C+ and were under direct exposure to the sun.

Using a data logger in the test device it was possible to access the humidity as well as the temperature. This was instrumental in showing that the environment the device was in exceeded temperatures of 60 degrees Celsius. The temperature is well above the operating temperature of the batteries. This caused the batteries to leak and the device to become disabled. This has not been an issue normally as, when the device has been plasti-dipped, the device generally has been heat-resistant with no identified issues while running and correctly installed.

Chapter 4 - Multispectral Aspect

As the quantity of the water has been monitored and assured by the former half of this device, for the device to be a complete and holistic look at water storage it needs to identify the water quality. This can usually be in a achieved a few ways including, but not limited to, taking a sample of the water, and adding chemicals to observe reactions. This method is not suitable in this instance as it relies on the removal and observation of samples or requires a constant supply of chemicals to identify issues in the water. However, having a device that performs a comprehensive analysis of the water is not technically needed. if signs of potential water quality degradation can be found preventative steps can be taken to prevent the situation from deteriorating further.

This meant it was necessary to identify the possible water quality issues and their key identifiers which was done by reviewing the literature surrounding potable water quality in storage and the various impactors.

- List of water quality Issues
- List of their defining features
- Discussion of overlapping features

Hyperspectral Design

Organic matter such as algae had a major impact on water potability and posed an issue to water quality inside a water tank. It is possible to further specialise the device by switching from a hyperspectral device, a device that finds the continuous spectral response of an ROI, to a multispectral device, a device that finds a spectral response within set spectral bands. This specialisation of the device allows for a lower cost in both financial and computing resources.

Scanner Decisions

To create an effective low-cost spectral camera, to find the organic matter in the water tank, it is necessary to decide, based on the supporting literature, which method is most effective: both cost and performance-wise. Firstly, the different encapsulating methods include:

- Snapshot
- Push broom
- Point Scanning
- Wavelength Scanning

These methods are the current methods used in the real world to create data cubes of spectral data. By comparing their benefits and limitations it is possible to select a method on which to base a device off.

Snapshot

Snapshot is a method of hyperspectral Imaging that excites the entire region of interest and uses a prism array to segment the area into spectral data. This gives an entire snapshot of the area without moving the sensor or stitching together multiple slices of data into one data cube.

This method is suitable for Stellar Classification, Fluorescence Microscopy, Geology Measurements, and Medical Scanning as done by William R. Johnson with the CTIS [40]. This is due to the device being able to not only find the key features in a data cube but also how they relate to each other as there is little to no error between the rows and columns of the data cube.

The way this method works is the device takes a long-exposed shot ≥5s which allows the device to absorb nearly all collected light up to 70% [36]. When the light is collected it is broken into its constituent waveforms by a prism array. This differs from other methods by the fact that it uses an array of prisms to avoid using moving parts. However, due to the prolonged exposure time, it is prone to movement artefacts and suffers when performing scans on non-stationary targets. Hence the reason the device used for the identification of celestial and terrestrial bodies which appear relatively stationary. For the use case of the inside of a water tank, the water stays relatively stationary unless the water tank is in use leading to a low possibility of movement artefacts.

Push broom Scanner

Push broom scanning is a method of hyperspectral imaging where the spectra of a slice of a region are recorded. The scanner is panned about the region of interest, which can be achieved by moving the device via a drone, or having the region move like the earth about a satellite or an assembly line.

This method is suitable for use in assembly lines [22] as a scanner is mounted in a stationary position above the moving conveyer belt which makes use of existing infrastructure to move the OOI through the scanner. This is like how a satellite would scan while staying stationary while the earth rotates.

Push broom scanners work on a smaller scale than the snapshot and only filters a section of light, a slice along the spatial plane, into its spectra using a filter/grating. The benefit of only scanning a single slice is the increase in spectral resolution that the device can have as it does not need to accommodate a prism array. This in turn means an equivalent grating or filter would offer a greater spectral resolution. However, the relationship between the columns is not as kept accurately as there is a time delay between the acquisition of each slice. The time delay causes slight differences in the spectral response due to the nature of the spectral response. For use inside a water tank, as the water is not always stagnant and the water can flow when being filled and emptied, there is no need to move the scanner across the surface and can just remain stationary. Due to the fact the device will not be checking constantly the time between readings will allow enough a change to be a baseline indicator of issues that can arise such as algae.

Point Scanning

Point scanning is one step more than the Push broom scanner as the device takes one point in the spatial plane and completes its data cube one point at a time. This gives a high spectral resolution for each spatial point.

This method is used with satellites such as the Landsat 8 for the use of land surveying. This is because the spatial resolution still covers a large area, and each point needs a greater spectral resolution to make up for the reduced spatial resolution.

This method works by focusing the light from a specific point in a spatial grid through a set of prisms that split the light into its spectra and onto the sensor. It differs from the Push broom by focusing on one sensor that encodes it into one column of the data cube. It does take longer due to the need to collect data from each individual point in the spatial plane. However, the greater spectral resolution can potentially offset this depending on the desired outcome when using the scanner. As the device only shows a signal point on the spatial plane, inside the water tank it would need to have a method to move around the entire space. However, as the media in the tank tends to propagate around, showing the spectral response of one point can still be a useful metric for finding widespread problems but will not give a holistic view of the entire tank.

Wavelength Scanning

Wavelength scanning differs from the other methods by recording the entire region but only a set of spectra at once. Hence the nomenclature "wavelength scanning."

This method is used in research in biological systems [23] due to its ability to focus on select spectra and, due to it collecting the entire spatial plane at the same time, preserve the relationship between adjacent points which is useful when comparing the behaviour of different points.

