An Efficient and Extended Range Tracking Method using a Hybrid FSK-FMCW System

Jing Wang, Zhengyu Peng, Changzhi Li

Department of Electrical and Computer Engineering, Texas Tech University, Lubbock, TX, 79409, USA

anna.wang@ttu.edu, zhengyu.peng@ttu.edu, changzhi.li@ttu.edu

***Abstract*— Radar systems are considered suitable sensors for detection of moving objects and motion-based tracking. Among various radar types, frequency-shift keying (FSK) radar are attractive for being able to track the absolute range of a moving target with little bandwidth requirement and free from surrounding background clutter interference. However, its maximum unambiguous range is limited due to the periodicity of the phase difference over 2π and it is inversely proportional to the frequency shift between two transmitted frequencies, while its measurement resolution is proportional to this frequency shift. Frequency modulated continuous wave (FMCW) radar has no range limitation on target tracking but occupies a large bandwidth. Therefore, in this paper, a hybrid FSK-FMCW system is proposed by using a short-time operating FMCW system with small bandwidth as reference to increase the FSK system maximum discernable range without losing measurement resolution. Range tracking experiment of a human subject was conducted and results are presented to demonstrate the performance of the proposed hybrid method.**

***Index Terms*—Range tracking, radar, frequency-shift keying (FSK), Frequency modulated continuous wave (FMCW).**

I. Introduction

There are significant interests in detecting and tracking of moving object due to its potential applications in both civilian and military areas such as traffic monitoring, autonomous driving, healthcare, and security surveillance. Hence, a number of technologies have been proposed and investigated in the literature including optical cameras, infrared detectors, LIDARs, and ultrasound sensors. However, optical cameras can be intrusive and have limited ability to detect objects in low visibility conditions. Infrared detectors are sensitive to ambient light and temperature changes. LIDAR technique uses optical signals, factors such as fog, dust, sunlight can change its optical wavelengths, resulting in unreliable measurement [1]. Moreover, ultrasonic sensors have short measurement range with only a few meters.

In contrast, radar-based solutions offer unique advantages in terms of better privacy protection, immunity to ambient light and temperature changes, robustness against weather conditions, and long range coverage. Wideband radar systems such as frequency modulated continuous wave (FMCW) radar [2] and ultra-wideband (UWB) radar [3] can detect the absolute range of moving object, but they occupy a large bandwidth which means a large interference window with increased jamming possibilities, more power consumption and higher bandwidth requirement on system components. In comparison, frequency-shift keying (FSK) radar is essentially a narrowband user which is also capable of tracking the absolute range of a moving target with the utilization of only two frequencies [4]. However, its maximum unambiguous range is limited due to the periodicity of the phase difference and it is inversely proportional to the frequency step between the two carrier frequencies, while its measurement resolution is proportional to this frequency shift. That is, the maximum detectable range can be increased by reducing the frequency step at the cost of losing measurement resolution.

This paper presents a hybrid FSK-FMCW method based on using a short-time operating FMCW system with small bandwidth as reference to extend the FSK system maximum discernable range without surrendering measurement resolution. Details of the tracking theories will be discussed in Section II. Operating principle of the hybrid system will be described in Section III. Experiment of a human subject was conducted and results are presented in Section IV. Finally, conclusions and future work will be set out in Section V.

II. Fundamental Theory and Implementation

A. FSK radar

FSK system transmits two discrete frequencies f_1 and f_2 sequentially with a switching frequency of f_T. The frequency step between the two carriers is represented as $\Delta f = f_1 - f_2$, assume $f_1 > f_2$. The echo signals reflected from the moving target are captured and down-converted with the transmitted carrier signals, producing baseband outputs which carry the Doppler frequencies generated by the moving target. By maintaining Δf very small in comparison to the transmitted signals, the Doppler frequencies extracted from the baseband outputs will be approximately the same. But due to this frequency shift, the phase difference associated with the two reflected signals will increase along with the distance to the target. Therefore, distance measurement can be obtained in relation to this phase difference as $R_{fsk} = (c \cdot \Delta\phi)/(4\pi\Delta f)$, where R_{fsk} represents the range between FSK radar and the target and $\Delta\phi$ is the phase difference between the received Doppler frequencies.

Downsides reside in terms of range resolution and maximum detectable range. Because FSK approach does not possess a bandwidth, it cannot differentiate multiple targets with the same moving velocities. Therefore, it is best suited for single

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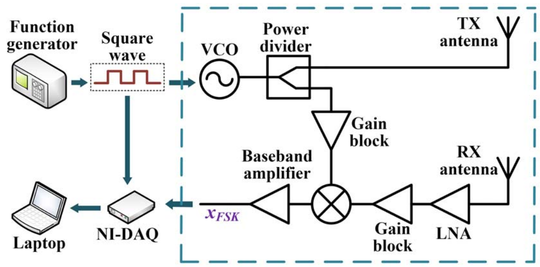


Fig. 1. Block diagram of the FSK system prototype.

