A Spectrum-Efficient FSK Radar Solution for Stationary Human Subject Localization Based on Vital Sign Signals

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***Abstract*—Beyond the traditional use of frequency-shift keying (FSK) radar in tracking moving targets, this work further extends its capability in localizing stationary human subject based on the phase information extracted from the detected vital sign signals. Unlike the *I/Q*-trajectory-based range detection method that relies on trajectory analysis and therefore is prone to the effect of DC offset and trajectory distortion, the FSK-based technique used in this paper works in spectrum domain utilizing only the motion frequency of the target with a reliable signal-to-noise ratio (SNR). A 5.8-GHz industrial, scientific, and medical (ISM) band FSK radar with a frequency difference of 15 MHz is designed and implemented. Experiments demonstrate that, besides tracking walking human subject, the proposed FSK technique can successfully recover range information of a seated human subject at different locations. A preliminary investigation of the detection robustness and consistency is presented by measuring the range of a 4-mm peak-to-peak periodic motion generated by an actuator over a 90-s observation window.**

***Keywords*—Spectrum efficiency, FSK radar, dual frequency radar, noncontact biomedical sensor, stationary human subject, vital signs monitoring, short-range localization.**

I. Introduction

Noncontact range detection and vital signs monitoring are emerging technologies supporting a range of civilian and military applications. For instance, hidden intruder detection by capturing and locating their vital signs and search of surviving victims immobilized under collapsed building debris. Unlike existing technologies such as infrared (IR) sensors that are sensitive to ambient light/temperature changes and video cameras that cause privacy concerns, radar sensors are attractive for their robustness against changing light and temperature conditions, being less intrusive, long range coverage, and easy implementation. While vital signs sensing can be achieved using single-tone Doppler radar, the majority of the radar-based range tracking approaches rely on wideband systems such as frequency-modulated continuous-wave (FMCW) radar and ultra-wideband (UWB) radar, which typically require a bandwidth on the order of hundreds of MHz or even GHz.

Significant growth in wireless communications has created a shortage in the available radio spectrum. Wireless communications such as commercial radar, mobile phone, and high-speed Internet access have to compete with existing users in military radar, government network, and environmental monitoring. Due to the broadcast nature of the radio propagation, wireless transmission is vulnerable to malicious attacks such as eavesdropping and jamming. Large bandwidth occupation means a large interference window with increased jamming possibilities and high bandwidth requirements on system components. A wireless radar system that utilizes less bandwidth for the aforementioned range detection and vital signs sensing applications becomes extremely important. For this reason, dual frequency radar is advantageous because it inherits the ability to measure vital signs from Doppler radar, while also having the ability to estimate the absolute range of a moving target with low bandwidth requirements. However, it requires two frequency sources to simultaneously generate two carrier frequencies. In comparison, frequency-shift keying (FSK) radar achieves the generation of two carrier frequencies by switching back and forth between two frequency levels with the use of a single frequency source, leading to simpler circuit architecture, less power consumption, and lower cost.

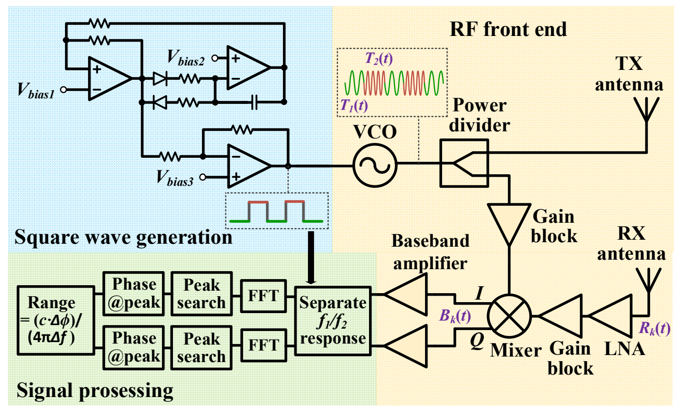

Fig. 1. Block diagram of the FSK radar system.

