BIO-INSPIRED ALGORITHM FOR TIME DELAY ESTIMATION

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1 INTRODUCTION

This paper demonstrates the use of a phase measurement based approach to estimate distance-ranging and speed of sound measurements using multi-component ultrasound signals. Bats and dolphins both use acoustic energy for echolocation but have adapted different ultrasound energy delivery strategies. Dolphins use very short duration high intensity broadband signals (Clicks) whereas bats use very long duration broadband FM signals (Chirps). The difference in energy delivery between bats and dolphins has probably evolved in response to the different environments these two species experience; air and water, respectively, have very different acoustic impedance and attenuation characteristics. In nature, it is evident there is a great variety of signals. Different creatures have adapted the signals they use to their particular need and particular environment. Au and Simmons [1] concluded that bats signals with a centre frequency of about 80 kHz (i.e. 4 mm wavelength) and 40 kHz bandwidth can have a spatial resolution in air approaching 20 microns. For this frequency, we see that the resolution achieved by the bat is about 200 times better than$\lambda/2$ (i.e. 2 mm at this frequency), where$\lambda/2$ is usually used as a guide for resolution for analogue systems. Dolphins using a central frequency around 100 kHz can achieve a resolution of 0.3 mm. Moreover, Au and Simmons [1] have shown, using time-frequency analysis, that there are essentially two time-frequency components present at any particular time within a single bat pulse. Capus et. al [2] have shown the same thing in the dolphin clicks. Considering this use of two time-frequency components, we may infer some relationship between the time-frequency component characteristics and a time delay corresponding to a distance. A new bio-inspired algorithm based on the phase difference between two components embedded in the received signal is presented for the ranging, speed of sound and with the potential to make accurate thickness measurements, when applied to underwater acoustics. This algorithm shows that a spatial resolution of 1/50th of the wavelength can be achieved in practice. A comparison with the correlator-based technique is presented to demonstrate the improved performance of the phase measurement based approach and also its enhanced effectiveness.

2 BACKGROUND OF THE METHOD

In this paper, we introduce the use of phase measurement to estimate the time delay. The motivation for this comes from the fact that bats have been shown to have very good resolution with regard to target detection when searching during night. Simmons [3] estimated some bats with a centre frequency of about 80 kHz (bandwidth 40 kHz) have a resolution of distance in air approaching a few microns. For this frequency, the wavelength λ of sound in air is about 4mm, and so using the half wavelength $\lambda/2$ as the guide for resolution, we see that this is about 200 times poorer than that actually achieved by the bat. In this work, we introduce a technique that is inspired by the way bats use ultrasound, and show how it can be applied to achieve spatial resolutions beyond $\lambda/2$ and greater than state-of-the-art correlation methods. Consider an acoustic source sending out an acoustic pulse of a single frequency. Let the initial phase offset of the frequency be zero for convenience. The pulse travels out, undertakes a simple reflection from a target and returns to be detected by the source. Normally, we would measure the arrival time of the pulse and assuming a value for the velocity of sound in the medium, estimate the target distance. However, our alternative technique is based upon using the phrase characteristics of the signal that can be measured, and thus, we capture the signal and measure the phase of the returned pulse at the frequency transmitted. Given this single uni-frequency phase measurement we cannot estimate the two way distance to and from the object, but this distance can be determined via a comparison with a phase measurement made at another frequency. For simplicity, let us assume that we only sent out a single cycle of the frequency. Let the frequency be f_1 (Hz) and let the wavelength be λ_1. If D is the distance to the target, it represents D/λ_1 full cycles; this is an integer number, let it be n_1. There is also a fraction of a cycle left over, denoted r_1, which is represented by the phase measurement, ϕ_1. So we have for this single frequency, where v is the velocity of sound in the medium.

