A Human Tracking and Physiological Monitoring FSK Technology for Single Senior at Home Care

Jing Wang, *Student Member, IEEE*, Changzhi Li, *Senior Member, IEEE*

***Abstract*—Respiration monitoring for apnea diagnosis and movement tracking for physical activity analysis are essential and valuable indicators of underlying medical conditions in senior health care. Compared with other health sensing technologies, radar has shown its advantages in terms of non-contact implementation, immunity to ambient light and temperature changes, hardware simplicity, and long range coverage. Among various radar types, frequency-shift keying (FSK) radar inherits the ability to measure respiration from Doppler radar, while also having the ability to track the absolute range of a moving target with much less bandwidth requirement than frequency modulated continuous wave (FMCW) radar and ultra-wideband (UWB) radar. Therefore, in this paper, an FSK radar system is employed for both remote respiration monitoring and absolute range tracking. Fundamental theory and operating principle of FSK system are detailed. Respiration monitoring and range tracking experiments of a human subject were performed in an indoor environment. Results are presented to demonstrate the practical feasibility of the FSK sensing technology being applied to single senior home care applications.**

I. Introduction

The large and growing senior population presents a unique challenge for all facets of society [1]. Because adult children are likely to move out of their parents' home due to job allocation and starting new families, the seniors are often left isolated and living independently without any accompany in daily activities [1]. Concerns have risen over the health knowledge of the seniors, since they tend to have chronic diseases, physical disabilities, or even apnea [2]. Chronic diseases can result in the loss of mobility and physical activity in a slow and sometimes unnoticeable mechanism [3]. Early detection and intervention are key to alleviating early stage conditions before they become irreversible. While accompanies living with seniors may be notified when apnea happens. First responders may not be alerted when seniors live independently. Therefore, continuous vital sign monitoring and mobility tracking of single living senior are essential for periodic health assessments in early detection of underlying medical conditions.

Respiration rate and heartbeat are two important components of vital signs. While heartbeat is relatively easy to measure using existing wearable devices such as wristwatch, wristband, and electronic patch, the majority of the current solutions for measuring respiration rate are still less than ideal. For example, the commonly used chest belt can cause physical discomfort to the subject in long-term continuous monitoring scenarios. Radar systems have been proposed and investigated for non-contact respiration monitoring providing the benefits of easy implementation and less constraint on the human body, for example, Doppler radar [4][5], frequency modulated continuous wave (FMCW) radar [6], and ultra-wideband (UWB) radar [7]. Among these radar approaches, Doppler radar is attractive due to the minimal spectrum requirements and circuit simplicity. However, compared with FMCW and UWB radar, it lacks the ability to detect the absolute range of the target. In contrast, Frequency-shift-keying (FSK) radar system is advantageous because of its capability in both respiration monitoring and absolute range tracking of moving target with minimal bandwidth requirement and short measurement time. Though FSK system cannot measure the range of a stationary target because its range detection scheme is based on the Doppler shift produced by the moving target, however also due to this reason, the FSK method is less vulnerable to surrounding background clutters and has longer detection range because of a better signal-to-noise-ratio. In addition, unlike other mobility and physical activity monitoring solutions such as infrared (IR) sensors [8] which are sensitive to ambient light and temperature changes, video cameras [9] which cause privacy concerns, and inertial sensors [10] which suffer from cumulative errors, FSK solutions are robust against changing light and temperature conditions, less intrusive, and free from accumulated errors. Therefore, this paper proposes to use FSK technology to track the movement of independent living seniors and monitor the respiration when they are stationary to provide valuable health awareness information.

The paper starts with the fundamental theories of absolute range tracking and respiration monitoring using FSK system in Section II. System design and implementation will be explained in Section III. Absolute range tracking and remote respiration monitoring experiments conducted on a human subject in an indoor environment will be described and measurement results will be presented to demonstrate the practical feasibility of the FSK technology being applied to single senior health monitoring applications in Section IV. Finally, conclusions of this work will be set out in Section V.

