Measurement of the Radial and Angular Velocity of Tagged Objects Using Interferometric Harmonic Micro-Doppler Radar

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***Abstract* — We demonstrate the joint detection of the radial and angular velocities of tagged moving objects using a harmonic radar with dual interferometric-Doppler measurement modes. The radar transmits a continuous-wave signal which is incident on a compact harmonic tag affixed to the moving object. The tag generates and re-transmits a signal at the first harmonic frequency, 11.4 GHz, which is more easily detected at the radar in complex environments than the scattered 5.7 GHz illuminating signal which can be masked by clutter responses. The radar receiver consists of an interferometric antenna pair separated by 10 wavelengths. Each channel provides a Doppler response, from which the radial velocity can be detected, while the complex cross-correlation of the output of the two receivers provides an interferometric frequency response that is proportional to the angular velocity of the object. We demonstrate the concept using at 5.7/11.4 GHz interferometric harmonic radar and show the time-frequency responses of a sinusoidally-moving harmonic tag.**

I. Introduction

Interest in human-computer interactions (HCI) technologies has been rapidly increasing as applications such as augmented or virtual reality (AR/VR), remote health, smart home, and generalized internet of things (IoT), among others, become more prevalent. These applications benefit from the ability to track people and objects in cluttered environments such as living spaces, and the ability to identify the motions of people and held objects. The most common approaches for addressing these needs rely on optical systems to visually identify and track various objects through image capture and image processing. However, these techniques can be computationally expensive, and furthermore have associated privacy concerns since they rely on optical imagery. Microwave radar systems address these limitations since they can detect and track object motion without imaging by measuring the time-varying Doppler shift of the scattered signals. Radar systems can also function in all lighting and weather conditions, and since they do not form images, privacy concerns are significantly alleviated. Micro-Doppler systems, which measure and process the frequency sidebands manifesting on time-varying Doppler signals, have been well-studied as a method for tracking the movement of both people and objects in cluttered spaces [1], [2], [3], [4], [5], and for classifying the motion and vital signs of people [6], [7], [8] .

Two principle challenges arise when using Doppler radar to measure moving objects in living spaces: First, the scattering response from objects in the environment can produce large signal responses, masking the desired responses of people and moving objects. While the Doppler frequency shift helps to separate the desired responses from the clutter in the spectral domain, systems with significant phase noise or clutter with strong responses nonetheless manifest broad spectral responses and can still mask the desired returns. This challenge can be overcome by using harmonic tags along with a harmonic radar. Tags receive the incident signal and generate a response at the second harmonic frequency, which is detected by the harmonic radar. Since the clutter responses manifest only at the fundamental frequency, the harmonic tag response can be more easily detected. The second challenge is that Doppler radar is capable of measuring only the radial velocity of moving objects. When the motion is highly angular, with minimal radial motion relative to the radar, the Doppler shift is low in frequency, making it challenging to detect and classify the signal responses. Micro-Doppler signal responses from moving people lose their classification capability when the angle of motion relative to the radar is less than 60° [9], [10]. This may be overcome by combining the radar with an interferometric receiver, which produces a signal response whose frequency is directly proportional to the angular velocity of the object, thereby providing a measurement of both radial and angular velocity [11].

In this work, we present a dual-mode harmonic radar that jointly measures the micro-Doppler responses of tagged moving objects in the radial and angular dimensions. The radar transmits a continuous-wave signal at 5.7 GHz that is captured by a compact harmonic tag. The tag generates a response at the second harmonic (11.4 GHz) that is radiated back to the radar. The receiver is a two-element interferometer, each channel of which generates a traditional Doppler response, and the cross-correlation between which generates the interferometric frequency shift. We demonstrate the detection of harmonic micro-Doppler signals in both the radial (Doppler) and angular (interferometric) domains.

