Angle Estimation Using an Active 38 GHz Interferometric Radar

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***Abstract*—The operation of a millimeter-wave interferometric radar for estimating the angle of a target is discussed in this paper. The transmitter emits a linear frequency modulated (LFM) signal, ranging from 37 GHz to 39 GHz. The millimeter-wave interferometric receiver is composed by two receive antenna elements separated by 51 cm (64.6λ). The number of sidelobes in the radiation pattern will change as a function of frequency, generating a frequency response that can be transformed to the angle of a target. The theory behind the technique is explained, supported by the experimental measurements.**

I. Introduction

Fast and accurate measurement of the location of objects is necessary in many radar applications. Research on radar sensing for autonomous vehicles is a particularly active area, where radar sensors will play an important role because of their good spatial resolution, and the ability of penetrating smoke, fog, clouds and other obscurants in microwave and millimeter-wave band [1], [2]. Earlier techniques on object angle estimation used mechanical or electrical scanning radars [3] which depend on the beam scanning speed and their resolution relative to the antenna beamwidth. Non-scanning angle estimation, which can provide faster angle estimation without beam scanning, has generally been approached by using arrays of antenna elements. Multiple-input and multiple-output (MIMO) radar [4], subspace estimation techniques, such as MUSIC [5] and ESPRIT [6], and other computational techniques have been developed to estimate the angle of a target by comparing the information discrepancy between each element's response. These techniques achieve improved resolution and staring operation, but generally require large computational load, because of the signal processing and the inversion of matrices, as well as an array of antenna elements.

Interferometric radar techniques have shown potential for fast and accurate angle-rate [7] and angle estimation [8]. Because of the constructive and destructive interference between two antenna elements, a fringe response is generated with a certain number of sidelobes. In this work a millimeter-wave interferometric radar is implemented which uses wideband linear frequency modulation (LFM) to modulate the grating lobes over the duration of the waveform. The response at the receiver is a signal whose frequency is directly proportional to the sine of the angle of an object within the field of view. In this manner, object angle can be estimated without scanning or complex computation. Compared to earlier works, the use of millimeter-wave components make the system more compact than the microwave counterpart and offer better resolution. Experimental measurements demonstrate angle estimation root mean square (RMS) error of only 1.7 degrees.

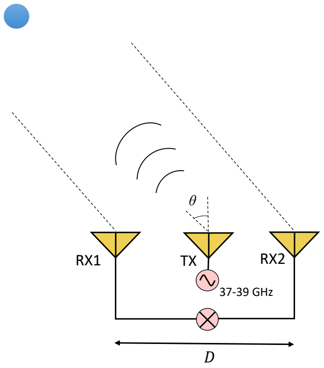

Fig. 1. Distributed radar observing a target at angle θ. The transmit signal is an LFM signal in the 37-39 GHz range. The two receive antennas separated by a baseline D are complex correlated, generating a frequency response proportional to the sine of the angle of the target.

II. Correlation Interferometry for Angle Estimation

Consider a configuration with two receivers and one transmitter observing a moving object, as seen in Fig. 1. For a transmitted LFM signal of the form

$$s(t) = \cos\left[2\pi\left(f_0 t + \tfrac{K}{2}t^2\right)\right] \tag{1}$$

where f_0 is the carrier frequency, and K (Hz/s) is the chirp rate, the normalized signals received by two antennas separated by a baseline D after reflecting off of the target at angle θ can be given by

$$v_1(t) = \cos\left[2\pi\left(f_0 t + \tfrac{K}{2}t^2\right)\right]) \tag{2}$$

$$v_2(t) = \cos\left\{2\pi\left[f_0\left(t-\tau_g\right) + \tfrac{K}{2}\left(t-\tau_g\right)^2\right]\right\} \tag{3}$$

where $\tau_g = \frac{D}{c}\sin\theta$ represents the geometrical time delay which is the time difference the plane wavefront faces in reaching the two elements spaced D apart, and the propagation delay has been ignored since only relative delays are needed.