This method works by using an optics filter to allow only certain wavelengths of spectra at a time. The spectral resolution the scanner is capable of is based on how finely the bandpass filter can filter. The light is focused onto the sensor building the data cube with each layer of the spectral plane. While this device works best when comparing the same wavelength in the data cube, the relationship between the different wavelengths can be slightly disrupted due to the time delay which causes artefacts like the snapshot method which relies on the prolonged exposure time and a constant system. In the context of a water tank cyanobacteria is a major cause of water insecurity in water tanks making the ability to find it important. Fortunately, the signature reflectance of the cyanobacteria occurs around the wavelength range of 665nm and 709nm [30]. As the band of interest is quite compact the time difference between the spectral plane may have less of an effect. There it is possible to work in a water tank. However, the device may struggle if multiple spectra being evaluated are of differing wavelengths.

Initial Design

Using this knowledge, it was possible to create a simplistic hyperspectral imaging device that could show the spectral response of objects. This was achieved by adapting a program called the PySpectrometer by Les Wright, his design uses a spectroscope attached to the lens of a raspberry pi camera. This design would only function as a spectrometer and record a single slice of a hypercube thus acting akin to a point scanner where it records a point of spectra and moves along. However, to prove the efficacy of a low-cost device it would be sufficient.

Breaking down the device gives a similar setup to existing Hyperspectral Cameras:

Table 11 - Hyperspectral Device Breakdown

Stage	PySpectrometer	Components
Probing	As this device is going to be used in a water tank that may be used for potable water it is not possible to add a doping agent to aid in the fluorescence of the potential points of interest. This is due to the potential for these doping agents not being fit for consumption and using a readily available and low-cost doping agent may be difficult to source for consumers.	None
Excitation	The Device can accommodate various excitation methods - however, natural light is used as it requires minimal power if a longer exposure is needed and befoulment of the excitation medium is not an issue.	Ambient Light
Delivery	The Device relies on the transmission of light via air, which may have a varying amount of humidity due to the fluctuation of environmental temperatures.	Air
Filtering	The device utilises a low-cost spectroscope to filter the light into its spectra.	Spectroscope
Detection	The device uses a digital camera to record the spectra that have been filtered.	Raspberry Pi Cam

The PySpectrometer has the added benefit of finding and labelling the incoming spectra. For the use case of finding the spectral response of water, it can only record a point of information. The point, while not a comprehensive data cube, is enough to find large issues with the water due to the flow inside the tank. Such as an algal bloom of cyanobacteria which can be found by their pigment which exists between the wavelengths of 665nm-709nm. This is possible with ambient light as seen in the experiment performed by Raphael M. Kadela et al [30].

Another major drawback of this device was the increased power consumption caused by running the raspberry pi. This was unavoidable for testing as the first device performed the analysis in situ and analysis could not be done efficiently on an ESP8266 processer with a camera attached. Therefore, for a successful testing device, it was necessary to create a portable version of the PySpectrometer. This was quickly overcome by fitting the spectrometer to a low-cost phone which acted in the stead of the raspberry pi camera. This change allowed a higher quality picture as the device was able to easily focus on the image that was being created through the spectroscope. This did remove the ability to use the PySpectrometer software at once and required the device to save the data and process it later. However, this time lag was acceptable as the device would update daily and being able to use a non-tethered imaging device is a bonus.