II. Fundamental Theory

A. Absolute Range Tracking

In FSK radar system, two discrete frequencies f_1 and f_2 are transmitted with a switching frequency of f_{switch}, while $f_{switch} = 1/T_{switch}$, as shown in Fig. 1. In other words, f_1 and f_2 are switched back and forth every time interval of T_{switch}. The frequency shift between the two transmitted frequencies is usually very small with MHz or KHz level, which is represented as $\Delta f = f_1 - f_2$, assume $f_1 > f_2$. The signals reflected from the moving target are received and down-mixed with the

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J. Wang and C. Li are with Department of Electrical and Computer Engineering, Texas Tech University, Lubbock, TX 79409 USA (e-mail: anna.wang@ttu.edu, changzhi.li@ttu.edu).

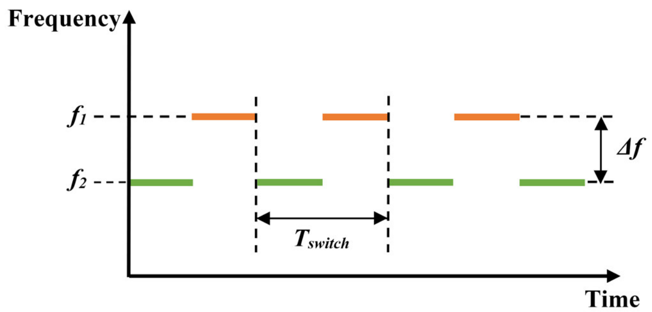


Figure 1. FSK radar modulation scheme.

transmitted carrier signals, producing baseband signals which contain the Doppler frequencies generated by the moving target, expressed as $f_{d,k} = f_k\,(1 + v/c)$, where $f_{d,k}$ stands for the Doppler frequency, v represents the velocity of the target, c is the speed of light, and f_k is the transmitted carrier frequency, $k = 1, 2$. By keeping Δf very small in comparison to f_k, the generated Doppler frequencies associated with the two transmitted carrier frequencies will be nearly the same, that is, $f_{d,1} \approx f_{d,2}$. Upon the creation of the echo signals at the target, they are in phase. Later on, due to the frequency difference, their phase will separate along with time as they travel back toward the receiver. The further they travel, the more they separate. Since phase difference is proportional to the round-trip travel time of the signal, and the signal travel time is proportional to the distance to the target, distance measurement can be produced in relation to the phase difference between the two received signals as:

$$R = \frac{c \cdot \Delta\phi}{4\pi \cdot \Delta f}, \tag{1}$$

where R is the range between the radar and target and $\Delta\phi$ is the phase difference between the received Doppler frequencies.

Downsides reside in terms of range resolution and maximum unambiguous range. Because FSK approach does not possess a bandwidth, it cannot differentiate multiple targets. Therefore, it is best suited for single user home care scenario. The maximum unambiguous range of FSK system is limited due to the periodicity of the sine wave. Since $\Delta\phi$ can only reach a maximum of 2π, range will become aliased beyond this limit. The maximum unambiguous range equation can be derived from (1) as $R_{max} = c/(2\Delta f)$. It can be noted that the unambiguous range is inversely proportional to the frequency shift between the two transmit frequencies. That is, the smaller the frequency shift, the longer the maximum unambiguous range. Thus, frequency shift can be adjusted accordingly depending on the range requirement of a certain application.

B. Respiration Monitoring

Due to the very short switching time between two transmit frequencies in FSK system, phase coherence is well preserved for both carriers. When only looking at one of carriers, it is simply a Doppler radar. Thus, FSK system inherits the capability of detecting small physiological movement from Doppler radar. The vital sign detection mechanism of FSK approach is fundamentally the same as CW Doppler radar system [11].

