Multi-range measurement for accurate remote deformation monitoring

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Abstract. Radar-based high-precision deformation monitoring has drawn more and more attention in the industry, automation, and other fields. For FMCW radar, a high precision measurement method based on the combination of frequency and phase estimation is proposed in this paper. The proposed method measures the distances of multiple targets simultaneously. The measurement accuracy is evaluated by theory and simulation, and the effectiveness of the method is verified by the measured data in the real scene for slope deformation monitoring application.

Keywords: Noncontact range measurement, Frequency-modulated continuous wave (FMCW), Remote detection, Deformation monitoring.

1 Introduction

High-precision ranging technology is widely used in building deformation monitoring, lake liquid level measurement, automatic vehicles, target positioning, and so on. Radar has been proved to be a potential technology in these applications. Frequency-modulated continuous-wave (FMCW) radar is gradually used in the field of high precision ranging because of its simple structure, high ranging resolution, and strong anti-noise ability.

A key technology of high-precision ranging of FMCW radar is to accurately obtain the frequency of beat signal after mixing echo signal with the transmitted signal, so as to obtain high-precision ranging information. The existing high-precision measurement methods can be divided into two categories: non-parametric methods and parametric methods. At present, the non-parametric methods for distance measurement usually include interpolation, spectrum thinning algorithm based on Fast Fourier Transform (FFT), phase difference method, and so on. The interpolation method mainly uses the amplitude ratio of several spectral lines near the peak of the spectrum to correct the frequency, and the amount of calculation of interpolation is large. The spectrum thinning algorithm based on FFT first uses the FFT algorithm with a small number of points to make a rough estimation and then uses the thinning algorithm to amplify the local spectrum to make a fine estimation. The

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main methods are zero-filling FFT, Chirp-Z, ZOOM-FFT. In order to achieve higher theoretical accuracy, it is necessary to sacrifice exponential computation and sampling time, which is very disadvantageous to engineering applications. Parameterization methods usually include model-based methods, such as Multiple Signal classification (MUSIC) and Estimation of Signal Parameters via Rational Invariance Techniques (ESPRIT). The parameterization method needs to know some prior information of the signal, and its estimation accuracy is higher than that of the non-parametric method. The disadvantage is that the performance is limited if the model does not match or the signal-to-noise ratio (SNR) is low.

The estimation accuracy of the phase difference method is much higher than that of the frequency estimation method based on signal spectral lines. Tretter [1] first uses the instantaneous phase of echo signal to realize frequency estimation, but it has the problem of phase ambiguity in long-distance measurement. The phase difference frequency measurement method which uses zero-filling FFT to refine the spectrum can make the accuracy approach the lower bound of the theory. Pauli [2] has proposed a two-step approach for single target range evaluation: a coarse determination of the target position by the evaluation of the beat frequency followed by an additional determination of the phase of the signal. Piotrowsky etc. [3] has described a phase evaluation algorithm for highly accurate distance measurements using FMCW radar systems. They measured a movable radar target in a non-ideal environment and achieved an accuracy of 4.5 μm over the entire measurement range maximum to 5.2 m.

Due to the growing demand for the use of radar in high-precision range measurement applications, the measurement range and accuracy are important system parameters, and the ranging algorithm needs to reduce the computational complexity in order to reduce the cost.

In order to solve this problem, the combination of rough and fine estimation can be used to determine the absolute position [2]. Accordingly, a high-precision range estimation algorithm based on the combination of coarse and fine estimation with linear regression model is proposed in this paper, which has the advantages of high precision and low complexity and can be widely used in high-precision ranging of FMCW radar.

This paper is organized as follows. The introduction part introduces the research background of the ranging technology of FMCW radar. The second section gives the principle and steps of the proposed algorithm, and then in the third section we give the real data experimental results in the real scene for slope deformation monitoring application. Finally, it is summarized in the fourth section.