$$D = n_1\lambda_1 + r_1 = n_1\lambda_1 + \lambda_1\frac{\phi_1}{360} = n_1\frac{v}{f_1} + \frac{\phi_1}{360}\frac{v}{f_1} = \frac{v}{f_1}(n_1 + \frac{\phi_1}{360}) \quad (1)$$

where $v = f_1\lambda_1$. D, λ_1, r_1 are in meters and n_1 is an integer. Thus, if the values of f_1 and v are known, by measuring ϕ_1 in degrees we can estimate the residual cycle distance as $r_1 = \frac{\phi_1\lambda_1}{360}$ metres. If we send out a second frequency f_2 within the same pulse as the first then it will also have associated with it a wavelength, residual phase etc. So we can write a second equation as

$$D = \frac{v}{f_2}(n_2 + \frac{\phi_2}{360}) \quad (2)$$

Again, if the values of f_2 and λ_2 are known, by measuring ϕ_2 in degrees we can estimate the residual cycle distance as $r_1 = \frac{\phi_1\lambda_1}{360}$ metres.

2.1 UNAMBIGUOUS RANGE MEASUREMENT

Assuming no dispersion of sound velocity between frequencies f_1 and f_2, by combining and rearranging equations (1) and (2), the distance D can be expressed as a function of wavelengths of the difference in frequency between f_1 and f_2 as follows,

$$D = (\frac{\lambda_1\lambda_2}{\lambda_1 - \lambda_2})((n_2 - n_1) + \frac{(\phi_2 - \phi_1)}{360}) = (\frac{\lambda_1\lambda_2}{\lambda_1 - \lambda_2})(\Delta n + \frac{\Delta\phi}{360}) \quad (3)$$

Using the fact that $v = f_1\lambda_1$ we obtain

$$D = \frac{v}{f_2 - f_1}((n_2 - n_1) + \frac{(\phi_2 - \phi_1)}{360}) = \frac{v}{\Delta f}(\Delta n + \frac{\Delta\phi}{360}) \quad (4)$$

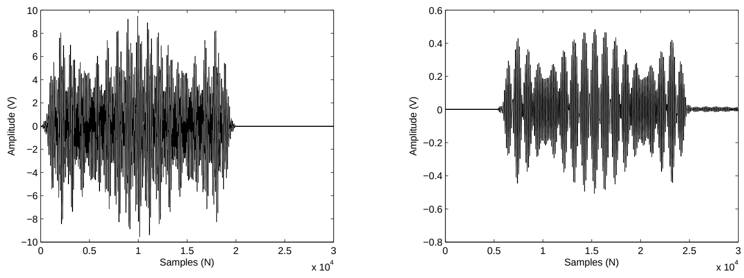
Equation 4 is the fundamental equation, where $\Delta f = f_2 - f_1$
Provided that the difference $\Delta n = n_2 - n_1$, in the integer number of wavelengths at each frequency is known or controlled, equation 4 can be used to make a distance measurement based on the difference in the residual phase measurements at each frequency. Solutions to equation 4 are non-unique in that different distances can be represented by the same phase difference measurement, at incremental increases in the difference in the number of cycles at each frequency. However, imposing the condition that $\Delta n \leq 1$, provides the unique case, which sets a maximum limit within which distance measurements can be unambiguously solved using the phase difference measurements in equation (4). In practice, this restriction on Δn is imposed via considering the required range of measurements as follows:

- Choose a distance D within which we require unambiguous range measurements.
- Select a frequency f_1 with its corresponding wavelength λ_1. This will give n_1 cycles in this distance.
- Then select frequency f_2 with its corresponding wavelength λ_2 such that the number of cycles in D is $n_2 = n_1 + 1$.
- Frequency f_2 can be chosen by using the parameter $R = v/\Delta f$ as a guide. The distance R is called the *Unambiguous Range* and using the two frequencies, f_1, f_2 any distance within this range can be determined unambiguously.