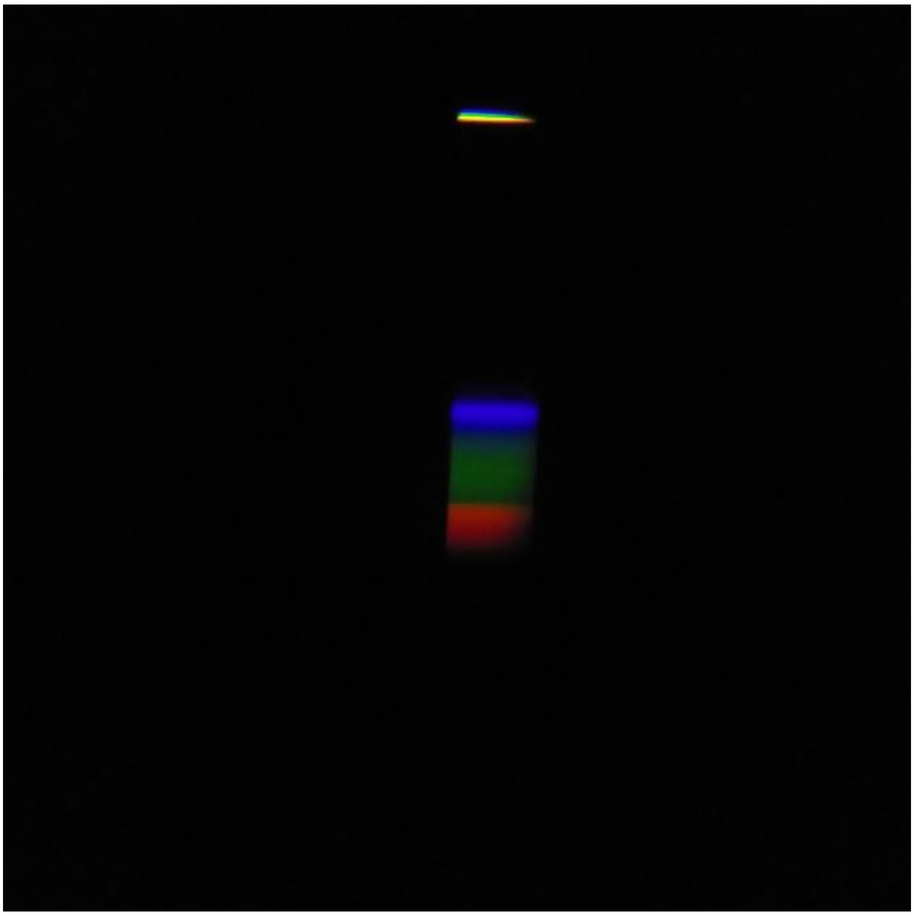


Figure 23 – Pre-processed image from hyperspectral imager

The device works by holding the phone with an attachment over the object of interest. A photo is then taken which is a slice of the Multispectral Data cube. This slice of data is then processed to find the peak values compared to a list of expected peaks. These expected peaks are based on the spectral responses of various cyanobacteria. As seen in the paper by Raphael M. Kadela et al [30] these peaks occur between 665nm-709nm which can be easily identified.

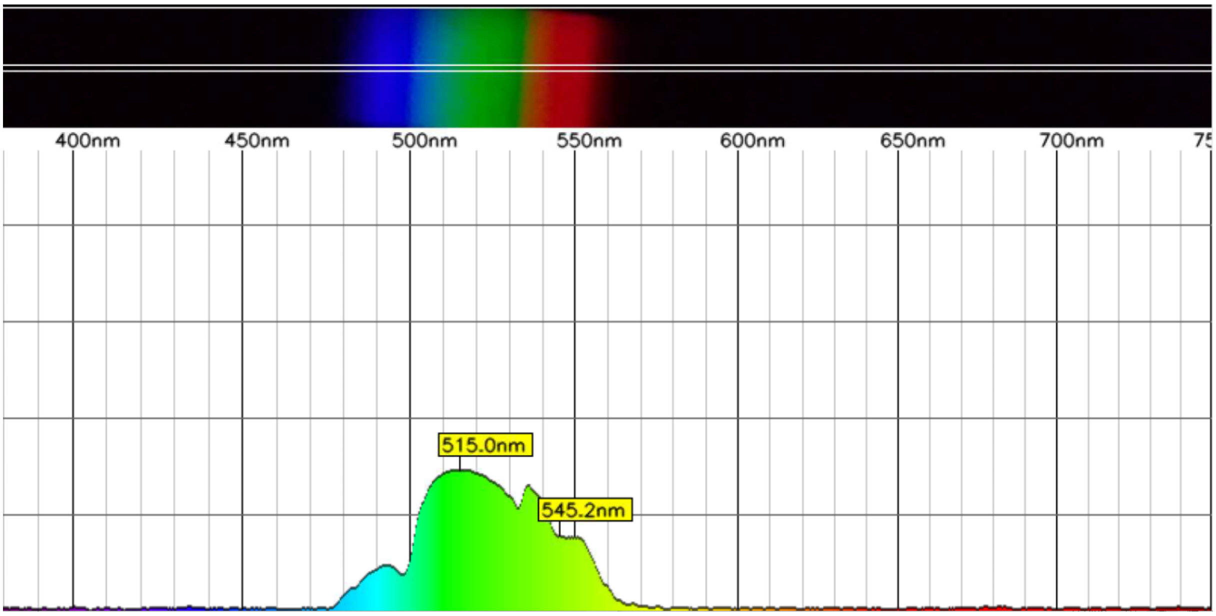


Figure 24 - Pyspectrometer Example of white ceiling

As can be seen in Figure 24 the software splits the information into two sections: one which displays the original diffraction of the light and one which displays the spectrograph of the image. To check the operability of the device a red book was placed in front of the device and the reading was taken and matched the expected response.

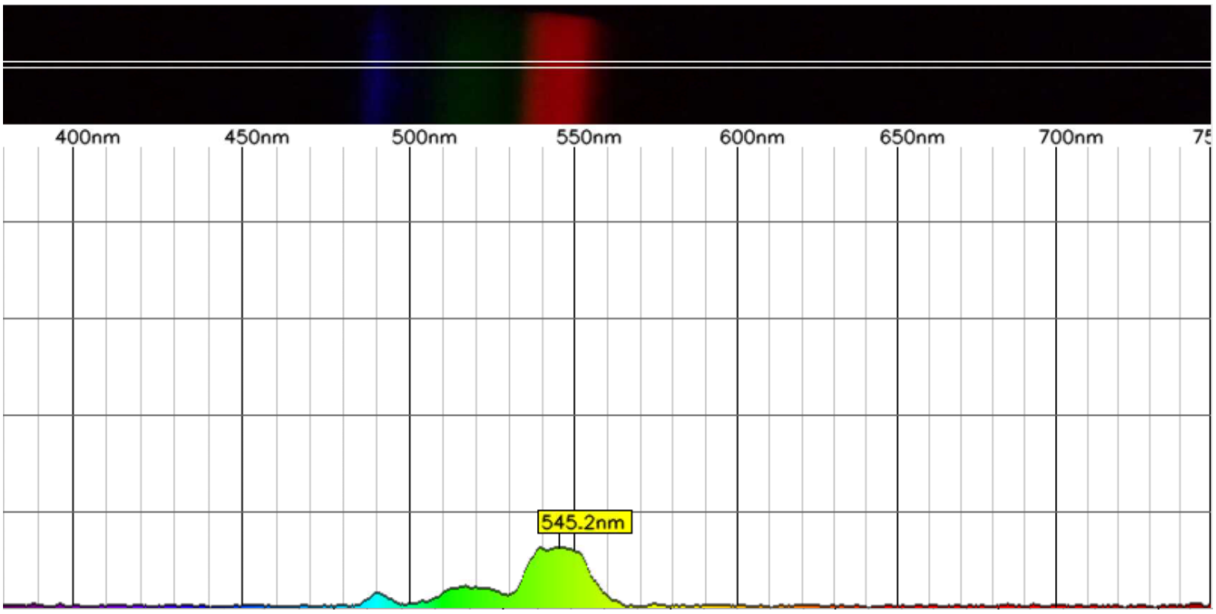


Figure 25 - Red Book Spectral Response

For in situ testing, the device would need to be calibrated properly with known wavelengths to get an exact reading. This calibration is done by showing the device three separate objects with known spectral responses. However, for a sign of possible changes in the tank environment, this may not be a necessity.