The authors in [1] proposed an *I/Q*-trajectory-based range detection method using two-tone radar. However, since AC-coupling will create amplitude and phase distortion in the baseband data, trajectory can be distorted and detection performance may be affected. If DC-coupling is adopted, undesired DC offset caused by clutter reflection and hardware imperfection will appear before baseband amplifier and may significantly limit the maximum dynamic range of the radar system [2]. In comparison, the proposed FSK radar solution works with both DC- and AC-coupling because the responses of the two carriers experience the same phase shift introduced by the AC coupling circuit at the motion frequency where the phase information is found. Traditionally, FSK radar is used for range tracking of a moving target based on phase comparison for the Doppler components [3]. This paper aims at extending its capability in localizing stationary human subject by

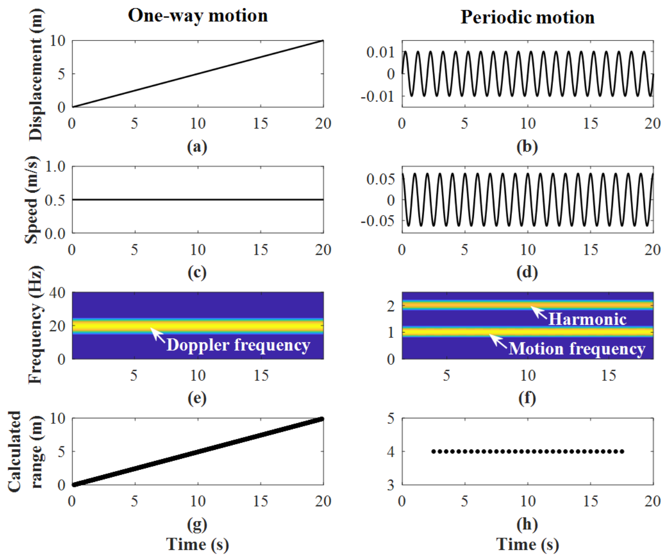

Fig. 2. Simulated one-way motion and periodic motion. (a)(c)(e)(g) correspond to a target with a one-way movement. (b)(d)(f)(h) correspond to a target with a small periodic motion.

leveraging phase estimation on the obtained vital sign signals. The fundamental theories of range detection of moving- vs. stationary-human subject are explained in Section II. Simulations are presented in Section III. System implementation and experiments are discussed in Section IV. Finally, conclusions are laid out in Section V.

II. Fundamental Theory

Fig. 1 shows a simplified block diagram of the FSK radar system. It mainly consists of three units, i.e., a square wave generation circuit, a radio frequency (RF) front-end, and a signal processing unit. An operational-amplifier-based circuit is employed to generate a square wave signal, which is used as the control signal of the voltage-controlled oscillator (VCO) to switch between two carrier frequencies f_1 and f_2. The frequency shift between the two carriers is usually very small in MHz or kHz level, which is represented as $\Delta f = f_2 - f_1$, assuming $f_2 > f_1$. These carrier frequencies are transmitted towards the target as:

$$T_k(t) = \mathrm{Re}\left\{\exp\left[j\left(2\pi f_k t + \varphi_{o,k}(t)\right)\right]\right\}, \tag{1}$$

where k = 1, 2 and $\varphi_{o,k}(t)$ represents the phase noise from the oscillator. Note that amplitude variation has been neglected and unit amplitudes are assumed.

A. Localization of Human Subject in Motion

For range-tracking of a moving target, the reflected signal will be shifted in frequency due to Doppler effect. A phase delay is also generated by the round-trip travel of the signal. The received signals can be approximated as:

$$R_k(t) \approx \exp\left[j\left(2\pi(f_k \pm f_{d,k})t - \frac{4\pi R_0}{\lambda_k} \mp \frac{2\pi R_0 f_{d,k}}{c} + \varphi_{o,k}(t - \frac{2R_0}{c})\right)\right], \tag{2}$$

where c is the speed of light, λ_k is the wavelength corresponding to each carrier frequency, $f_{d,k}$ stands for the generated Doppler frequency, and R_0 represents range to target at a particular time $t = t_0$. After down-conversion, the baseband output can be obtained as:

$$B_k(t) = \exp\left[j\left(\mp 2\pi f_{d,k} t + \frac{4\pi R_0}{\lambda_k} \pm \frac{2\pi R_0 f_{d,k}}{c} + \varphi_k\right)\right], \tag{3}$$

where $\varphi_k = \varphi_{o,k}(t) - \varphi_{o,k}(t-2R_0/c)$ is the total residual phase accumulated in the circuit. According to the range correlation theory, φ_k is very small compared to other phase terms in (3) and hence will be ignored in the following analysis. By keeping Δf very small in comparison with f_k, $f_{d,1}$ and $f_{d,2}$ will be almost identical, i.e., $f_{d,1} \approx f_{d,2}$. Therefore, the phase difference between the two baseband signals is:

$$\Delta\varphi(t) = \frac{4\pi R_0}{\lambda_2} - \frac{4\pi R_0}{\lambda_1}. \tag{4}$$

