HIGH-ACCURACY DISTANCE MEASUREMENT USING MILLIMETER-WAVE RADAR

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ABSTRACT

We present a method to estimate distance using millimeter-wave radar with an accuracy of around a few micro meters. With the radar operating using frequency-modulated continuous waves (FMCW), we show how both frequency and phase of radar beat signal is used to precisely determine the distance between the radar sensor and the object from which the radar signal is reflected. The method was tested using single-chip FMCW radar operating at 77 GHz employing a chirp bandwidth of 4 GHz. We compared the estimated relative distance against the true relative distance at a few different locations of the object. The estimated distance has a variance of less than 10 μm, which approaches the Cramer-Rao lower bound. We will also present a novel solution to minimize estimate bias due to reflections from neighboring objects as well as a solution to the undesired phase ambiguity problem that is associated with phase recovery during distance estimation.

Index Terms— Millimeter-wave, radar, FMCW, distance measurement, high accuracy.

1. INTRODUCTION

In many industrial applications, accurate distance measurement of the order of few tens of micrometers is desired [1],[2],[3],[4]. Examples include (1) hydraulic applications, where exact position of the piston is required for control purposes in construction machines, (2) computer hardware manufacturing for measuring thickness of hard drives to ensure balance, (3) dental and orthodontic appliance manufacturing, where high precision is desired, and (4) industrial liquid level measurement systems. In these applications, the sensor to object distance can be as much as a few meters. Contact based distance measurement is not possible in many applications because of inaccessibility of object whose distance is to measured. Such measurements are also not precise [5],[6]. On the other hand, contact-free distance measurement is preferred because it is less prone to damage; In fact, in some situations, contact-free distance measurement is the only possible method. Contact-free distance measurement has gained traction with the availability of ultrasonic, laser, and microwave sensors [7],[8]. As reported in [5], however, their integration in an industrial machine is challenging because of space constraints and also because of the propagation medium that the signal has to traverse through [7].

In this work, we present a method to estimate sensor-to-object distance using a frequency-modulated continuous wave (FMCW) radar operating at 77 GHz. It has been shown that highly-accurate distance estimates are obtained using frequency and phase estimates from the matched-filtered received signals, commonly known as the beat signal (see [9] and references therein). It has also been established that the frequency of beat signal provides coarse distance estimate, which is subsequently refined by extracting phase of demodulated beat signal. In this paper, we illustrate practical challenges in using this method in a real environment. We present a method to suppress the impact of undesired, and sometimes unavoidable, reflections from other than the object of interest. Furthermore, we show that a slight error in estimation of coarse distance estimate may result in an amplified error in refined estimate after phase retrieval. This error happens to be of multiple of $\lambda/2$. We investigate the cause of this error and propose a method that avoids its occurrence. Experiments in a real-time set up show the effectiveness of proposed method. We also analyze the performance of this method at different distances and perform variation analysis. The proposed method has the capability to estimate distance up to around 10 μm of accuracy.

2. DISTANCE MEASUREMENT USING FMCW RADAR

A FMCW radar measures distance by transmitting periodic linear frequency ramps or chirps towards the object. The duration of each chirp is T sec and it spans a bandwidth of B Hz resulting in a chirp ramp of B/T Hz/sec. Fig. (1) shows transmitted and received chirps. The beat frequency is defined as the difference between transmitted and received chirps along the frequency axis. As we will see later, the beat frequency is related directly to the sensor-object distance and provides its estimate. For an introduction to FMCW radar, the reader is referred to [1] and [9].

Mathematically, the FMCW radar beat signal obtained after received signal mixing from an antenna is given by

$$x(t) = Ae^{j(2\pi f_b t + \phi_b)}, \tag{1}$$

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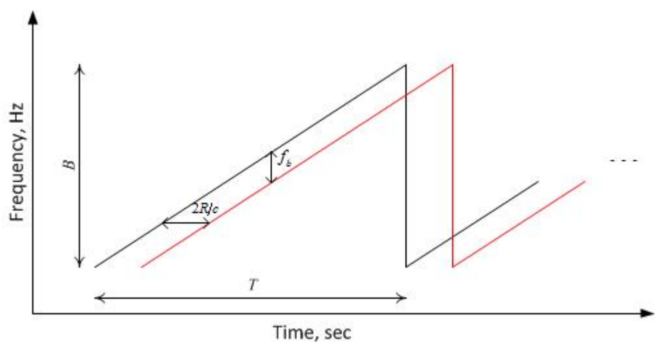