Improvements

During the testing of the device with the USB camera and spectroscope attachment there were minimal issues as most tests were performed inhouse as there was no sustainable way to install the device in-situ

Light Leakage

When using the original mount for the spectrometer there were cases of light leakage into the lens as seen in Figure 23 with the stripe at the top of the image. This was an issue as the light leakage would lead to the software calculating the intensity of light at that point as a different wavelength. This was quickly remedied by adding black adhesive around the connection between the spectroscope and the camera to prevent any small gaps in the construction that let light through. This led to an increase in the quality of images and reading.

Chapter 5 – Results and Findings

Prototypes of the device were placed in situ on a local rural home with a 25,000L above-ground water tank as seen in Figure 14 - Logging Device in Situ. During the case studies the devices were communicating with an online database which allowed the updated information to be checked constantly. These case studies allowed a more detailed look into how the device would work in the field and find any issues that were unexpected.

Network Limitations

During these case studies different issues arose when using the current setup of Sigfox communication. When initially installing the devices, the communication inside the John Lyttleton building, where Massey Agrifood digital lab is based, was strong as there was a Sigfox station nearby. However, when it was taken out into situ there were periods where the device's signal strength would decrease and increase due to the surrounding environment. This is to be expected as it is a non-wired communication method.

As the design for the PCB became more complex as it was improved, the interference that the components had on the antenna was limited. As the design was using the entire ground plane as a part of the antenna it was expected to have impacts when installing new components. However, when changing the antenna to the new monopole design the signal strength change was insignificant. This was in line with what was seen with the testing of the device with the Sigfox analyser as seen in Figure 7.

An issue that appeared was in the communication between the Sigfox network and the MAFDL servers. Because the Sigfox chip between each individual PCB had changed, the backend that parsed the Sigfox chip id had to change on the server. However, As the backend on the servers was altered, as it was a shared resource, there was a miscommunication with the process for introducing new devices. The new protocol required a unique API key to be generated for each new device and synced with the Sigfox API so that the post request has the correct key for the device on the database. However, with new devices, the ID was not related to their correct API key in a table on the database and could not be updated as the server was getting an incorrect message. This issue was solved by allowing the same API key for each unique device. Allowing all the devices to use the same API key is acceptable as each device has a unique ID which can be either authorised or blocked to avoid security issues in the future.

During the development and testing case studies the owners of Sigfox networks met difficulties, so the certainty of its continued operation was called into question. However, as of August 2022, the network is still running and the Sigfox network is still expanding to accommodate new devices. The difficulty in adapting the device to a different network is solely related to applying the new messaging system into the firmware and changing the antenna if necessary. Most long-range IoT devices that do not use Sigfox communicate on the same 902 to 928 MHz band, in New Zealand, via ZigBee and LoRa. As these are the same bands as Sigfox there would be no need to change the antenna completely. Therefore, the difficulty would be around: reformatting the PCB to fit a different communication chip and possibly different power constraints which would take 2-3 weeks including delivery, changing the firmware to include different commands which would take at most one week, and testing which is variable based on the earlier two.

Limitations of Ultrasonic sensors in noisy environments

During testing in situ, another issue appeared. It was found that there were instances where the abundance of acoustic noise caused by external factors such as rain filling the tank or turbulence due to rapid emptying the of the tank. After seeing the noise through visual aids, it was at a manageable amount of error roughly and became a minor issue when combined with earlier readings. As the device works over a large period, small increments have less of an overall impact so the impact of acoustic noise is lessened and can be safely ignored when using the algorithm to compensate.

Batteries

Another issue that was experienced was when the batteries leaked due to exposure to an average summer day. This had shown the device would stop working if the environment had extreme changes in temperature and the device would need further environmental testing to ensure consistency in overseas environments.

The number of messages per battery was better seen while in the field. This could be seen with a 9V battery giving only 269 messages, while the AA returns 1442 readings.

Use

During one of these case studies at the farm, there was an event where water was constantly drained from the tank. This leak was caused by a nearby herd of cattle knocking the tap on the tank and causing the tap to drain. This was confirmed the following day when the device was inspected for faults due to the decreasing reading of the water and the water level was found to be at the level of the tap. This could be seen on the website as the water decreased from the overflow by about 2.5 metres down to the height of the tap. As there was no method for alarms to be placed it was not notified until the following morning. However, when inspecting the site with the owner the leak was not clear and would not have been found until later. In future water leak events, the user will be notified if they are experiencing a drain. This will be possible by showing consistent decreases in water level and, as the programme goes through the algorithms to see if the device is malfunctioning, comparing the rate of regular use to see if the decrease is due to usage or a possible leak. Therefore, the user and the owner of the tank can act sooner and mitigate any issues that might arise from a possibly major leak. If this was a rural household and they got notified as soon as possible they can minimise the amount of money that have to spend to recover from the loss. As that is the only source of water it will improve the water security that they experience rather than having to rely on a neighbour who may also be having water security issues at that time.