Range estimation is thus derived based on this phase difference associated with the Doppler frequencies as:

$$R_0 = \frac{c \bullet \Delta\varphi(t)}{4\pi\Delta f}. \tag{5}$$

B. Localization of Stationary Human Subject

When the target of interest has a periodic small motion $x(t) = m \cdot \sin\omega t$ at a nominal distance D_0, the signal will be reflected back with its phase modulated by the time-varying periodic motion and a constant phase determined by D_0. The received signals are approximated as:

$$R_k(t) \approx \exp\left[j\left(2\pi f_k t - \frac{4\pi x(t)}{\lambda_k} - \frac{4\pi D_0}{\lambda_k} + \varphi_{o,k}(t - \frac{2D_0}{c})\right)\right]. \tag{6}$$

Different from the target in motion scenario, the acquired baseband signal will be frequency-modulated by the periodic motion frequency, which can be represented and analyzed by spectral analysis as [4]:

$$\begin{aligned} B_k(t) &= \exp\left[j\left(\frac{4\pi x(t)}{\lambda_k} + \frac{4\pi D_0}{\lambda_k} + \varphi_k\right)\right] \\ &= \sum_{l=-\infty}^{\infty} J_l\left(\frac{4\pi m}{\lambda_k}\right) \bullet \exp\left[j\left(l\omega t + \frac{4\pi D_0}{\lambda_k} + \varphi_k\right)\right], \end{aligned} \tag{7}$$

where J_l is the Bessel function of the first kind. The phase difference can be extracted from the $l = 1$ frequency component, which is the motion frequency. This phase difference is:

$$\Delta\varphi(t) = \frac{4\pi D_0}{\lambda_2} - \frac{4\pi D_0}{\lambda_1}. \tag{8}$$

Accordingly, the target range can be estimated based on this phase difference associated with the motion frequency following (5). As can be seen from (7), phase extraction at the motion frequency eliminates the effect of motion displacement. In addition, motion frequency will be separated from other noise on the spectrum. Therefore, this technique operates based on a reliable signal-to-noise ratio (SNR) and enables robust nominal distance estimation.

However, the maximum unambiguous range of an FSK system is limited due to the periodicity of the sinusoidal wave.

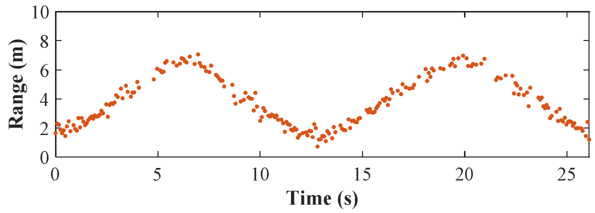

Fig. 3. Range-tracking result for a walking human subject.

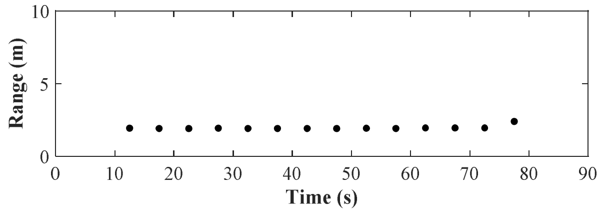

Fig. 4. Range detection results of the mechanical vibration measurement.

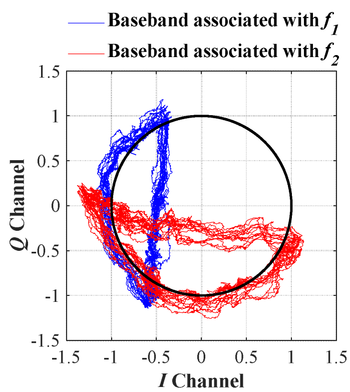

Fig. 5. *I/Q* constellation graph of a 30-s data segment chosen from the mechanical vibration measurement. Strong distortion is observed for the trajectory-based method.