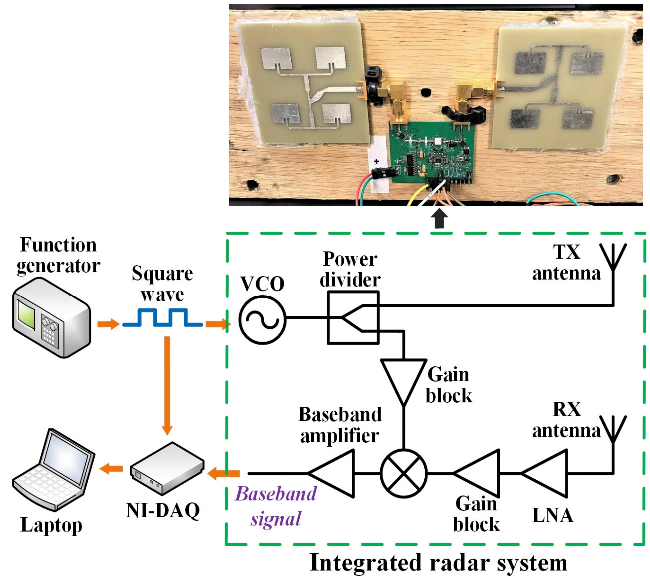


Figure 2. Block diagram of the FSK system prototype.

An un-modulated signal $T(t)$ with carrier frequency f_k and residual phase ϕ_1 is transmitted towards a human body as:

$$T(t) \approx \cos\left(2\pi f_k t + \phi_1\right), \tag{2}$$

where $k = 1, 2$ in the case of FSK system. The signal will be reflected back with its phase modulated by the time-varying body movements $d(t)$ (i.e., respiration and heartbeat) and a constant phase determined by the nominal distance R to the human subject, expressed as:

$$R(t) = \cos\left(2\pi f_k t - \frac{4\pi d(t)}{\lambda} - \frac{4\pi R}{\lambda} + \phi_2\right), \tag{3}$$

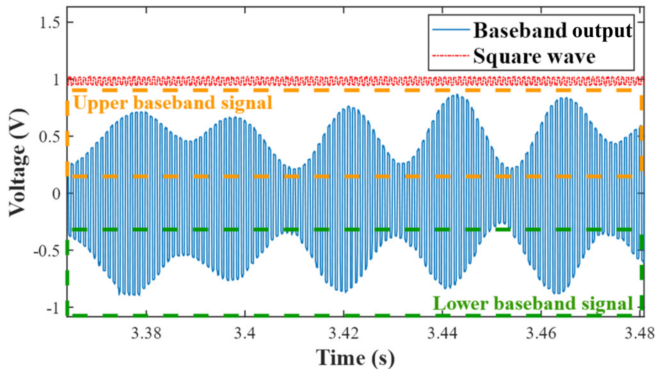
where λ is the wavelength of the carrier frequency and ϕ_2 is phase noise. After down-mixing the received signal with transmitted signal, baseband signal containing the micro motion information can be obtained and is presented as:

$$B(t) \approx \cos\left(\frac{4\pi d(t)}{\lambda} + \frac{4\pi R}{\lambda} + \Delta\phi\right), \tag{4}$$

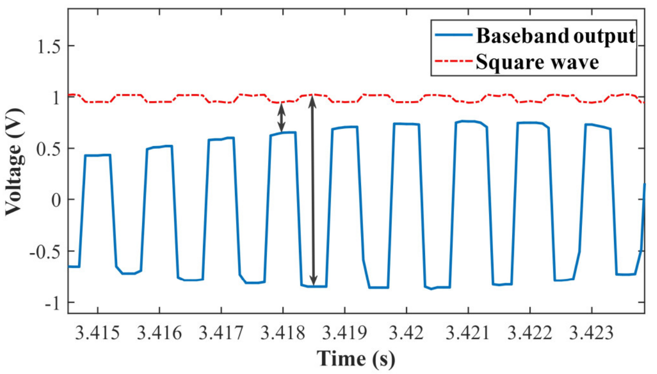
where $\Delta\phi$ stands for the total residual phase noise. Note that the amplitude variation has been neglected and unit amplitudes are assumed.

III. FSK System Design and Implementation

Fig. 2 shows the block diagram of the FSK system prototype. A 1 KHz external square wave generated by a function generator is used as the input signal of the voltage-controlled oscillator (VCO) to control the switch between f_1 and f_2. The square wave amplitude level determines VCO output frequencies and their frequency shift, which are $f_1 = 5.797$ GHz, $f_2 = 5.783$ GHz, and $\Delta f = 14$ MHz. The maximum unambiguous range is calculated to be 10.7 m in this case. The power divider splits the carrier signals into two equal parts, while half of the carrier signals is transmitted with an average power of 8 dBm, the other half is amplified first by



(a)



(b)

Figure 3. (a) Recorded range tracking baseband signals and square wave control signal. (b) Zoom-in of (a).

