AIR-COUPLED ULTRASOUND TIME-OF-FLIGHT ESTIMATION FOR SHIPPING CONTAINER CARGO VERIFICATION

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ABSTRACT

The falling cost of embedded sensor systems has opened up the possibility of in-transit air-coupled ultrasound interior imaging of shipping container cargo. This new technology could allow for real-time cargo integrity verification and improved shipping and transportation security. This paper takes the initial steps in developing a temperature invariant descriptor by comparing three time-of-flight (TOF) estimation methods from the literature using *in situ* data. The methods compared are matched filter, leading edge envelope line fit, and a simple envelope half-peak intercept. The results show that the simple half-peak intercept method provided the most consistent TOF estimate with respect to overlapping pulse data.

Index Terms— Security, Ultrasound, Shipping, Delay estimation, Acoustic fingerprint

1. INTRODUCTION

With the falling cost of low-power microprocessors and transducers it is becoming economically feasible to embed dedicated sensing systems inside and/or within cargo shipping containers. These systems offer a platform for a wide array of sensing modalities including chemical, biological, GPS, vibration, and ultrasound. This advance in technology opens new research fronts from logistics to security [1],[2].

This paper initiates an investigation into developing embedded air-coupled ultrasound fingerprinting of cargo configurations for container integrity verification. More specifically, the use of time of flight (TOF) estimation to construct a temperature-invariant descriptor of reflecting surfaces in a complex environment [3],[4]. Information about the cargo configuration or any changes in it is assumed to be encoded in the reflections of the cargo and in the absence of reflections from known intrinsic or wall mounted corner reflectors (Fig.1).

The primary complicating factor for developing a cargo configuration acoustic image is variation of constructive and destructive interference caused by changes in sound propagation velocity due to temperature variations. As the ambient temperature varies the relative offset between overlapping echoes varies causing substantial changes in the ultrasound return signal.

Three methods for TOF estimation were chosen from the literature for comparison Matched filter, envelope rising edge, and half-peak envelope intercept.

Matched filter, or cross-correlation estimator (CCE), is well-known to be optimal according to maximum-likelihood criterion for localizing undistorted non-overlapping pulses in additive Gaussian noise [2],[6]. In a complex shipping container environment returned pulses tend to overlap and distort due to the distribution and character of the reflecting surfaces. In addition, CCE is computationally expensive when compared with the other two methods which will be discussed and compared.

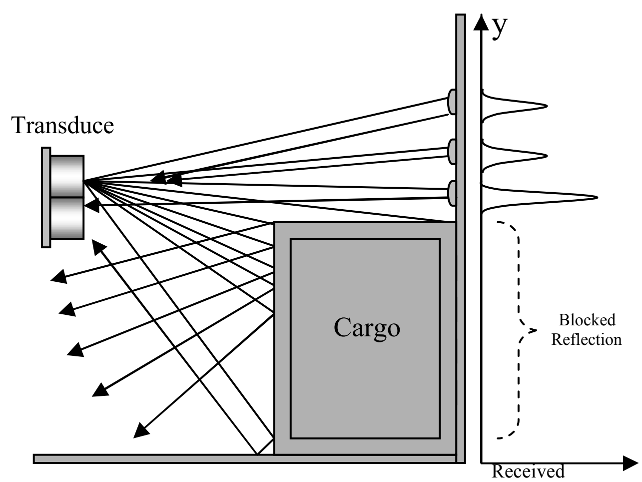

Fig. 1. Return paths of an ultrasound pulse in a shipping container environment.

The envelope rising edge estimator (EREE)[7] provides one alternate for comparison. In EREE the acquired ultrasound signal is demodulated using a classical quadrature-demodulator scheme, which is used to estimate the envelope of the signal. The TOF is then determined by the time-axis intercept of a line of best fit for the points on the leading edge.

Half-peak threshold (HPT) provids an even simpler estimate of TOF. In HPT the TOF is determined by the half-peak intercept of the rising edge of the pulse envelope.

The performance of the three methods was compared using *in situ* container data spanning a reasonably wide range of temperatures. To more fully account for multi-path echos and distortion caused by non-ideal reflecting surfaces in the complex within-container echo environment, an in situ test was chosen over model simulations. In addition, testing over a range of temperatures allowed for the relative assessment of the changing levels of constructive and destructive interference caused by changes of propagation velocity.