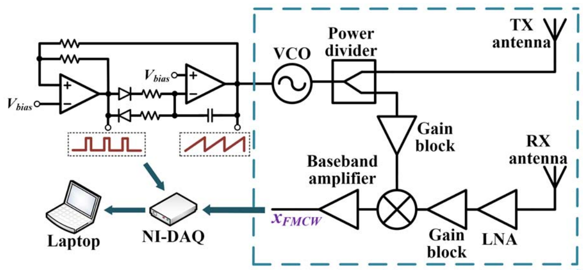


Fig. 2. Block diagram of the FMCW system prototype.

user scenario. The maximum detectable range R_{max} is limited due to the periodicity of the sine wave, which is derived as $R_{max} = c/(2\Delta f)$. By theory, the maximum unambiguous range can be adjusted by the selection of Δf. However, another evaluation factor named measurement resolution is also related with this frequency shift, which is defined as $\delta = 360^{\circ}/R_{max}$ [5]. Though the maximum unambiguous range can be extended by reducing the frequency shift, the measurement resolution will degrade as a consequence. Hence, to optimize the detectable range without surrendering measurement resolution, an FMCW radar is used to obtain the range reference, which will be illustrated in the following section.

Fig. 1 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 control signal of the voltage-controlled oscillator (VCO) to output f_1 = 5.80 GHz and f_2 = 5.77 GHz, with Δf = 30 MHz. The maximum unambiguous range is calculated to be 5 m. Half of the carrier signals from the power splitter is transmitted with an average power of 8 dBm, the other half is amplified first by a 14 dB gain block, then goes to the local oscillator (LO) path of the mixer. The received signal is 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. The sampled data will then be sent to a laptop through a USB port and fast Fourier transform (FFT) algorithm will be performed on the sampled baseband data to obtain the absolute distance to the target.

B. FMCW radar

In FMCW radar, a ramp waveform or a saw-tooth waveform is used to linearly modulate the transmitting frequency across a

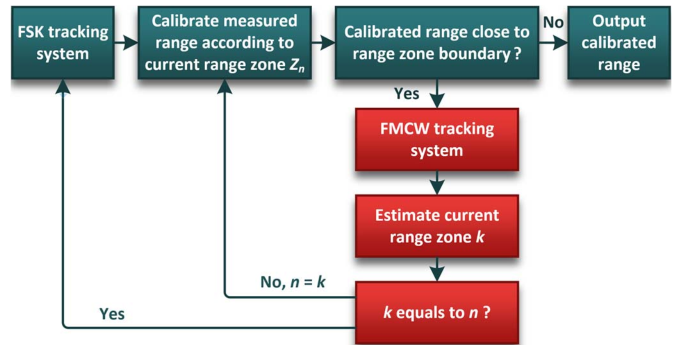


Fig. 3. Operation flow chart of the hybrid FSK-FMCW system.

set bandwidth in time domain. If a target is at a distance R_{fmcw}, the signal reflected by the target will return after a time delay τ. There will be a Doppler frequency in the received signal if it is a moving target, which will be added to the frequency shift caused by τ. By mixing the emitted and the received signals, the difference between them named beat frequency can be obtained, which is proportional to the distance between the target and the radar system. Therefore, the speed and distance of the target can be determined by measuring the beat frequency. The disadvantage of this scheme is that it occupies a large bandwidth in order to maintain a good range resolution, meaning a large interference window with high jamming possibilities, more power consumption, and more bandwidth requirement on system components. In this work, the need for high bandwidth in the assisting FMCW system can be significantly relaxed since FSK approach is only suitable for single target scenario, no range resolution is required.

The block diagram of the implemented FMCW system is shown in Fig. 2. Compared with FSK system in Fig. 1, the portions that are labeled with blue dashed boxes in both figures are the same, with the difference being the VCO control signal. In FWCW prototype, the operational-amplifier-based circuit synthesizes a 1795 Hz pulse wave, which simultaneously generates a sawtooth ramp voltage signal. The bandwidth of the transmitted signal is 50 MHz with a center frequency around 6 GHz. Note that the allocated frequencies for FSK and FMCW systems are separated to avoid the interference between them.

III. OPERATING PRINCIPLE OF THE HYBRID SYSTEM

Due to the maximum unambiguous range limit, range measured by the FSK radar will become aliased beyond this limit. For example, R_{max} equals 5 m in this work, if the distance to the target exceeds 5 m and the target keeps moving until it reaches 15 m, the estimated results after the first 5 m will be 0 m to 5 m and 0 m to 5 m again instead of 5 m to 10 m and 10 m to 15 m. The aliased range section can be defined as FSK range zone, symbolized as Z_n, n = 1, 2, …, N, Z_N is the maximum range zone that the FSK system is able to detect. When the target is at range zone Z_n, the measured ambiguous range R_{fsk} can be calibrated by adding back the range offset associated with Z_n, that is, $R_{cal} = R_{fsk} + (n-1)R_{max}$.