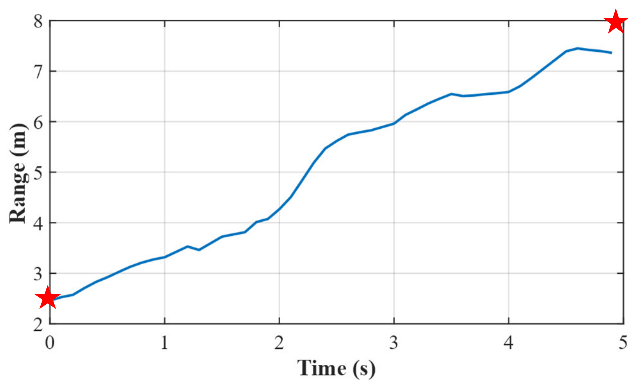


Figure 4. Range tracking result of a human subject.

a 14 dB gain block, then goes to the local oscillator (LO) path of the mixer. The reflected signal is captured by the receiving antenna and amplified by a 11 dB low-noise amplifier (LNA) and a 14 dB gain block, next down-converted with the transmitted signal to produce the baseband output. Two 2 × 2 patch antennas are used with 11.3 dB gain and 46◦ half-power beam width. Both the square wave and the baseband output are sampled using NI USB-6009. Finally, the sampled data will be sent to a laptop through a USB port for signal processing.

IV. Experiments

The experiments involving human subject described in this paper were approved by the Institutional Review Board.

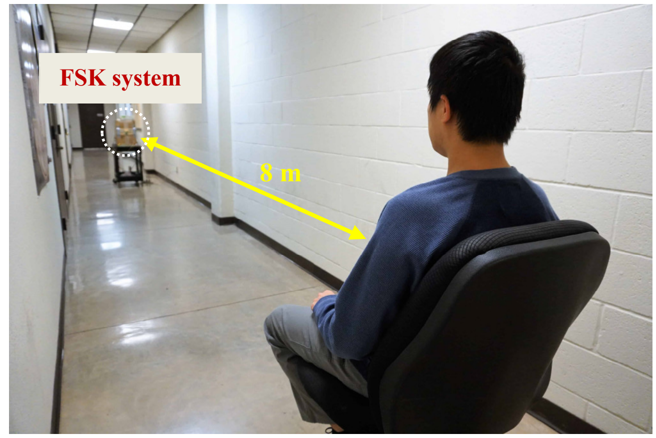


Figure 5. Photograph of the experimental setup of the human respiration monitoring scenario.

A. Absolute Range Tracking Experiment

In this experiment, the FSK system was set up in an interior corridor. To avoid antenna near-field, a human subject started the movement 2.5 m away from the radar with a constant walking speed and stopped at 8 m. The sampled baseband and square wave signals were sent to a laptop and fast Fourier transform (FFT) algorithm was performed on the baseband data, while square wave data were used to find the correspondence between the two carriers and their baseband signals and time the baseband signals. As depicted in Fig. 3, the upper baseband signal was produced at the same time with the lower amplitude level of the square wave, since the lower square wave level generated the lower carrier frequency f_2, that means the upper baseband signal is associated with f_2. Similarly, the bottom baseband signal is associated with f_1. In addition, a noticeable phase difference between the two baseband signals can be easily found, which verifies the fundamental working theory of FSK technology. It is worth mentioning that since FSK system does not detect stationary objects, existing background clutters in the corridor such as walls and pillars have no effect on the FSK range tracking measurements, which makes it advantageous than FMCW radar [12] and UWB radar [13] in such tracking environment.