Since $\Delta\varphi(t)$ can only reach a maximum of 2π, range will become aliased beyond this limit. The maximum unambiguous range equation can be derived from (5) as $R_{max} = c/(2\Delta f)$. For a given application, the frequency shift can be adjusted to achieve the desired detection range. If high measurement resolution is demanded, other reference systems can be adopted to extend the maximum discernable range without sacrificing the measurement resolution [5].

III. Simulation

To demonstrate the two range detection mechanisms, a one-way motion and a periodic motion have been simulated in MATLAB and range estimations were made based on the above theories. The FSK radar frequencies were chosen as f_1 = 5.8 GHz and f_2 = 5.81 GHz. A one-way motion was simulated with a constant speed of 0.5 m/s and starting distance of 0 m. On the other hand, a periodic motion was simulated with 1 Hz frequency, 2-cm peak-to-peak amplitude, and a nominal distance of 4 m from the radar. 100-Hz sampling frequency was used for both motions. As shown in Fig. 2, the Doppler frequency shows up on the short-time Fourier transform (STFT) spectrum for one-way motion scenario in (e), whereas the motion frequency and its harmonic appear on the spectrogram for the periodic motion case in (f). Instantaneous ranges of one-way motion were recovered based on the phase difference of the Doppler frequencies, while the nominal distance of the periodic motion was successfully retrieved from the phase difference extracted at the motion frequency, as plotted in (g), (h), respectively. It should be noted that the Doppler frequency in Fig. 2 (e) depends on both the target speed and the wavelength, whereas the baseband detected frequency in Fig. 2 (f) is always the same as the periodic motion frequency.

IV. System Implementation and Experiments

In the implemented FSK radar sensor, a 380-Hz square wave was generated onboard. The square wave amplitude determined the VCO output frequencies, which were f_1 = 5.823 GHz and f_2 = 5.838 GHz, with Δf = 15 MHz. The maximum unambiguous range was calculated as 10 m in this case. Both the square wave and *I/Q* channels were sampled and data acquisition was realized using NI USB-6009 with 15-kHz sampling frequency for all experiments. The square wave control signal was utilized to synchronize the data acquisition and separate the baseband responses for carrier frequencies f_1 and f_2. Note that to eliminate the null detection problem [4], *I/Q* channel data were combined to recover the actuator motion frequency and respiration rate in the following experiments.

A. Range-Tracking of Human Subject in Motion

The FSK radar sensor was mounted on a tri-stand and placed in an interior corridor. To avoid the antenna nearfield and limit the experiment within the maximum unambiguous range, a human subject was asked to complete two round trips from 1.5 m to 8.5 m with a normal walking speed. After performing fast Fourier transform (FFT) on the separated baseband responses, Doppler frequencies caused by human walking can be obtained at both frequency spectra. By comparing the phase difference between the two Doppler frequencies, instantaneous range of the walking subject was estimated according to (5) and plotted in Fig. 3.

B. Localization of Actuator with Mechanical Movement

Range detection experiment with a periodic mechanical motion was conducted in a typical lab environment. An actuator (Zaber TSB60-I) with a motion frequency of 0.5 Hz and peak-to-peak amplitude of 4 mm was placed 2 m away facing the radar. A 90-s data were recorded and processed with a sliding window to investigate the detection robustness and consistency. A 25-s FFT sliding window was used with a 5-s sliding step size. A total of 14 range estimations were obtained, as plotted in Fig. 4. Standard deviation of 13 cm was calculated from the results with mean error of 4 cm. Future work will include measurements in various indoor environments with target at different locations to further evaluate the detection performance in real-life scenarios.

To compare the performance with the *I/Q*-trajectory-based range detection method [1], a 30-s data segment was used to plot the *I/Q* constellation graph in Fig. 5. As can be seen, the baseband data were severely distorted because AC coupling was used before baseband amplification. In this case, accurate phase extraction on the *I/Q* trajectory becomes difficult, resulting in unreliable range estimation. If DC-coupled radar is adopted, DC offset will have to be dealt with in order to achieve