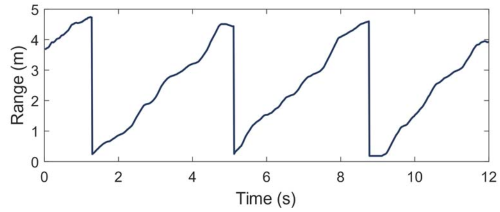
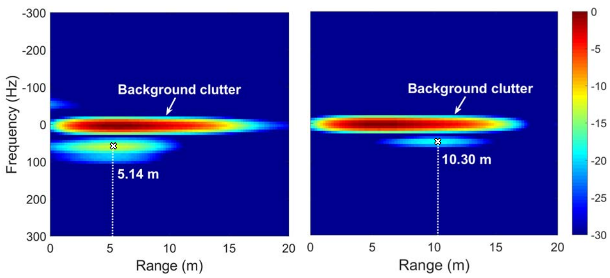


Fig. 4. Range measured by the FSK tracking subsystem.



(a) (b)

Fig. 5. Two frames of FMCW range-Doppler image during range zone transitioning.

For this reason, a reference FMCW radar is chosen to determine this range offset, as illustrated in Fig. 3. Assume a target starts the movement within range zone Z_1 with $n = 1$. FSK tracking system constantly measures the distance to the moving target and output the calibrated range until the target is close to the range zone transitioning boundary. At that time FMCW radar will be triggered and switched on to check the current range zone by using $k = floor(R_{fmcw}/R_{max}) + 1$. k is the range zone number calculated from the FMCW subsystem, R_{fmcw} is FMCW range measurement, and *floor* is a function used to round the result to the nearest integer less than or equal to the result. If k equals n, that means the target has not changed range zone yet. If k is not equal to n, which indicates that range zone has changed and n should be updated according to k. In this way, the range zone that the target is present will be immediately checked whenever the range zone transitioning happens. Therefore, the maximum detectable range of FSK radar is efficiently extended. It is worth mentioning that the power consumption is optimized since the FMCW subsystem employing a small bandwidth will only be switched on and operating for a short time period.

IV. Experiment

The hybrid FSK-FMCW prototype was set up in an interior corridor. To avoid antenna near-field, a human subject started the movement 3.5 m away from the system with a constant walking speed and stopped at 19.5 m. Both FSK and FMCW subsystem baseband outputs along with their control signals were sampled and sent to a laptop to produce the range results. Measurement result using only the FSK tracking subsystem is plotted in Fig. 4. Range aliasing problem can be clearly observed when range exceeds the maximum unambiguous limit of 5 m. Errors exist due to various factors such as square wave high frequency noise, hardware imperfection, and measurement error. Fig. 5 shows two frames extracted from the FMCW range-Doppler output during range zone transitioning. It can be noted that since a small bandwidth of 50 MHz was utilized, range resolution was at a poor level. Nonetheless, reliable range zone detection was realized by applying a running average to all the frames to smooth out the random variations and improve signal-to-noise-ratio. In Fig. 5 (a), aside from the background clutter return centered at zero Doppler frequency, the highest Doppler frequency amplitude was found at 5.14 m, which indicated the moving object was at range zone Z_2. Similarly, the maximum Doppler frequency amplitude was detected at 10.30 m in Fig. 5 (b), which implied the target has moved to range zone Z_3.

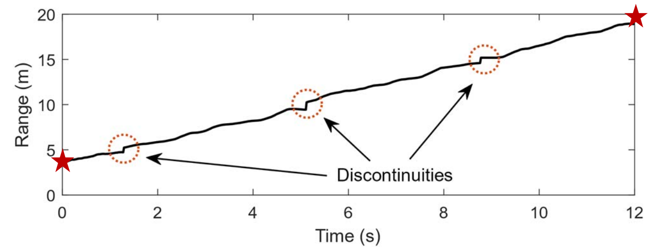


Fig. 6. Range measurement obtained using the hybrid FSK-FMCW system.

The combined tracking result of the hybrid FSK-FMCW system is shown in Fig. 6. The ground truth starting and ending points are indicated by red star symbols. The measured range result clearly shows that every time when the subject moved into a different range zone, the FSK measured result was calibrated with the corresponding range offset obtained using the FMCM reference subsystem. The small discontinuities circled in Fig. 6 were caused by existing errors in FSK and FMCW systems. Therefore, reducing errors in both systems may potentially further improve the overall system performance.

V. Conclusion

An efficient and extended range tracking scheme using a hybrid FSK-FMCW system is presented in this paper. Fundamental tracking theories are discussed. The operating principle of the hybrid method is detailed. Absolute range tracking experiment was carried out to demonstrate the capability of using a short-time operating FMCW subsystem as a reference system to extend the maximum unambiguous range of the FSK subsystem. The proposed hybrid tracking method has shown good performance which proves its potential use in motion-based tracking applications. Future work will be integrating the subsystems into a single device and improving the accuracy of the hybrid-tracking approach.

Acknowledgment

The authors would like to acknowledge grant support from National Science Foundation (NSF) CNS-1718483 and ECCS-1254838.

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