Results

During the development of the device, most tests performed were discussed in the earlier chapters as they were run for the sole purpose of improving the design to the point it could be placed in situ reliably. The last tests were either to show the limits of the device or to show how reliable the device is in actual use.

Water Level Sensor Results

The water level sensor needed to be assessed both in situ and in the lab. For the device to be reliable it needs to send a message when expected and have a consistent reading. Consistent readings are needed so that there is no unexpected fluctuation due to the device that is not due to the environment. This is because these fluctuations were an issue during the original tests.

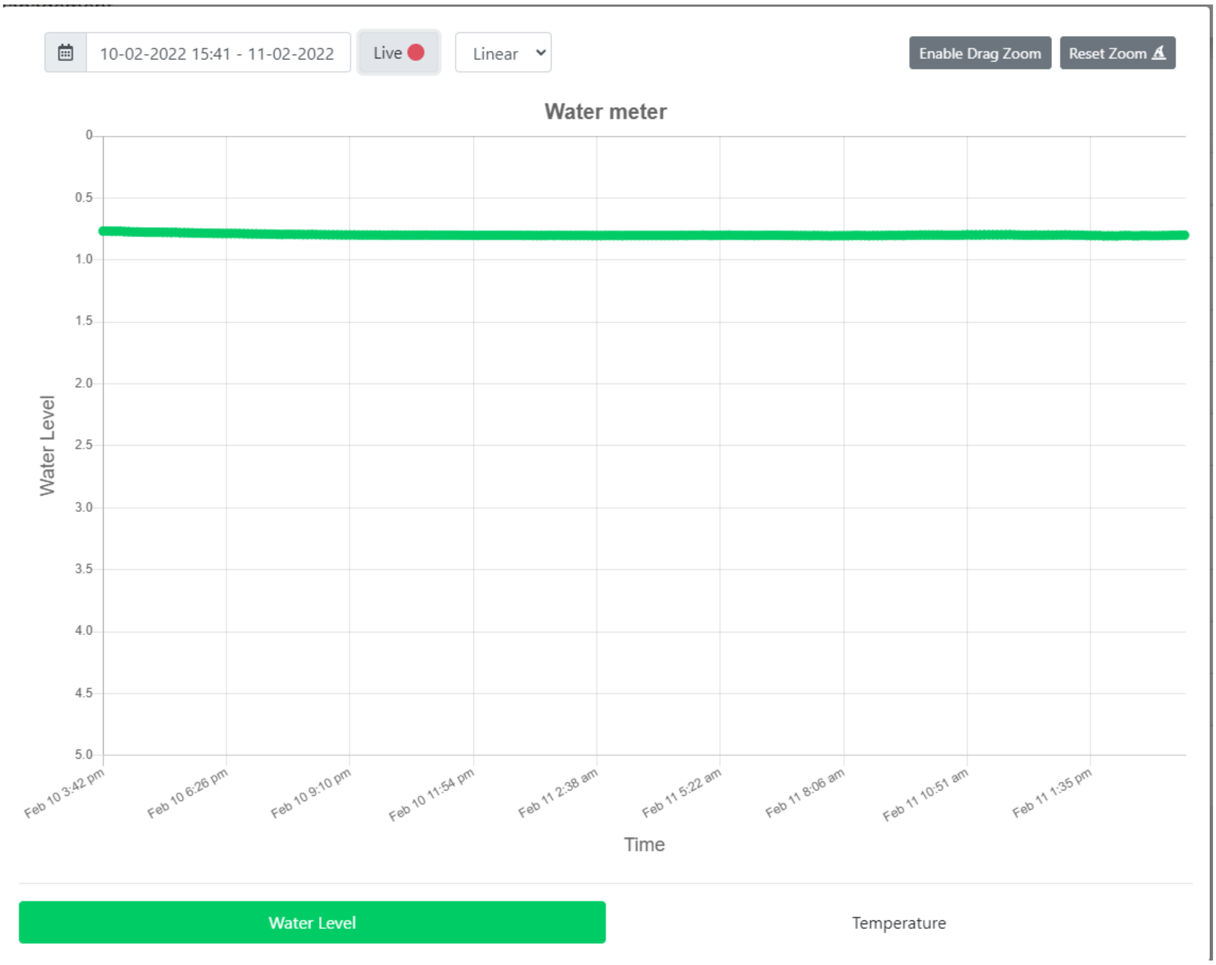


Figure 26 - Excerpt of Readings taken between 10/02/2021 - 11/02/2021.

The device works by triggering one to two times a day. Therefore, to check the consistency of the device the frequency of transmits was increased to once every 1-2 minutes to simulate a longer period in the field. Figure 26 displays 24 hours of continuous readings which equates to roughly 1440 readings with no error in service. This was the norm for the performance of the final device.