3 APPLICATION

To demonstrate this methodology and evaluate the theory, a series of measurements were performed in a water tank of size $1530 \times 1380 \times 1000\ mm^3$. Two broadband ultrasonic transducers were used (Alba Ultrasound Ltd). These underwater transducers have a wide bandwidth with a centre frequency of approximately 100 kHz. They were designed to operate effectively as both transmitters and receivers of ultrasound with a beam width of around 10 degrees at the device centre frequency. The -3dB bandwidth is 99 kHz (72 kHz to 171 kHz). The transducers are mounted on a trolley moveable in the Y-direction, which is in-turn mounted on a rail that is moveable in the X-direction. For this purpose, linear encoders (Newall Ltd.) are used to measure the displacement of the rails in the x-direction; note however, that the encoders are off-set from the actual transducer position. Software written in Visual Basic was used to obtain readouts of the encoder positions. The transmitter was driven directly by a 10 V peak-to-peak signal, comprising four mixed frequency sine waves (70 kHz, 71 kHz, 80 kHz and 170 kHz) sampled at $10MSs^{-1}$. Figure 1a shows the original signal to be transmitted which represents mixing of the 70 kHz, 71 kHz, 80 kHz and 170 kHz sinusoids frequencies. The signal is generated in Matlab© and saved as .txt file. A modular system containing a ZT530PXI, 16-bit arbitrary waveform generator (AWG) and a ZT410PXI, 16-bit digital storage oscilloscope were used to transmit and receive signals (Ztec Instruments Inc). A program written in the C++ language was used to control the signal transmission and acquisition, where the final signal recorded was the result of averaging 32 repeated signals. Different distances between the transducers were chosen arbitrarily within the unambiguous range of about $R = v/\Delta f$ = 1500 mm. These distances were recorded by the linear encoders. At each distance 3 repeat measurements were made. The pulses were 3 ms long consisting of all 4 frequencies with no windowing. The sampling frequency was set at fs=10 $10MSs^{-1}$ giving 30000 samples. The 30000 samples were captured but only the last 10000 (N) samples were used. This gives a resolution fs/N=1 kHz, which is consistent with the smallest step between the 4 frequencies in the analysis. These 10000 samples were taken within a window that overlapped with a proportion of the received waveform. Figure 1b shows the received signal. Note that the range of unambiguous distances that we can measure in this case is from 15 mm up to 1.5 m (assuming the sound velocity in water to be 1500 m/s). A Discrete Fourier Transform (DFT) was then used on these samples to obtain the amplitude and phase at each of these 4 frequencies. Using frequencies to provide this decadal step interval enables the real and imaginary components to be determined exactly on a DFT frequency bin and hence, give an accurate measure of the phase and minimise spectral leakage of the response at that frequency.

After transmitting and receiving each signal, 3 times for the same distance, the DFT was applied to get the relative phase between the 4 frequencies for each signal for the different distances as shown in table 1. Each received signal gave us 4 phase values related to the 4 frequencies. At each distance a linear chirp was transmitted and a time delay calculated using a cross-correlation between the source signal recorded on the transmitter and the detected signal recorded on the receiver. The overall time delay was corrected for delays through the transmitter and receiver. Also, using the four-frequency component signal, we applied both the phase-based and correlation-based techniques to calculate the time delay at each distance. However, application of a correlation-based technique using a linear chirp provided a far greater signal to noise ratio than use of the 4 frequency components signal.



(a) (b)

Figure 1: Mixed sine wave [70kHz, 71kHz, 80kHz and 170kHz] a)Transmitted, b)Received