Fig. 1. Transmitted and received chirp.

where the beat frequency is

$$f_b = \frac{2BR}{cT} \tag{2}$$

and the beat signal phase is

$$\phi_b = \frac{4\pi f_{\min} R}{c}. \tag{3}$$

In (2) and (3), B is FMCW ramp bandwidth, R is the range or distance to be measured, c is the speed of light and equals $3\times\ 10^8$ m/s, T is FMCW chirp duration, and $f_{\min}$ is the starting FMCW ramp frequency. With all parameters known, the distance R can simply be obtained by estimating the beat frequency f_b in (2). It is to be noted that the beat signal phase in (3) also contains distance information. Direct estimation of distance from phase may become challenging because of phase unwrapping issue. However, as we will note in Section 3, the estimation variance is greatly improved if distance is estimated using phase. In the method that we use, a "coarse" distance estimate is first obtained using frequency estimate f_b, which is then improved to produce "fine" estimate using the phase estimate ϕ_b.

3. ACHIEVABLE ACCURACY OF ESTIMATING BEAT SIGNAL FREQUENCY AND PHASE

As accuracy and precision is desired in distance measurements, it is important to review the achievable variance bounds. The Cramer-Rao Lower Bound (CRLB) determines the limits of estimating the range using (a) frequency only and (b) frequency and phase. These bounds, derived in [5], are given by

$$\mathrm{CRLB}(R_{f_b}) = \frac{3c^2}{(2\pi)^2\, NB^2\mathrm{SNR}} \tag{4}$$

and

$$\mathrm{CRLB}(R_{f_b,\phi_b}) = \frac{c^2}{(2\pi)^2\, Nf_{\min}^2\mathrm{SNR}} \tag{5}$$

respectively.

In above equations, R_{f_b} represent the coarse distance estimate obtained using beat frequency, and R_{f_b,ϕ_b} represents fine distance estimate obtained using the beat signal frequency and phase. The signal-to-noise ratio, denoted by SNR, is defined as A^2/σ^2, where σ^2 is noise variance. Among the chirp parameters generally used in our application, $f_{\min}$ is around 76 GHz and B is 4 GHz. Consequently, the minimum achievable variance is smaller when both frequency and phase is used to estimate distance.

4. DISTANCE MEASUREMENT USING BEAT SIGNAL FREQUENCY AND PHASE

Knowing that the accuracy of distance estimates can be improved by employing beat signal frequency and phase, we follow the following procedure for high-accuracy distance estimation.

- Estimate $\widehat{f}_b$ from (1) using FFT. Prior to computing the FFT, the beat signal can be zero padded for interpolation.
- Using $\widehat{f}_b$, estimate the coarse distance estimate, R_{f_b}, from (2).
- Plug the estimate R_{f_b} for R in (3) to get $\widehat{\phi}_b$.
- Demodulate the beat signal using

$$\begin{aligned}\tilde{x}(t) &= x(t)\cdot e^{-j\left(2\pi\widehat{f}_b t+\widehat{\phi}_b\right)}\\ &= Ae^{j\left[\left(2\pi f_b-\widehat{f}_b\right)t+\left(\phi_b-\widehat{\phi}_b\right)\right]}\\ &= Ae^{j(2\pi\Delta f_b t+\Delta\phi_b)}.\end{aligned} \tag{6}$$

4.1. Impact of Spurious Reflections

In the case when only one frequency component f_b was present in the beat signal, the phase of demodulated signal $\tilde{x}(t)$ in (6) is linear in time with slope Δf_b and y-intercept $\Delta\phi_b$. The distance estimate ΔR can be obtained from $\Delta\phi_b$ and then used to obtain the fine estimate $R_{f_b,\phi_b} = R_{f_b} + \Delta R$ [9].