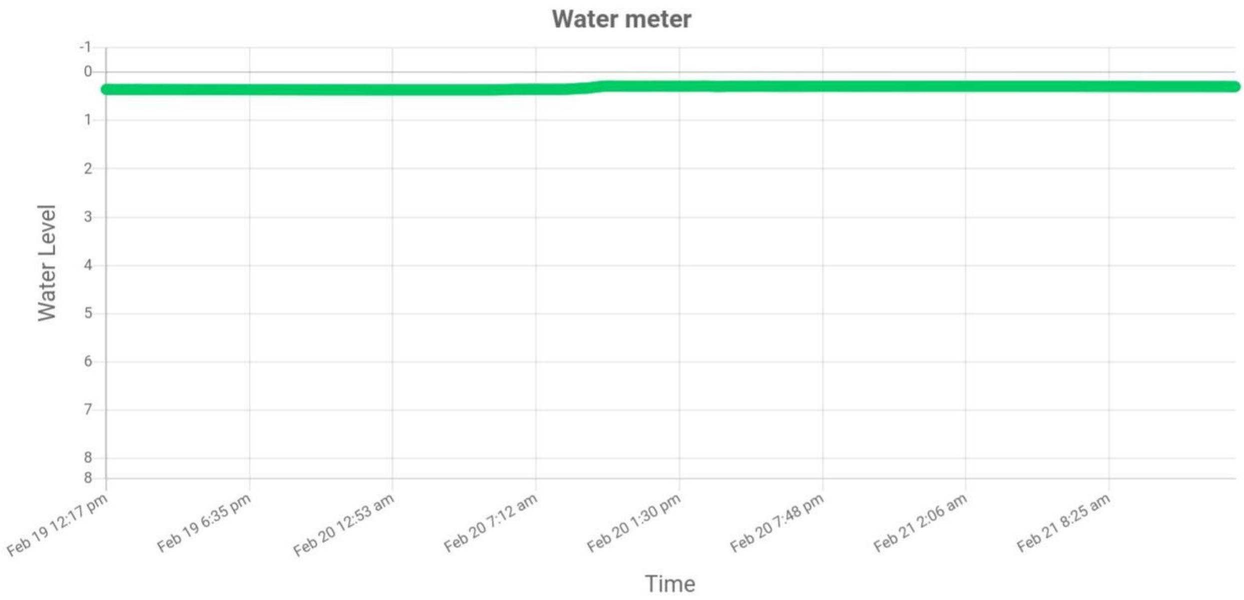


Figure 27 - in-situ reading of water use at farm.

To ensure consistent distance readings, the device was set at 0.72m and 2.2m respectively to check the consistency at range as well as up close due to the behaviour of the ultrasonic sensor discussed earlier.

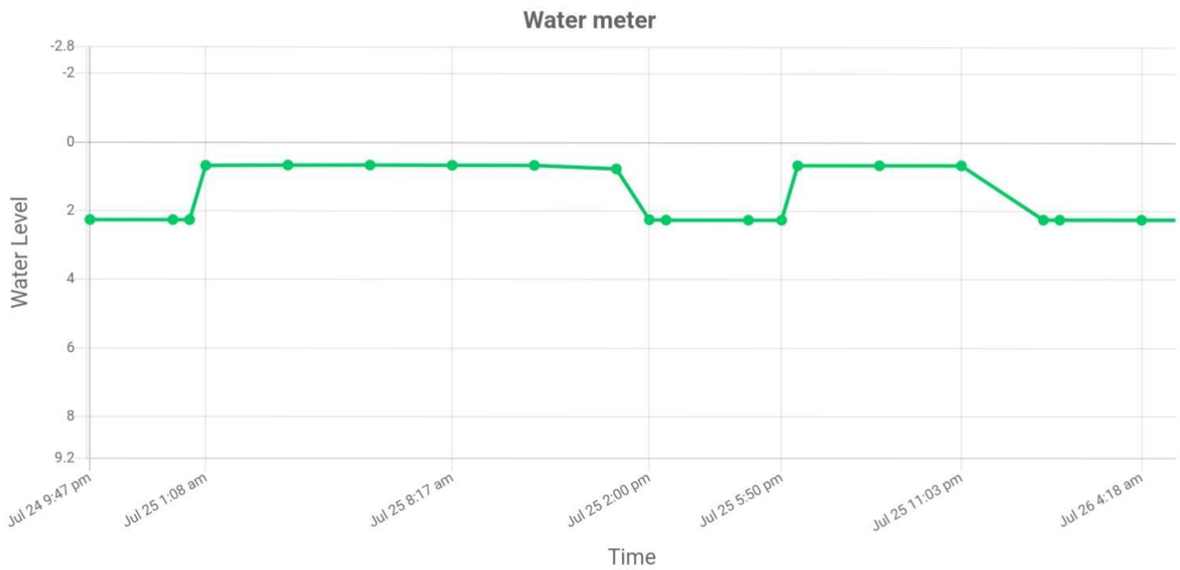


Figure 28 - Ultrasonic Sensor Switching Between 0.65m and 2.24m

The figure above highlights an excerpt of these tests where the device was changed between the two measurements.