II. Radial and Angular Micro-Doppler Radar

The dual-mode harmonic radar measures both Doppler frequency shift and interferometric frequency shift of moving harmonic tags (Fig. 1). A continuous-wave harmonic radar transmits a signal at a carrier frequency f_c with amplitude α given by

$$s_{\mathrm{tx}}(t) = \alpha e^{j2\pi f_c t} \tag{1}$$

which generally is scattered off a moving object in the scene and collected by the radar receiver. At this point, the signal

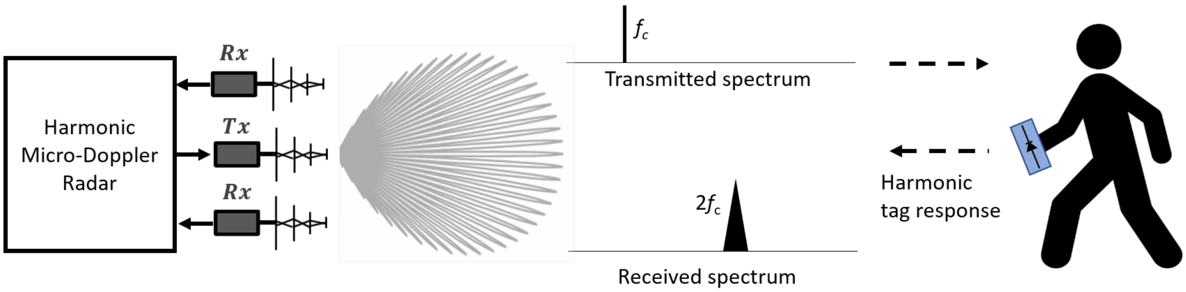


Fig. 1. Diagram of the harmonic interferometric micro-Doppler radar. The system transmits a CW that is received and re-transmitted at the second harmonic by the harmonic tag. The received signal is then processed in the two receivers to measure the radial motion, and their responses are cross-correlated to generate the interferometric angular velocity measurement. The interferometer beam pattern manifests as a series of grating lobes.

can be given by

$$r_{\rm rx}(t) = \beta_1 e^{j2\pi(f_c - \frac{2v_r}{\lambda})t} \tag{2}$$

where β_1 includes propagation loss, v_r is the radial velocity of the scattering object and $\lambda = c/f_c$. When incident on a harmonic tag, the transmitted signal is input to a nonlinear device, such as a Schottky diode, which generates harmonics of the incident signal. For a radar collecting the second harmonic, the received signal is given by

$$r_{\rm rx}^{(2)}(t) = \beta_2 e^{j4\pi(f_c - \frac{2v_r}{\lambda})t} \tag{3}$$

where β_2 includes propagation loses and the conversion loss of the diode or nonlinear device. The harmonic Doppler frequency shift is thus given by

$$f_{D_2} = \frac{4v_r}{\lambda} \tag{4}$$

This signal can be processed in the time-frequency domain, using, e.g., the short-time Fourier transform (STFT), to measure the time-varying radial motion of the object.

Angular velocity is obtained by cross-correlating the signals received at the two antennas. At the fundamental frequency, an interferometer with baseline (antenna separation) D observing an object moving with angular velocity ω, this process generates a signal represented by [11]

$$r_{\rm int}(t) = \beta_3 e^{j2\pi f_c \frac{D}{c}\sin(\omega t)} \tag{5}$$

The frequency of this response near broadside ($\omega t = \theta \approx 0$) is $f_I = \frac{\omega D}{\lambda}$ which is directly proportional to the object angular velocity. At the harmonic frequency $2f_c$, the interferometric frequency shift is simply

$$f_{I_2} = \frac{2\omega D}{\lambda} \tag{6}$$

The received signal can thus also be processed in the time-frequency domain to determine the time-varying angular motion of the object.

III. Harmonic Radar and Tag Design

The 5.7/11.4 GHz system comprises a harmonic radar (see Fig. 2) and a harmonic tag (see Fig. 3). The tag is based on that demonstrated in [1], and is composed of a 5.7 GHz narrow-band ring antenna and a 11.4 GHz embedded patch antenna. The nonlinear device connecting these two components is the SMS-201 Schottky diode which generates the harmonic signal. The harmonic radar is composed of one transmit chain and two receive chains. The transmitter used a 19 dB amplifier and a ZVBP-5800-S+ cavity filter operating at a frequency range of 5.725–5.875 GHz with a pass-band attenuation of < 1 dB, which was used to mitigate the transmission of any residual signal at the second harmonic $2f_c$. The transmit antenna for the system was a biquad antenna with a gain of 9 dBi. The receiver of the harmonic radar