In practice, however, additional frequency components appear in the beat signal due to spurious reflections from neighboring objects or from the same object. The presence of these spurious frequencies in (6) impact the fine estimation of R_{f_b,ϕ_b}. While the existence of these frequencies is inevitable, its influence is neglected in existing methods [2],[10]. Our study suggested that additional processing is needed in order to suppress these frequencies. One of the methods is to place a lens in front of the radar; it focuses transmitted (and received) energy to (and from) the object and hence minimizes any reflection other than from the object of interest. The use of lens is, however, impractical in applications where the radar sensor is placed in a small housing. In this paper, we propose a new method to minimize the influence of these spurious frequencies. This method is based on the following additional processing steps.

- Knowing that the unwanted frequencies are higher than Δf_b, low-pass filter the demodulated signal in (6).
- Fit a straight line to the phase of low-pass filtered demodulated signal.
- Estimate $\Delta\phi_b$ as the y-intercept of the straight line fit from Step 6.
- Estimate ΔR from $\Delta\phi_b$ using (3).
- Finally, an accurate, and fine, distance estimate is obtained using $R_{f_b,\phi_b} = R_{f_b} + \Delta R$.

5. EXPERIMENT RESULTS

In order to evaluate the efficacy of FMCW radar based distance measurement, various experiments were performed. Initial investigation was conducted in a dark room surrounded by RF absorbing cones. This was followed by experiments in an office with reflecting walls. A corner reflector was used as the target. The target object was mounted on a motorized linear translation stage, which could traverse away from or towards the radar in variable micrometer increments. Since the absolute distance between the radar sensor and the object was unavailable, the estimation performance was assessed using the following two objective criterion

1. By changing and noting the sensor to object distance in increments and comparing the incremental distance estimate with the actual incremental distance traversed.
2. By evaluating the distribution of distance estimates at a fixed sensor to target distance. This will help assess estimation accuracy.

In the following experiment, the linear stage was advanced in 50 μm increments. Radar returns for 100 frames were recorded for each sensor-to-radar distance. The 32 chirps in each frame were averaged prior to computing the FFT. The following operating parameters were used in this experiment.

- Frequency ramp from 76 GHz to 80 GHz; Bandwidth B = 4 GHz; $f_{\min}$ = 76 GHz
- Chirp time, T = 125 μsec.
- Sampling frequency, f_s = 7.031256 MHz
- Time samples in a chirp, N = 879
- FFT was performed on radix 2 sized data with oversampling factor of 128. The effective FFT size is $1024 \times 128 = 131072$.

Fig. 2 shows the FFT spectrum for one of the frames, plotted against radar to sensor distance. The highest peak of the spectrum corresponds to the sensor to object distance whereas other lower peaks are due to reflections from the stand and other object in view of the radar. The low-pass filtering suggested in Section 4.1 was able to eliminate the undesired impact of spurious reflections.

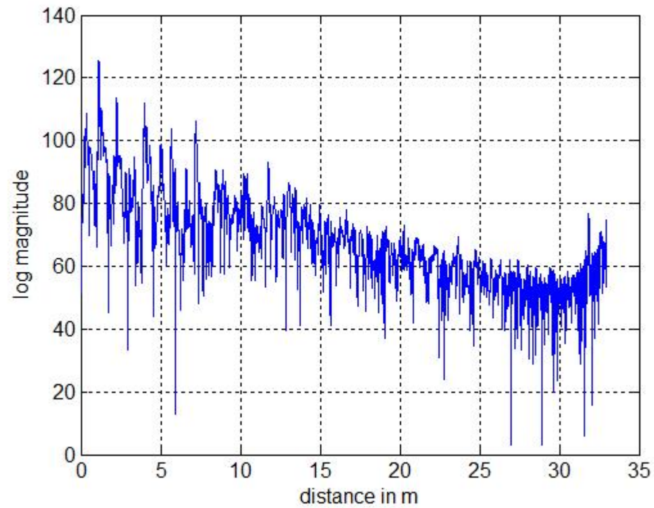

Fig. 2. FFT Spectrum of radar beat signal. A total of 32 chirps were averaged prior to computing the FFT.