2 Method

In addition to FFT, a variety of frequency estimation algorithms can be used to improve the accuracy of beat frequency estimation to some extent, including zero-filling method, interpolation algorithm and CZT.

$$\hat{r}_{coarse} = \frac{CT\hat{f}_b}{2B} \tag{5}$$

As the round distance of the target is equal to an integral multiple of the center wavelength plus a residual distance. The round distance between the target and the radar can be derived as

$$2r = m\frac{C}{f_0+B/2} + 2r_{fine} \tag{6}$$

where $m = \lfloor(2\frac{f_0}{B}+1)T\hat{f}_b\rfloor$. The coarse range estimation $\hat{r}_{coarse}$is used for calculating the integral multiple m. The residual distance can be calculated by fine range estimation.

Fine range estimation is realized by measuring the phase ϕ_b of the beat signal. This can be obtained from the second term in the index, so that the refined distance can be estimated.

$$\hat{r}_{fine} = \frac{C\phi_b}{4\pi f_0} \tag{7}$$

Then we obtain the accurate range estimation as

$$\hat{r} = m\frac{C}{2f_0+B} + \hat{r}_{fine} = m\frac{C}{2f_0+B} + \frac{C\phi_b}{4\pi f_0} \tag{8}$$

It should be noted that blurring will not occur when the accuracy of rough distance estimation is better than that of the central wavelength.

Therefore, the realization of high-precision ranging has become a problem of parameter estimation of frequency and phase. According to [1], the information to estimate the frequency and phase is included in the phase angle sampling sequence

$$\Phi(n) = 2\pi f n\Delta T + \phi + \epsilon(n) \tag{9}$$

The phase vector can be calculated by the phase unwinding algorithm for the principal value of the angle of the complex signal. The estimation of the parameters f and ϕ can be obtained by solving the minimum mean square error or linear regression.

Moreover, when the noise ϵ obeys the Gaussian distribution, the minimum mean square error estimation is equivalent to the Maximum Likelihood (ML) estimation.

If the center of the sequence is set to 0, that is, the initial time is $-(N-1)/2$, then the mean square error (RMSE) can be expressed as

$$\ell = \sum_{-(N-1)/2}^{(N-1)/2} [\Phi(n) - 2\pi f nT - \phi]^2 \tag{10}$$

Solving the problem we get the estimations

$$\hat{f} = \frac{6}{\pi\Delta T N(N^2-1)} \sum_{-(N-1)/2}^{(N-1)/2} n\Phi(n) \tag{11}$$

$$\hat{\phi} = \frac{1}{N} \sum_{-(N-1)/2}^{(N-1)/2} \Phi(n) \tag{12}$$

where $P = N(N-1)/2, Q = N(N-1)(2N-1)/6$.

The estimations of frequency and phase are unbiased. The covariance is

$$\mathrm{cov}\begin{bmatrix}\hat{f}\\ \hat{\phi}\end{bmatrix} = \begin{bmatrix}\dfrac{6}{\Delta T^2 N(N^2-1)\mathrm{SNR}} & 0\\ 0 & \dfrac{1}{2N\mathrm{SNR}}\end{bmatrix} \tag{13}$$

The linear regression estimator does not need complex calculation, but only needs to calculate the phase and simple summation operation. Moreover, the phase can be obtained by inverse tangent or DACM algorithm. The extended DACM algorithm can be written in discrete form as

$$\Phi[n] = \sum_{k=2}^{n} \frac{I[k](Q[k]-Q[k-1]) - Q[k](I[k]-I[k-1])}{I[k]^2 + Q[k]^2} \tag{14}$$

where $I(k) = \Re(s_b(k\Delta T))$ and $Q(k) = \Im(s_b(k\Delta T))$ are the real and imaginary part of the discrete beat signal in the digital domain.

According to the corresponding relationship between phase and distance, the Cramer-Rao bound (CRB) of phase estimation is

$$\mathrm{Var}(\hat{r}_\phi) \geq \frac{C^2}{16N\pi^2(f_0 + \frac{B}{2})^2\mathrm{SNR}} \tag{15}$$

In multiple target scenes, the targets can be separated first, and then the high-precision range estimation can be carried out respectively. According to the above derivation, the steps of the proposed multi-target high-precision distance estimation method are shown in figure 1. Firstly, the echo signal received by FMCW radar is preprocessed to get the beat signal, and then the FFT is calculated to get one-dimensional range profile, so as to separate multiple targets by locally windowing at the detected peak position. Then the Inverse Fast Fourier Transform (IFFT) of the one-dimensional range profile of the separated multiple targets is performed, and the corresponding frequency and phase are estimated by linear regression. Finally, the accurate estimation of the target distance is calculated according to (8).