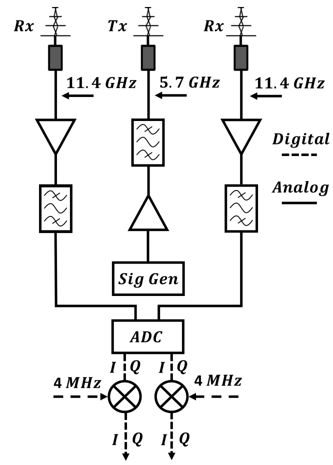


Fig. 2. Diagram of the radar design. The signals are digitally down-converted via Nyquist subsampling to 4 MHz prior to processing. Each receiver generates a Doppler response, and the cross-correlation of the two yields the interferometric response.

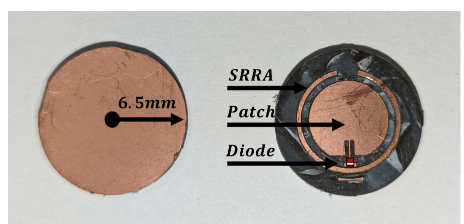


Fig. 3. Image of the 5.7/11.4 GHz harmonic tag. The split ring resonator antenna (SRRA) operates at the fundamental frequency, while the patch antenna operates at the second harmonic.

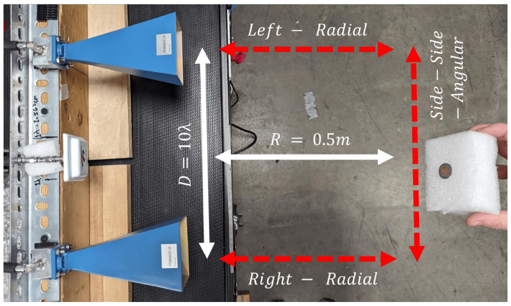
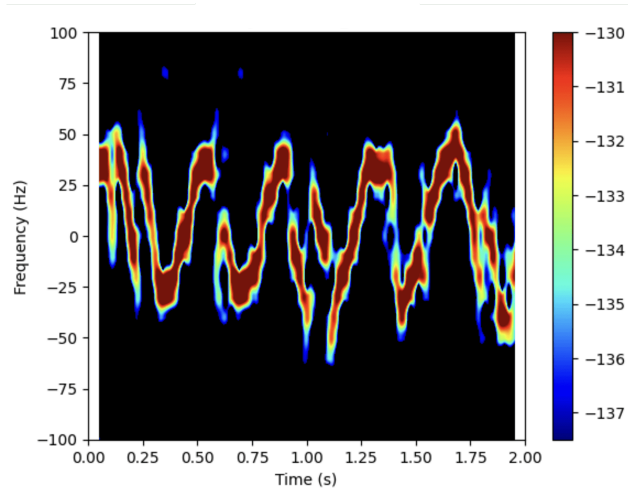


Fig. 4. Image of the harmonic interferometric micro-Doppler system with the three measured motions overlaid, showing the radial motion in front of each individual receiver and orthogonal motion in front of the receive array.

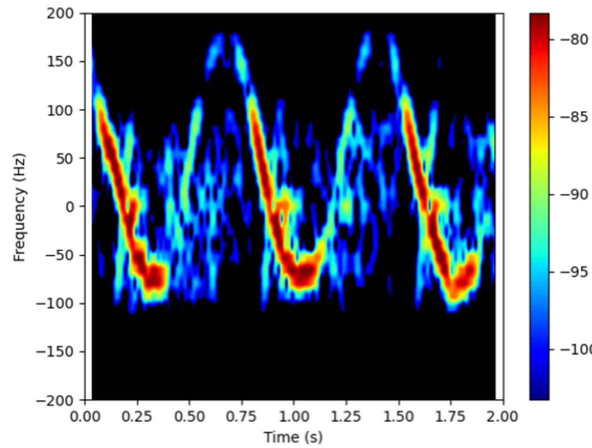
was composed of two 20 dBi horn antennas with a baseline separation D of 10Λ. Each receive antenna was connected to a 6 GHz - 18 GHz ZX60-06183LN+ LNA with a gain of 20 dB, after which was a VHF-8400+ band pass filter, further isolating the harmonic response of the harmonic tags from the clutter existing at the fundamental frequency. The harmonic tag was based on the 2.8/5.6 GHz harmonic tag presented in [1]. In this work, the ring antenna shown in Fig. 3 has been designed to operate at a frequency of 5.7 GHz and the embedded patch antenna has been designed to operate at a frequency of 11.4 GHz. Each component of the harmonic tag was simulated in ANSYS HFSS, which yielded a fractional bandwidth of 0.48% at the fundamental frequency and 0.24% at the harmonic frequency. The frequency of this harmonic tag can be varied by altering the angular separation of the gap in the ring.