2. TIME OF FLIGHT DISTANCE ESTIMATION

Estimating distance via time-of-flight (TOF) requires an accurate estimate of propagation velocity. This is commonly done though the well known relation for an ideal gas

$$c = \sqrt{\frac{\gamma RT}{M}} \tag{1}$$

where c is the propagation speed, γ is the adiabatic index, R is the molar gas constant, T is absolute temperature, and M is the molar mass of the gas. Since the adiabatic index and molar mass of the atmosphere are roughly constant, the propagation speed can be considered purely a function of temperature. The propagation speed can then be estimated with an onboard temperature sensor alone. Assuming an ideal reflector and a variance of temperature in space which is negligible, the distance to reflector is then given by the common relation

$$x = \frac{c \cdot \tau}{2} \tag{2}$$

where x is the distance to the reflector, c is the propagation speed, and • is the TOF. Assuming no distortion other than overlap of multiple reflections, the received signal is modeled by the sum of modulated envelopes [7]. This received signal is commonly formulated as

$$y(t) = \sum_{i=0}^{N-1} A_i s(t - \tau_i) + n(t) \tag{3}$$

with

$$s(t) = \left(\frac{t}{T_p}\right)^{\alpha} e^{\left(-\frac{t}{T_p}\right)} \sin(2\pi f_0 t + \phi) \tag{4}$$

where N is the number of received echoes, A_i is a scaling factor, τ_i is the TOF, α and T_p are transducer specific shape factors, f_0 is the carrier frequency, and ϕ is a constant phase term. When τ_i scales with temperature the overlap between echos varies. This overlap is particularly deleterious since constructive and destructive interference can very pulse amplitude and shape wildly, thus affecting the TOF estimate in a complicated way.

3. METHODS AND MATERIALS

A prototype test module was used that consisted of a ultrasound module (Devantech, SRF08) and a temperature and humidity sensor (Sensirion, SHT10). The analog ultrasound signal was sampled at 100 kHz using an on-board analog-to-digital converter of a Microcontroller (NXP, LPC2103 ARM7). The analog signal and temperature data were quantized into an unsigned 8 bit format and stored remotely on a PC. The accuracy of the temperature measurement was limited to ±0.5º F due to quantization

The prototype test module was placed in a standard 40 foot ISO cargo shipping container and positioned 1.7 meters away from the within-container ceiling that acted as the main perpendicular reflecting surface. Data were taken over a 24-hour interval with a sampling interval of 25 seconds resulting in 3456 samples. The temperature compensated expected arrival times were then calculated using equations 1 and 2. For each of the TOF estimators, bias was removed since it represents a calibration offset constant easily removed in a practical system.

3.1. Matched Filter Cross-Correlation Estimator (CCE)

The reference signal (shown in Fig. 3) for the matched filter was constructed by averaging 20 pulse returns from a small perpendicular reflector 0.5 meters away from the transducer. The samples were taken in within a 10 second interval to ensure very close to a constant temperature.

TOF estimation for the matched filter was done by convolving the returned signal with a reversed copy of the reference signal and extracting the time index representing maximum amplitude. For better resolution of the peak location in time, the sampled result of the convolution was interpolated by a factor of 20.

3.2. Envelope Rising Edge Estimator (EREE)

The envelope of the returned signal was estimated using the magnitude of the Hilbert transform. The envelope was smoothed using a low-pass filter according to [7]. The pulse was initially located with a threshold and the leading edge was determined using a local threshold of half the local maximum value. The 5 adjacent points on each side were used in a line of best fit regression and the TOF was recorded as the time axis intercept.

3.3. Half-Peak Time (HPT) Estimator

The pulses were located and the leading edges found in the same manner as the above EERE estimator. The TOF was determined using the leading edge envelope intercept with the half-maximum threshold. To increase the accuracy the intercept was determined using a linear approximation between the two spanning indices.

4. RESULTS

As shown in figure 2, over the period of data collection the ambient temperature fluctuated between 64º F and 114º F. This corresponds to a range of propagation speeds from 342 meters per second to 358 meters per second according to equation 1 and a range of TOF from 4.75 ms to 4.97 ms according to equation 2.

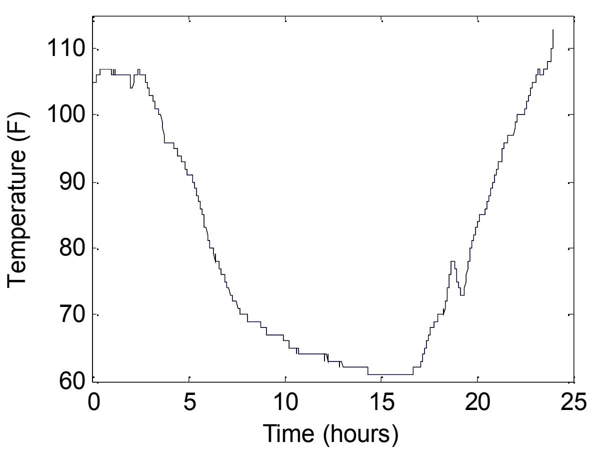

Fig. 2. Temperature swing over the sample period.

The reference signal in Fig. 3 was constructed by averaging 20 pulses from a small perpendicular reflector. This reference signal exhibited envelope constants with α equal to 2.1 and T_p equal to 130 microseconds. For comparison, the returned echo at 90º F is shown in Fig. 4. It is easy to see the distortion due to the non-ideal yet expected multiple reflections.