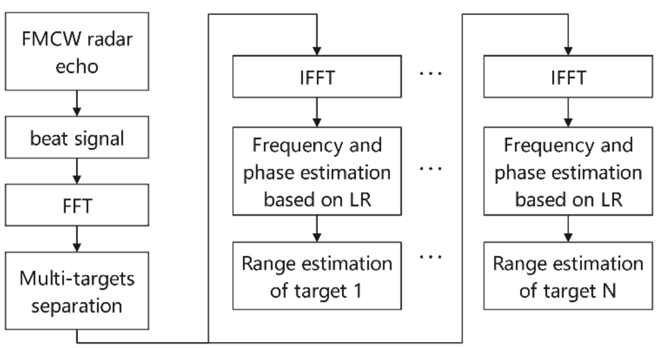


Fig. 1. Processing steps of the proposed multi-target high-precision range estimation method.

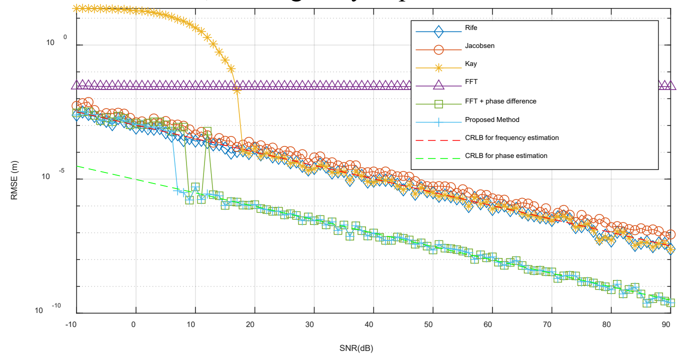
In order to analyze the performance, we have exploited simulation data the estimation error of the proposed algorithm with different signal-to-noise ratio (SNR) and different target distance, and compare it with different methods, such as rife estimator, jacobsen estimator [4], Kay's estimator [5], FFT-based estimator [6], and FFT combined phase estimator [7]. The starting frequency of the ramp is 77GHz, the bandwidth is 2.5GHz, the frequency modulation slope is 15.44MHz/μs, and the echo is sampled by 1024 points.

Figure 2 shows the RMSE when the target is at 20m and compares it with the corresponding CRB. When the signal-to-noise ratio is low, the performance of the proposed method is similar to that of the method based on frequency measurement. When the signal-to-noise ratio is improved, the corresponding ranging accuracy is improved. Furthermore, the RMSE with target distance is plotted in the case of 20dB signal-to-noise ratio.

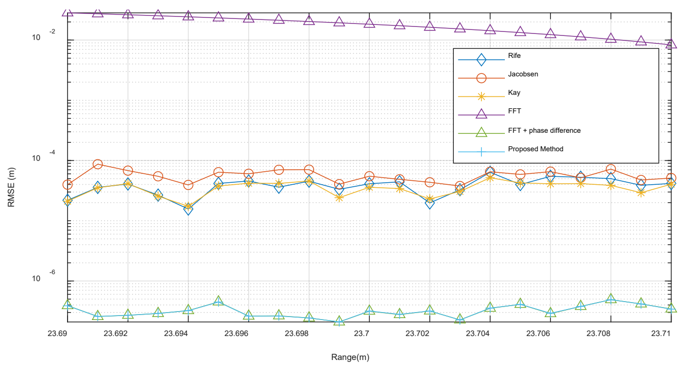
The simple phase-based method has the phenomenon of ambiguity, which leads to a large error in some distances. The method proposed in this paper combines frequency and phase and eliminates ambiguity while maintaining high precision. The results show measurement performance.

Furthermore, we give the results of RMSE varying with SNR and distance, as shown in figure 3.