Table 12 - Raw Data of Figure 26

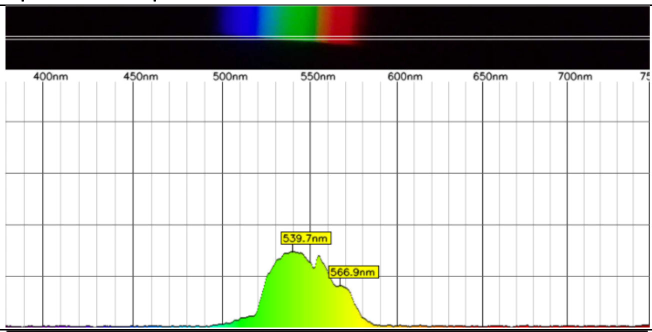
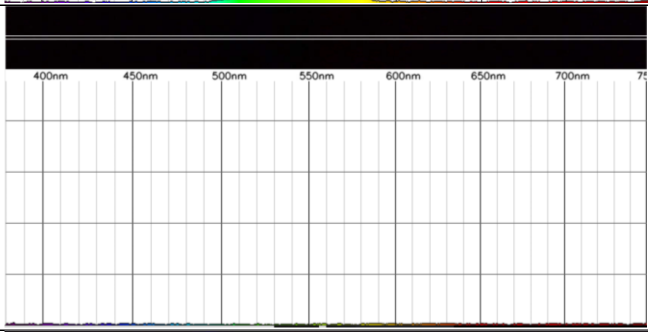
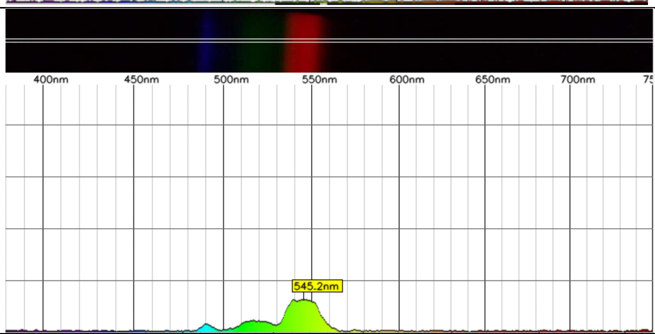
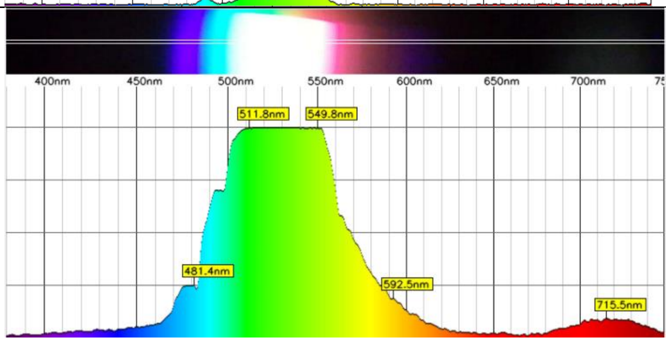
Measured Distance	Set Distance	Error
2.24	2.24	0.0
2.24	2.24	0.0
2.25	2.24	0.01
2.25	2.24	0.01
0.674	0.65	0.024
0.673	0.65	0.023
0.677	0.65	0.027
0.677	0.65	0.027
0.679	0.65	0.029
0.678	0.65	0.028
2.24	2.24	0.0
2.24	2.24	0.0
2.25	2.24	0.01
2.25	2.24	0.01
2.25	2.24	0.01
0.676	0.65	0.026
0.675	0.65	0.026
0.682	0.65	0.032
0.677	0.65	0.027
0.677	0.65	0.027

The closer measurements deviate from the real measurement by roughly 0.02-0.03m which is most likely due to the distance inside the chassis causing a discrepancy in the reading. This gives the error to be roughly 1mm in lab conditions. It was not possible to measure millimetre accuracy in the tank due to environmental issues that would add enough error to mitigate the millimetre precision. Therefore, the reading can be considered reliable.

Multispectral Sensor Results

The multispectral device was assessed based on its ability to find spectral responses and its response to water.

Table 13 - Data cube Points

Object	Spectral Response
White object	
Water in a black dish	
Red object	
Direct Light	

Direct light and water were included as they were the two extreme states that the device could undergo. The hyperspectral image of water was within expectations because there were no media inside the water to cause a spectral response strong enough to be registered and any reflections off the surface were too weak to be picked up. Direct light was also important as it showed the limitations of the current spectroscope to split into the different spectra and be used for algae which was the intended purpose.

The other two OOI did not behave as expected as what was supposed to be a red spectrum was identified as being in a central green band.

Result Analysis

Water Level Sensor

The current state of the water level sensor given the results is it can accurately find distances but might be limited by its battery life which allows approximately 1440 messages. The water level sensor is also capable of supporting consistent readings and will only significantly deviate if the OOI also deviates significantly in distance. The device performs with 0.03m of accuracy in nominal environments. The accuracy changes based on the external conditions as seen when the external temperature throughout the day caused a fluctuation in the readings slightly. This was as the internal speed of sound was changing to match the fluctuating temperature.

Hyperspectral Device

The current state of the hyperspectral device is that it can find the different wavelengths. However, the calibration sequence is possibly wrong as the device was showing the red band as green. Another plausible reason for the mediocre performance is that the device's enclosure was incorrectly set up so that the light that was diffracted through the grating was incorrectly collected by the camera.

The communication of the data from the device was also difficult as the amount of data that can be transferred over Sigfox is limited and would be reduced to solely peaks. This would severely limit the off-site processing capabilities leading to the device having reduced efficacy.

Chapter 6 – Discussion & Conclusion

Further Applications and Limitations

Decentralised Supplies

The benefit of this device is not solely for the user, as it has the potential to be utilised on a regional scale. The data of individual households can be combined and given to the local council for a fee. With this information, the council can track the true input and output of rural homes that are only estimated.

Using this information, a council can appropriately control its wastewater infrastructure's ability to oversee waste that is from decentralised input. Another use the council could have with the water level and usage data is to map areas with water security issues and appropriately respond to infrastructure changes or new legislation for water.

The monitoring of a region's decentralised water supply is important in rural environments as each rural household must keep extra water tanks for firefighting. If the council can check these firefighting supplies the possibility that the tank is at critical levels of water and cannot be used due to a leak is diminished. Therefore, it would increase the safety of rural environments, especially during the summer months when drought and the risk for fire increase and the need for firefighting increases as a result.