In Fig. 3, we show the distance estimates and the true distance for the five positions that the linear stage traversed. Both the FFT-based distance estimates as well as the phase-corrected distance estimates are shown. It is to be noted that since absolute distance is not known, the mean estimate for the first position over 100 frames is considered as the true estimate and the remaining true distance locations are based on and calculated from that assumption. The improvement of FFT-based distance estimate using only the beat frequency and its improvement after phase correction is evident in the figure.

In Fig. 4, a histogram plot of (phase corrected) distance estimates is shown. Data from 500 frames was collected in displaying this histogram. From the ensemble estimates, the variance and standard deviation of distance estimates was $1.9118 \times 10^{-5}\ \mathrm{mm}^2$ and 4.4 μm, respectively.

6. THE PHASE AMBIGUITY AND ITS SOLUTION

Another issue that plays a key role in high-accuracy distance estimation is the phase-wrapping that may happen when phase is estimated from the demodulated beat signal. In order to understand this, let us expand and rewrite (6) as

$$\tilde{x}(t) = Ae^{j\left[\frac{4\pi B}{cT}\left(R-R_{f_b}\right)t+\frac{4\pi}{\lambda}\left(R-R_{f_b}\right)+\phi_c\right]}, \tag{7}$$

where ϕ_c is constant phase difference between the true and reconstructed beat signals. It is present in the transmitted sig-

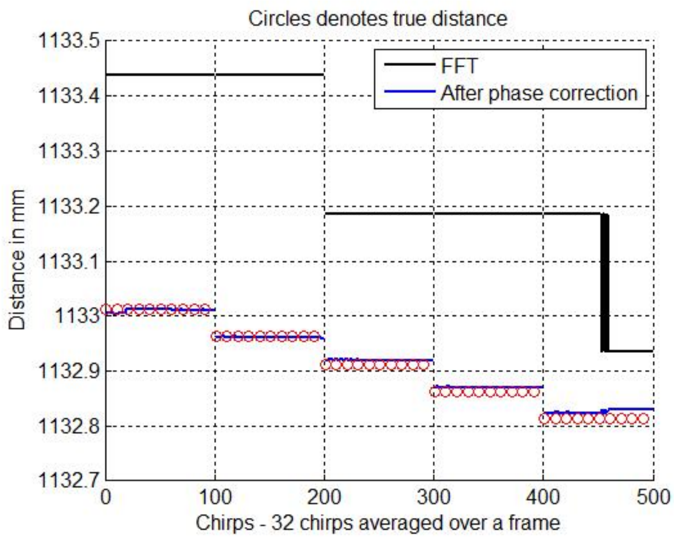

Fig. 3. Distance estimates at five locations of linear stage. The separation between two successive locations of linear stage is 50 μm.

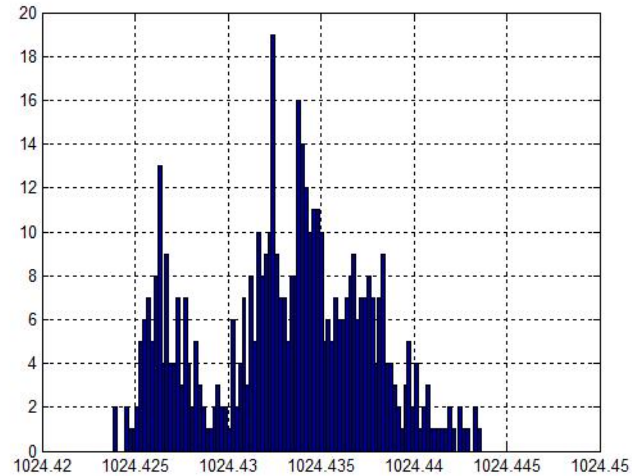

Fig. 4. Histogram of (phase-corrected) distance estimates. The x-axis shows distance in mm.

nal and remains in the demodulated (beat) signal after mixing with the received signal. From (7) we note that for certain values of ϕ_c, the recovered phase $4\pi\Delta R/\lambda + \phi_c$ may wrap around 2π, resulting in $\lambda/2$ shift in the estimate ΔR. For $f_{\min}$ =76 GHz, $\lambda/2$ =1.97 mm. The phenomenon is illustrated in Fig. 5, where it is seen that the estimated distance R_{f_b,ϕ_b} flips between $\pm\lambda/2$ as frames are processed across time. If this phase wrapping is not accounted for, it results in misleading distance estimates. To the best of our knowledge, no solution exists to solve this important problem.