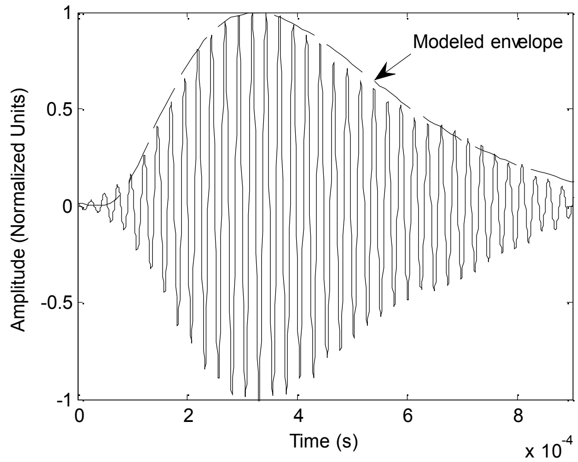

Fig. 3. Reference signal with modeled envelope modeled as in equation 4.

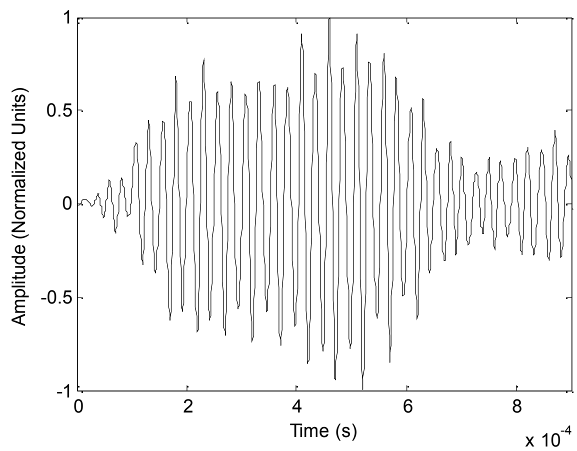

Fig. 4. Returned signal with in situ distortion.

Figure 5 shows the relative variance and temperature sensitivity of the TOF estimators. A constant offset was added to each of the estimators to remove overlap of the three plots. The expected TOF figure 5 was calculated using the data from Fig. 2 using equation 1 and 2.

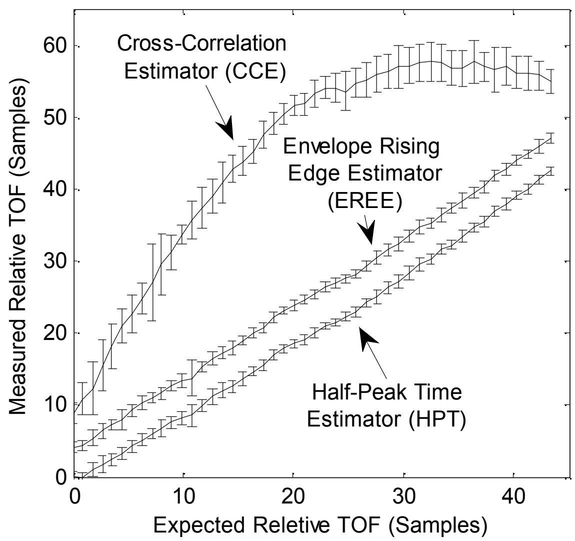

Fig. 5. Relative measured vs. expected TOF for the three estimators.

Table I

TOF Estimator Standard Deviation from Expected

Method	σ		
	Index	Time (μs)	Distance (mm)
CCE	7.26	72.6	12.4
EREE	0.966	9.66	1.65
HPT	0.912	9.12	1.55

5. CONCLUTION

By a significant margin, the matched filter TOF estimate (CCE) had the highest variance of the three methods. This inaccuracy was attributed to severe pulse distortion caused primarily by multiple overlapping echoes that displaced the relative peak location significantly over the temperature range. Since the assumptions of optimality for a match filter were violated, this severe degradation in relative performance was expected. In addition, the non-linearity of this mean estimator was caused by peak offset due to interference as well.

The EREE line of best-fit estimator preformed far better then the matched filter (CCE) but still suffered from echo overlap. The slope of the leading edge was affected by the interference and thus added noise to the TOF estimate.

For the data collected the simplest TOF estimation scheme had the lowest variance. The half-peak time estimator (HPT) proved to be a relatively stationary in spite of the variability of constructive and destructive interference caused by changing temperature.

Since computations are costly in terms of battery life, the performance of the simplest computational method bodes well for a practical embedded sensor system. In addition, many paths for future work are open in the general field of sensing and estimation for shipping container security.

It may also be possible to take advantage of the temperature related changes in constructive and destructive interference in the return signal to decouple overlapping pulses. Investigation of this possibility is the subject of future research.

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