Communication Limitations

Another limitation that is inherent with IoT long-range devices is the cost of a message being transmitted. it costs a certain amount to send a message with a set number of bytes to the Sigfox network. As the device expands into the commercial market this is going to become more of an issue as the cost of maintenance increases. the current device does not have a laid-out subscription service. However, should the device move along it will become necessary to gain partnerships with different companies for example a water tank company or a water supplier. This can be done by selling the data of the surrounding region so that they can be our so they can supply people who are long water who are expecting to be running low on water based on local weather reports and their water usage. These partnerships allow the cost of supporting the device and the servers to be offset. If this were not the case MAFDL would need to take yearly expenses to ensure the devices could communicate on the Sigfox network or the consumer would need to pay a fee each month to be able to use their originally low-cost device.

Hyperspectral Improvements

During the masters, the theory around identification was solid, however, the implementation could be improved. Firstly, the hyperspectral device created was a low-cost version of a point scanning hyperspectral device. This was allowable as the state of a water tank could be estimated by a smaller region if issues such as algae were suspected to be an issue. However, the device's communication of its findings was a challenge as the files were too large over Sigfox and using solely peaks was too simplistic when compared to existing spectral responses to get a clear identification. This would need to be improved if the device were needed to work in a completely rural environment with limited access to WIFI.

The Hyperspectral device needs to have a robust calibration method that can be undertaken remotely as the device can lose its calibration over time.

Conclusion

From the key aims set in beginning the following objectives were developed:

- Develop a device that is cost effective and consumer oriented for detecting the water level in a tank.
- Set up wireless communication of the device for remote monitoring.
- Field Test the device.
- Use a multispectral device to identify algal bloom.
- Develop a low-cost multispectral sensor that can be used to identify the algal bloom.

By splitting the device into two clear components allowed the devices to be fine-tuned in tandem. The water level sensor was developed and performed consistently both in the Lab and in situ. The water level sensor was also able to communicate over Sigfox, a long-range network, and be read by users.

However, the hyperspectral device was not fully able to meet the objectives to acceptable standards. Firstly, the hyperspectral device was able to find different spectra between the bands of 400nm and 700nm. This was due to the range of the spectroscope not having the capability to diffuse the non-visible light to an acceptable level to be registered. The range of visible light was also relatively small. However, the ability to use a low-cost camera with a simple spectroscope to work as a basic hyperspectral device was proven. This leads to the possibility of improving the end design to accommodate a spectroscope of a wider range. Therefore, allowing easier identification of the Cyanobacteria with their key spectral response being above the ranges reliably found by the current setup. However, this smaller range could also be due to an incorrect calibration method.

In conclusion majority of objectives were completed to an acceptable standard. However, the objectives that were not completed still proved the concept enough to give confidence it can be adapted for future use.

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Appendix I – Harmonic Code

```
bool harmonicCheck(int pos, int measSet) {
  float allowable = 0.2;
  //check if roi is the first instance in the list
  if (pos == 0) {
    Serial.println("First Value");
    return false;
  }

  int finalHarm[8] = {0, 0, 0, 0, 0, 0, 0, 0};

  for (int i = 0; i <= 5; i++) { //Check for existing harmonics
    int harmonics[8] = {0, 0, 0, 0, 0, 0, 0, 0};
    int flag = 0;
    float roi = convertToFloat(i, measSet);
    if (roi < 1160) {
      continue;
    }
    else if (roi == 0xFFFF) {
      break;
    }
    for (int j = i + 1; j <= 7; j++) {
      float compared = convertToFloat(j, measSet);
      if (compared == 0xFFFF){
        break;
      }
      if (flag == 0 && compared / roi <= (2 + allowable) && compared / roi >= (2 - allowable)) { //2nd harmonic
        flag = 1;
        harmonics[j] = 2;
        harmonics[i] = 1;
        Serial.print("2nd Harmonic ");
      } else if (flag == 1 && compared / roi <= (3 + allowable) && compared / roi >= (3 - allowable)) { //3rd harmonic
        flag = 2;
        harmonics[j] = 3;
        Serial.print("3rd Harmonic ");
      } else if (flag == 2 && compared / roi <= (4 + allowable) && compared / roi >= (4 - allowable)) { //4th harmonic
        flag = 3;
        harmonics[j] = 4;
        Serial.print("4th Harmonic ");
      } else if (flag == 3 && compared / roi <= (5 + allowable) && compared / roi >= (5 - allowable)) { //5th harmonic
        flag = 4;
        harmonics[j] = 5;
        Serial.print("5th Harmonic ");
      } else if (flag == 4 && compared / roi <= (6 + allowable) && compared / roi >= (6 - allowable)) { //6th harmonic
        flag = 5;
        harmonics[j] = 6;
        Serial.print("6th Harmonic ");
      } else if (flag == 5 && compared / roi <= (7 + allowable) && compared / roi >= (7 - allowable)) { //7th harmonic
        flag = 6;
        harmonics[j] = 7;
        Serial.print("7th Harmonic ");
      }
    }
    if (flag >= 2) { //Copy any harmonics that exist to the final list

      for (int i = 0; i <= 7; i++) {
        if (harmonics[i] != 0) {
          finalHarm[i] = harmonics[i];
        }
      }
    }

  }

  Serial.println("Harmonics Identified");
  for (int i = 0; i <= 7; i++) {
        Serial.print(finalHarm[i]);
        Serial.print(" ");
      }
  Serial.println();
  if (finalHarm[pos] != 0 || finalHarm[pos] != 1){ //if the reading is a harmonic, beyond the 1st, return true
    return true;
  }else{
    return false;
  }

}

```