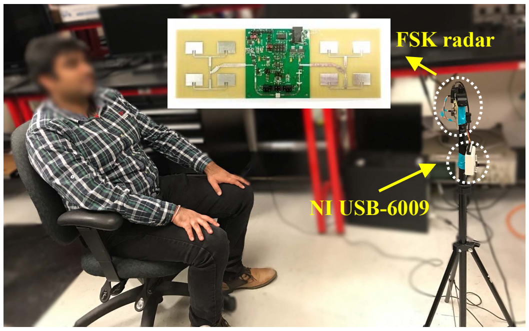

Fig. 6. Photograph of the experimental setup of the vital-sign based stationary human subject localization.

reliable detection performance for the *I/Q* trajectory-based method. In comparison, the proposed FSK detection technique does not have the coupling condition limitation since phase extraction happens at the measured periodic motion frequency only, where the responses of the f_1 and f_2 tones experience the same phase shift introduced by the AC coupling circuit. Hence, phase difference between the baseband responses is kept intact from the phase distortion and range estimation is unaffected.

C. Localization of Stationary Human Subject from Vital Sign

Stationary human subject detection experiments were performed with the same system setup and in the same lab environment. A photograph of the experimental setup is shown in Fig. 6. A seated human subject facing the radar was asked to breath normally during the measurement time period of 60 seconds. Measurements were recorded at 0.5 m, 1.2 m, and 1.7 m, respectively. Fig. 7 shows a segment of the recorded *I* channel data when the seated human subject was at 1.2 m. As depicted in the zoom-in view of Fig. 7, the red baseband signal was produced at the same time with the higher square wave amplitude level and hence it is associated with f_2. Similarly, the green baseband signal is associated with f_1. A noticeable phase difference between the two baseband signals is clearly shown, which verifies the fundamental theory of the FSK technology. Respiration rate can be obtained from the baseband spectra for both the f_1 and f_2 tones. By comparing the phase difference between the respiration tones on both spectra, the absolute distance of the subject was estimated. A 20-s FFT sliding window was used with a 5-s step size. Nine range estimations were obtained at each location. Range results are listed in Table 1. Though the mean of the measured range at each location was close to the ground truth, standard deviation results show that noticeable range variations exist in the measurements. Through extensive experimentation, it has revealed that multipath propagation is likely the main contribution to the range fluctuation among other possible error sources including frequency drift, *I/Q* channel mismatch, and effect of antenna directivity. Future work will analyze the contribution of each error source. Nevertheless, the results have demonstrated acceptable accuracy of using FSK technology to detect the range of a stationary human subject based on the vital signs.

V. CONCLUSION

A spectrum-efficient FSK technology for both moving- and stationary-human subjects tracking is presented in this paper.

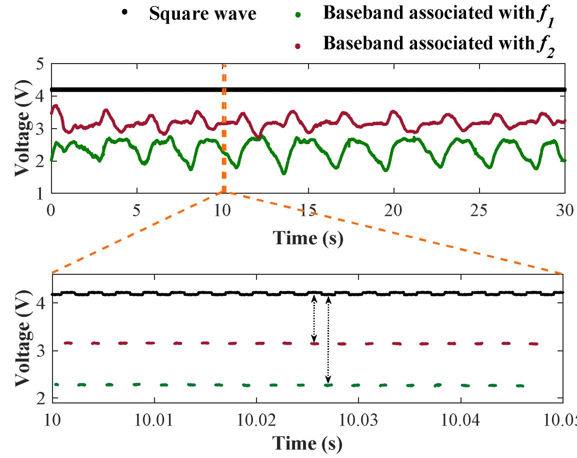

Fig. 7. Recorded *I* channel respiration signal (for f_1 and f_2 tones) and square wave VCO control signal at 1.2 m.

Table 1. Range measurement results of a seated human at three difference distances.

Ground truth	0.50 m	1.20 m	1.70 m
Mean of measured range	0.66 m	1.12 m	1.70 m
Error	16 cm	- 8 cm	0 cm
Standard deviation	18 cm	32 cm	37 cm

Fundamental theories of the range tracking mechanisms were explained. Simulations were provided to validate the tracking theories. Preliminary investigation on the range detection performance involving both human subject and actuator was discussed. Compared with the *I/Q*-trajectory-based localization solution, it is shown that this method has no limitation on the baseband coupling condition. The proposed spectrum-efficient vital-signs-based range detection method using FSK radar has great potential in various human sensing applications such as intruder detection, human search and rescue, and senior health care.

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