In summary, the ranging method based on frequency measurement is limited by the CRB of frequency measurement, so its measurement accuracy is limited. The method proposed in this paper makes use of the advantage of phase, and the measurement accuracy is improved by more than 10 times, which greatly improves the measurement accuracy.



(a)



(b)

Fig. 2. Root-mean-square error (RMSE) vs. (a) SNR and (b) range by different methods.

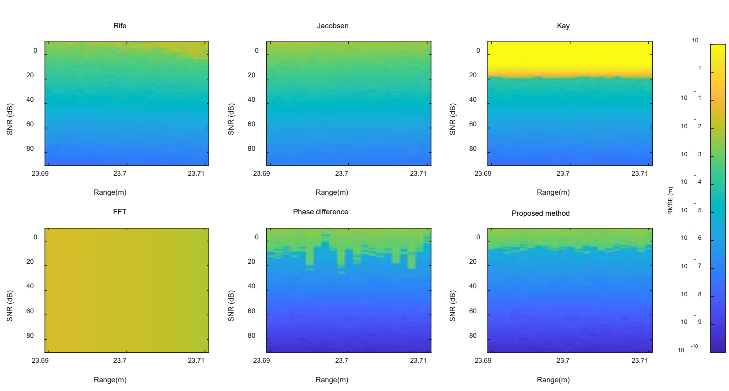


Fig. 3. RMSE comparison of different algorithms.

3 Real scene validation

We have further verified the proposed phase difference algorithm in a real scene of slope deformation monitoring. Considering the ranging performance of different types of scatterers, the trihedral corner reflector is selected as the measurement target according to [8]. The two trihedral corner reflectors are fixed firmly in the deformation position of the slope, and the non-contact distance is measured in the light rain environment. The trihedral corner reflector faces the radar detection direction, and the test scene is shown in figure 4.

We exploit IWR1642 radar module (Texas Instruments, TI), which is a single-chip 76-GHz to 81-GHz mm Wave sensor integrating DSP and MCU evaluation module. One radar wave is transmitted per second, and each frame signal includes 128 ramping cycles. During one period, the signal frequency ramps from 77GHz to 80.86GHz, the sampling frequency of the AD collector is 6.25MHz, and the corresponding sampling duration is 163.84 us with a total of 1024 points. The two trihedral reflectors are stationary at a distance of 19.7705 m and 30.0325 m respectively. During the monitoring, total data of 300 frames were collected during 5 minutes.

Fig. 4. Test scenario. The radar is installed on the side of the highway and the targets are on the slope.

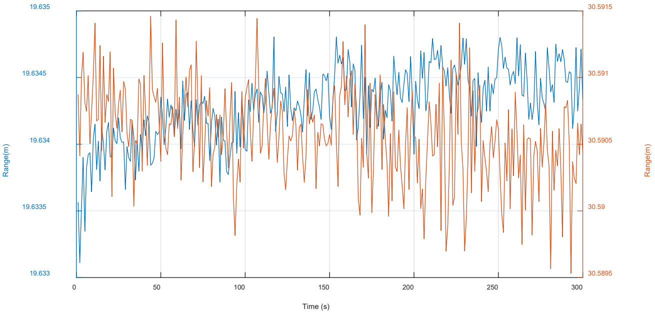


Fig. 5. Continuous monitoring results in the real scene. The blue line indicates the nearer target and the orange line indicates the farther one.

Figure 5 shows the range measurement result in the real environment. The results show that the distance change can be accurately tracked by the radar. At different moments, external construction and rain water cause surface vibration and slope deformation, which leads to the dynamic change of the distance from the monitoring point to the radar. By using the beat signal to accurately measure the distance change, the micro-deformation in submillimeter can be monitored, thus the long-distance dynamic monitoring of the slope can be realized.

4 Conclusions

In this paper, we propose a high precision ranging method for multiple targets by exploiting FMCW radar. The simulation and measured data show that the proposed method has high accuracy, low complexity and easy to be implemented in engineering practice. Moreover, it is a practical method of high-precision measurement which can be used for multiple targets and can be used in applications where accurate distance measurement is needed. These applications include but not limited to deformation monitoring, lake level measurement, automatic vehicles, high-precision target positioning and other automatic measurement fields.

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