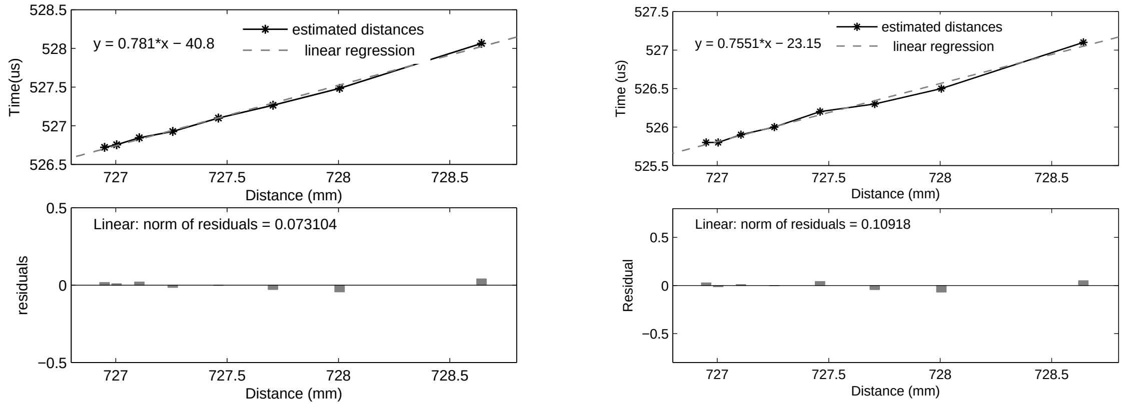
After obtaining sets of phase for each distance, the above phase-based time delay estimation (PBTDE) algorithm (equation 4 above) was applied to estimate the corresponding times for each phase difference $\Delta\phi_{12}$, $\Delta\phi_{13}$, $\Delta\phi_{14}$, $\Delta\phi_{23}$, $\Delta\phi_{24}$ and $\Delta\phi_{34}$ for the pairs f_1f_2, f_1f_3, f_1f_4, f_2f_3, f_2f_4 and f_3f_4, respectively. Using a simple calculation of the first estimate by $t_{12} = \Delta\phi_{12}/(f_2 - f_1)$.
This gives a corresponding estimated times t_{12}, t_{13}, t_{14}, t_{23}, t_{24} and t_{34}, respectively, for each distance. The resolution in the time delay and distance measurements is controlled by the difference between the frequencies at which each phase difference measurement is made. In the case of the four-component signal, the greatest resolution is achieved using the t_{14} time delay estimate and the least resolution using the t_{12} estimate.

Table.1 shows the estimated time delay for different distances using phase-based approach and cross-correlation technique.

Distance (using the encoders) (mm)	Estimated time (using TDPBE) (μs)	Time delay using Cross-correlation
664.49300	484.53880	483.90000
677.70600	493.50682	492.80000
688.29500	500.73589	499.90000
703.03100	510.73959	509.90000
726.95000	526.72007	525.80000
727.00400	526.75394	525.80000
727.10600	526.84455	525.90000
727.25600	526.92685	526.00000
727.46100	527.09942	526.20000
727.70600	527.26457	526.30000
728.00500	527.48274	526.50000
728.64200	528.06404	527.10000
747.13800	540.39806	539.40000
758.55400	548.08447	547.00000
771.07000	556.56907	555.50000

Table 1: The estimated time delays for the 15 distances with different signals: distances from Tx to Rx1

In our testing the PBTDE technique performed better than the cross-correlation technique. Note that the data presented in Table 1 for the cross-correlation technique were gathered using a linear chirp. If we look to the first column and the distances from 726.950 to 727.706 where the distance is increased by 50, 100, 150, 200 μm, respectively. Using the PBTDE approach, the measured time delays are consistent with a constant velocity through the water of 1480 m/s. We can see that the corresponding time is 526.75394-526.720= 0.033 us (as shown in figure 2a) which is expected because the speed of sound in the water calibrated at 1480 m/s at 20C [4], this gives a time delay for a 50 μm distance equivalent of 50/1480=0.0337 μs, as measured using the PBTDE. However, using the cross-correlation approach we are not able to detect this small displacement. If we take for example, the 50 μm displacement corresponding to the displacement from 726.950 to 727.005 mm. Using the cross-correlation approach gives a time delay of 525.800-525.800 = 0 μs (as shown in figure 2b), which means that the cross-correlation algorithm is not peaking at the correct time that corresponds to this displacement, i.e. the displacement was undetected. The figure 2b shows the cross-correlation to be unreliable when the displacement is less than 150 μm. However, displacements within 50 μm to 150 μm ramge were resolved using the PBTDE method. The resolution of the cross-correlation approach (is restricted by the sampling frequency, which in this case: 10 MHz), setting a limit of resolution of the time delay to 0.1 μs corresponding to a displacement of 148 μm (speed of sound of 1480 m/s). The speed of sound measured from the slope Equation y = 0.675109x + 36.000797 obtained by the linear regression of the 15 distances was v=1481.200 m/s, which is consistent with [4] at $20°C$. Note that the offset of 36.000797 μs is due to the propagation delay through the transducers.