IV. Experimental Results

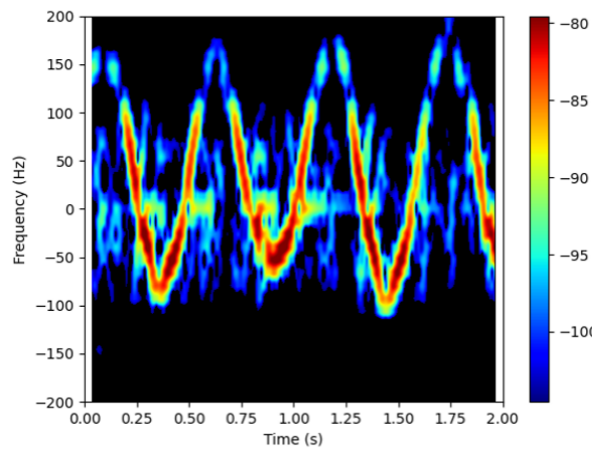
A tag was used to measure the harmonic micro-Doppler responses in the angular and radial domains. The tag was placed onto a foam block for stabilization and moved sinusoidally between each receiver in an orthogonal trajectory at a constant speed as shown in Fig. 4 to measure the interferometric frequency shift. The tag was also moved sinusoidally in a radial motion relative to each receiver to measure the time-varying Doppler shift. Each measurement was captured over a time of 2 seconds at a sample rate of 10 MSa/s. The in-phase (I) captured samples from each receiver were used to compute the quadrature (Q) components using the Hilbert transform. The complex signals were then sub-sampled to 8 kHz and cross-correlated to generate the interferometric signal response. The resulting samples were interpolated using a simple binary comparator based on thresholding the I and Q components individually and resolving the binary response with an N-factor quadratic interpolation function. The output of this binary comparator yields an amplitude-invariant signal equivalent of the original cross-correlated signal, mitigating range-dependent amplitude variations. Each signal was then processed using the STFT, from which the magnitude was taken to generate spectrograms. The measurement results are shown in Fig. 5. The first plot shows the spectrogram of the harmonic interferometric response, showing the sinusoidal



(a)



(b)



(c)

Fig. 5. (a) Spectrogram of the interferometric response of sinusoidal side-side motion after down-conversion and interpolation via binary comparator. Showing the result of only angular velocity with a baseline receiver separation of $D = 10\lambda$. (b) Spectrogram of the radial motion response in from of left channel receiver antenna with equivalent interpolation techniques as described in the cross-correlated response. (c) Spectrogram of the radial motion response in from of right channel receiver antenna with no interpolation techniques.

motion of the tag. The second two plots are separate spectrograms of the tag moving sinusoidally relative to each receiver. In each plot, the time-varying frequency shift follows the sinusoidally motion of the tag, demonstrating the capability to measure the angular and radial velocities of tagged objects in a single harmonic radar system.

V. Conclusion

A new approach to measuring the motion of objects in cluttered environments was demonstrated using harmonic tags and harmonic interferometric/Doppler radar. Time-frequency responses from both the Doppler and interferometric receivers match to the radial and angular motions of the moving tag. From these signatures, classifiers can be applied to identify the motions of tagged objects regardless of their motion relative to the radar, leading to a robust, reliable method of motion tracking in future sensing systems.

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