The two baseband signals have two separate FFT outputs. Due to the small frequency shift between the transmitted carrier frequencies, target will appear at the same Doppler frequency location on both the FFT output frequency spectrums, while differ in phase. After comparing the phase difference between the two Doppler frequencies, absolute distance to the subject was obtained according to (1). The final range measurement is plotted in Fig. 4. The ground truth starting and ending points are indicated by red star signs. Errors were caused by various factors such as square wave high frequency noise, hardware imperfection, and measurement error. Nevertheless, the preliminary results have demonstrated the ability of using FSK technology to track the movement of a human subject with acceptable accuracy.

B. Respiration Monitoring Experiment

The remote respiration sensing experiment was conducted in the same corridor with the same FSK system setup. A photograph of the experimental setup of the human respiration monitoring scenario is shown in Fig. 5. A human subject sat about 8 m in front of the system and was asked to breath

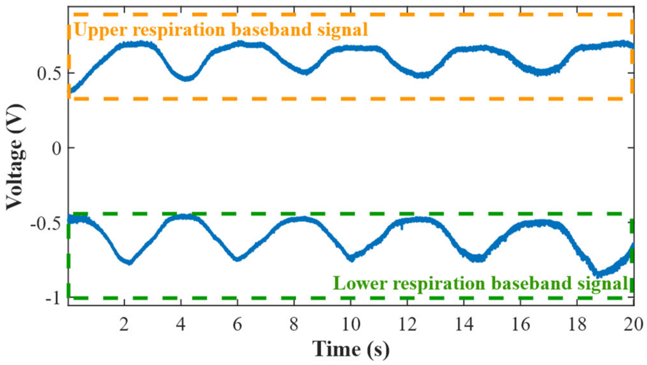


Figure 6. Respiration monitoring baseband signals.

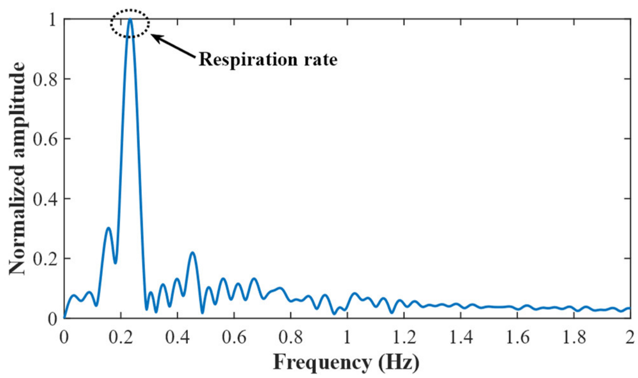


Figure 7. Respiration monitoring result of a human subject.

normally during the measurement time period of 20 seconds. Both of the obtained baseband outputs were recorded and are plotted in Fig. 6. To eliminate null point problem, both baseband output data were combined to recover the respiration rate [14]. The measurement result is presented in Fig. 7. A respiration rate of around 0.23 Hz can be clearly identified which proves the remote respiration monitoring capability of the FSK system prototype.

Currently, only one direction has been measured, which is having the subject directly facing the radar antenna. However, in real-life scenarios, the target does not necessarily sit in front of radar, therefore, future work will cover the respiration measurements with the subject rested in different positions. Moreover, since theoretically FSK approach can also monitor heartbeat, heartbeat may be measured at closer distance, but it is not the interest of this work. In-phase/quadrature (*I/Q*) channels will be used to investigate the heartbeat sensing performance in the future.

V. Conclusion

An FSK technology for remote respiration monitoring and absolute range tracking for single senior home care is presented in this paper. Fundamental theories of deriving absolute range information and vital signs (i.e., respiration and heartbeat) are discussed. Absolute range tracking experiment was carried out to demonstrate the FSK system tracking capability of a human subject. Remote respiration monitoring experiment at a distance of 8 m was performed to reveal the FSK approach respiration sensing capability when subject is stationary. The proposed non-contact health monitoring solution for continuous respiration monitoring and mobility tracking has shown good performance which proves its potential for periodic health assessment in early detection of underlying medical conditions in real-life remote health monitoring for single senior home care. Future work will address and investigate more complicated scenarios such as target in various resting positions relative to the system, random body motion noise cancellation, the detection of heartbeat, larger range coverage, and long-term operations.

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