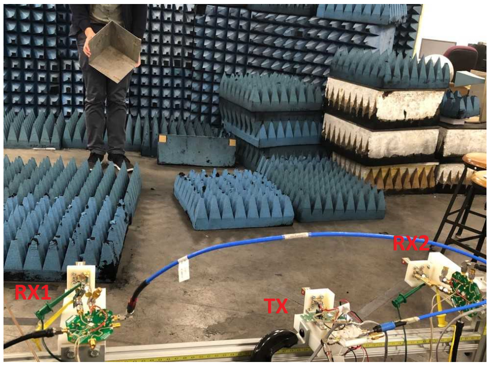

Fig. 2. Configuration for the experimental measurements consisting two receivers on the side and a transmitter in the middle. The trihedral reflector inside the semiarch range was moved to multiple locations.

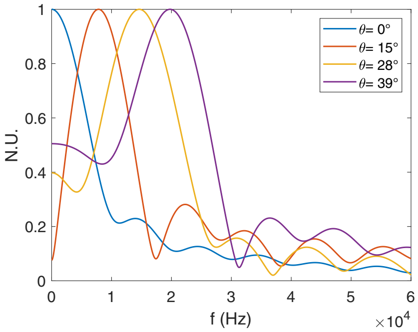

Fig. 3. Frequency response for four different angle locations, showing the increase in frequency proportion to $\sin\theta$ as the target moves away from broadside.

The two received signals are cross-correlated and then low-pass filtered, yielding

$$v_{out}(t) = \cos\left[2\pi\left(f_0 + Kt - \tfrac{K}{2}\tau_g\right)\tau_g\right]. \tag{4}$$

The derivative of the phase of the received signal

$$f_i = \frac{1}{2\pi}\frac{d\phi}{dt} = K\tau_g = K\frac{D}{c}\sin\theta \tag{5}$$

gives its instantaneous frequency which is directly proportional to the chirp rate K, the baseline D and the sine of the angle of the target. The angle of a target can thus be measured directly with a simple frequency estimation of the output.

III. EXPERIMENTAL MEASUREMENTS

Measurements were conducted in a 7.3 m semienclosed arch range with two receive elements separated by a baseline $D = 51$ cm and a transmitting antenna placed between them, as shown in Fig. 2. A trihedral reflector was used as the reflecting target and moved to multiple locations. Three 10 dBi horn antennas were used for the transmitter and receivers. The transmitted signal was generated at baseband with a Keysight M8190 Arbitrary Waveform Generator with a chirp rate of $2{\cdot}10^{13}$ Hz/s and a pulse duration of 100 μs centered at 2 GHz. The signal was upconverted with a 37-40 GHz GaAs MMIC I/Q upconverter (Analog Devices HMC6787ALC5A) and then amplified using a 24 dB power amplifier (Analog Devices HMC7229LS6). The two received signals were amplified by 23 dB gain low-noise amplifiers (Analog Devices HMC1040LP3CE), and then downconverted to baseband using 37-44 GHz GaAs MMIC I/Q downconverters (Analog Devices HMC6789BLC5A). Both up- and down-converters were driven by an LO of 18 GHz. The normalized frequency response of the cross-correlation output for three cases at different angles can be seen in Fig. 3. The maximum values of the instantaneous frequency from the experimental measurements for different angles and the theoretical instantaneous frequency from Eq. 5 are shown in Fig. 4. Experimental and theoretical values show good agreement, with RMS error between measured and theoretical of 1.7 degrees, verifying the potential of the technique for accurate and fast angle estimation.

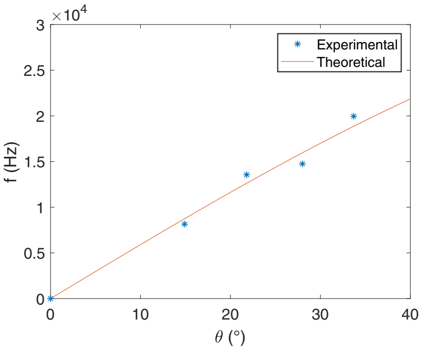

Fig. 4. The value of the maximum instantaneous frequency from the experimental measurements for different angles and the theoretical instantaneous frequency from Eq. 5.

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