We propose the following steps to greatly reduce 2π wrap around and resulting $\lambda/2$ distance errors.

- For only the first chirp of the first frame, demodulate the beat signal using fine range estimate R_{f_b,ϕ_b} to give

$$d_b(t) = Ae^{j\left[\frac{4\pi B}{cT}\left(R-R_{f_b,\phi_b}\right)t+\frac{4\pi}{\lambda}\left(R-R_{f_b,\phi_b}\right)+\phi_c\right]}. \quad (8)$$

- Assuming that the fine range estimate is close to the true value, obtain the estimate $e^{j\phi_c} \approx d_b(0)$.
- For all subsequent chirp and frame processing, multiply the received beat signal by $d_b^*(0)$.

We process the same signal of Fig. 5 using above method. The results are shown in Fig. 6, where the $\pm\lambda/2$ estimate transitions are eliminated.

7. SUMMARY

We presented method for high-accuracy distance estimation using millimeter-wave radar. Two challenging problems were identified that limit the applicability of high-accuracy distance measurement in a real set up. By investigating the cause of these problems, we proposed solutions that improved the reliability, accuracy, and precision of these methods with little additional complexity. We presented multiple experiments to illustrate the performance of these methods.

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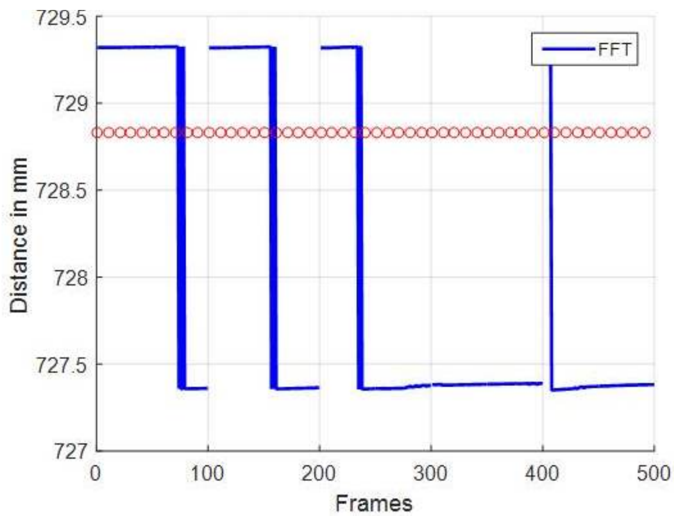

Fig. 5. Effect of phase ambiguity on high-accuracy distance estimates. Circles shows the true distance.

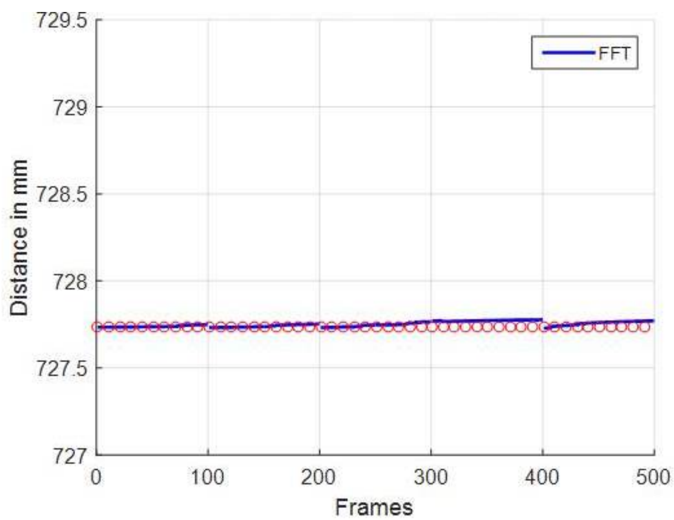

Fig. 6. Corrected distances estimates of Fig. 5. Circles shows the true distance.

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