(a) (b)

Figure 2: The variation shown in the small distances for Tx-Rx when using a) PBTED, b) Cross-correlation

Fig.2 shows the graph for the linear regression of the data in table1, which were measured using the PBTDE and the cross-correlation methods. We can see in Fig.2a that the linear regression using the PBTDE is consistent and has a high level of fit to the series of eight small displacement from 726.950 mm to 728.005 mm (see the first column of table1). whereas, there is a poor level of fit between these data and the linear regression derived using the cross-correlation method. For example, there appears a stepwise nature to the data where there is a little difference between successive measurements for small displacements such as 50 μm, 100 μm.

Measured Dist-Rx1 (mm)	Displacement between Measured Dist (μm)	Estimated Dist (mm)	Displacement Measured Dist (μm)	Difference between Measured and Estimated Dist (μm)
726.95000		726.87414		76
727.00400	54	726.92431	50	80
727.10600	102	727.05852	134	47
727.25600	150	727.18043	122	76
727.46100	205	727.43605	256	25
727.70600	245	727.68068	245	25
728.00500	299	728.00384	323	1

Table 2: The difference between the measured and estimated distances

Table 2 shows the distances between the TX and the RX within the range from 726.95 mm to 728.005 mm measured using the encoders (Column 1) and estimated using the PBTDE algorithm (Column 3). Table 2 also shows corresponding differences between these measured and estimated distances (Column 5). For the series of small displacements from 50 μm up to 300 μm the measured distance was always greater than the estimated distance. Possible causes of this difference include the fact that at these fine displacements the movement registered on the encoders was not fully transferred to the transducers. This effect would reduce the ability of any sonar distance ranging technique detecting these small displacements. However, a comparison of the measured (Column 2) and estimated displacements (Column 4) between each step within this range indicates both under and over-estimation of the incremental displacements. It is suspected that these displacements are close to the limit of movement that, when registered by the encoders, is faithfully transferred to the transducers. Other factors such as the forces imposed on the transducers by the cables are also considered to affect their movement in a variable manner. The mean difference between the measured and estimated distances was 48.8 μm for the complete range of distances tested from 664.493 mm to 771.07 mm.

4 CONCLUSION

A novel non-correlation based technique for time delay and distance ranging estimation has been developed based upon the measurement of the difference in the residual phase at different frequencies in a multi-component received signal. This range of unambiguous distance measurements made using this technique is limited by the minimum difference between the lowest frequency components in the signal. The performance of this method to estimate time delays and distances up to 1.5 m was evaluated using a four-frequency signal from 70 kHz to 170 kHz. Accurate speed of sound determination was achieved from the time delay and distance ranging measurements within this range and the results are consistent with the literature. Our experiments indicated that the phase-based approach (PBTDE) has far greater resolution and provided more accurate time delay estimation than the cross-correlation approach even when using signals with good autocorrelation characteristics. The PBTDE achieved a limit of distance resolution of 50 μm with smallest wavelengths of around 8.7 mm at 170 kHz, whereas the theoretical limit of resolution with a correlation-based technique is 148 μm. Although the distance measurement accuracy of the encoder technology was 5 um, it is suspected that the same accuracy could not be achieved in the position of the transducers via the linear slide movement system. It is considered that this contributed to the variability in the reported data and reduced variability could be achieved with improved accuracy in transducer positioning. Also, the PBTDE technique needs further testing in harsher environments to see how sensitive to noise it is.

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