Acoustic micro-Doppler radar for human gait imaging

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Abstract: A portable acoustic micro-Doppler radar system for the acquisition of human gait signatures in indoor and outdoor environments is reported. Signals from an accelerometer attached to the leg support the identification of the components in the measured micro-Doppler signature. The acoustic micro-Doppler system described in this paper is simpler and offers advantages over the widely used electromagnetic wave micro-Doppler radars.

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1. Introduction

The velocity of a moving object relative to an observer can be estimated by measuring the frequency shift of a wave radiated or scattered by the object, known as the Doppler effect. If the object itself contains moving parts, each moving part will result in a modulation of the base Doppler frequency shift, known as the micro-Doppler effect (Chen and Ling, 2002).

For example, the frequency spectrum of acoustic or electromagnetic waves scattered from a walking person is a complex time-frequency representation of human gait. It includes not only the Doppler shifted components from the velocity of the entire body but also the micro-Doppler components from the motion of the arms and legs. The acquisition of human gait signatures is important in diverse applications, ranging from rehabilitation engineering to human biometrics and surveillance. Previous studies of gait acquisition have employed electromagnetic micro-Doppler systems, such as continuous-wave (CW) X-band radars operating at 10.5 GHz (Geisheimer *et al.*, 2001; Otero, 2005). In other studies, ultrasound was used to study human gait (Sabatini and Cholla, 1998) in conjunction with infrared trigger mechanisms for pulsed ultrasound (Weir and Childress, 1997), but they have not employed micro-Doppler signature acquisition.

In this paper, we report on a portable acoustic micro-Doppler system operating in the 40 kHz acoustic frequency range and present experimental results from its application in human gait imaging.

2. Principle of operation

Given an acoustic wave transmitted by an observer, the frequency of the received wave due to a simple single-point scatterer is $f=f_0(1+2v/c)$ (Tipler, 1991), where f_0 is the frequency of the transmitted acoustic wave, v is the velocity of the scatterer relative to the observer, and c is the speed of sound. The Doppler frequency shift due to the scatterer is $f_{\mathrm{Doppler}}=f_0 2v/c$, which is proportional to the velocity of the scatterer relative to the observer.

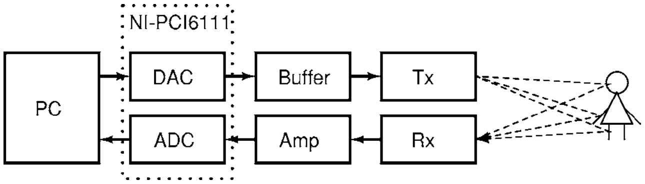

Fig. 1. Block diagram of the ultrasound micro-Doppler system. A personal computer (PC) is used to control a National Instruments (NI) PCI6111 data acquisition (DAQ) card. A continuous 40 kHz sine wave is digitally synthesized by the DAQ card and sent to a buffer to drive an ultrasonic transducer (Tx). The received signal is digitized at 1 Msamples/s and stored on the PC.

In the case of an articulated body such as a walking person, the torso, each arm, and each leg has its own velocity, and even when the torso's velocity is constant, the velocity of the limbs changes over time. The Doppler signature f_{Dsig} for such a complex object has multiple time-dependent frequency shifted components and is defined as

$$f_{\mathrm{Dsig}}(t) = f_0 \sum_i \frac{2v_i(t)}{c}, \tag{1}$$

where $v_i(t)$ is the velocity of the torso or an individual limb as a function of time.

A two-dimensional representation of human gait can be obtained from the returned Doppler signal by applying the short-time Fourier transform (STFT) to the received signal as follows:

$$\mathrm{STFT}(t,f) = \int x(t+\tau)g(\tau)\exp(-j2\pi f\tau)\,d\tau, \tag{2}$$

where $x(t)$ is the received signal, $g(t)$ is a sliding window function (e.g., a Hamming window), t is time, and f is frequency. In this time-frequency plot, the horizontal axis is time, the vertical axis is frequency, and the magnitude of the short time Fourier transform output at each point is represented by the hue of the point's color (or the intensity in the case of a gray-scale representation).

3. Experimental setup and results

A block diagram of our experimental setup is illustrated in Fig. 1 with a picture of the system in Fig. 2. The acoustic wave produced by the transmitter (Tx) is directed at a walking human and is reflected by the head, torso, and limbs. The reflected signal is received by another ultrasonic transducer (Rx), amplified through a variable gain chain, and then digitized by the data acquisition card at 1 Msamples/s. The digitized data are stored on the PC for subsequent analysis in MATLAB.

We tested the operation of the acoustic micro-Doppler radar system both indoors in a 30-foot-long corridor and outdoors in a parking lot. The ultrasonic transducers were placed at knee height, and a volunteer was instructed to walk toward or away from the transducers. We collected 10 s of data at a time and performed the short-time Fourier transform in MATLAB using a 50 ms Hamming window and $1/2$ overlap between adjacent transform windows.

Figure 3 shows the spectrogram of a person walking towards the radar. An accelerometer was attached to the person's ankle and the output was acquired simultaneously with the acoustic signal from the radar receiver. Acquired accelerometer data were processed in MATLAB to calculate the Doppler frequency shift.

4. Discussions

An acoustic radar is capable of resolving motions of objects whose dimensions are equal to or larger than the wavelength of the acoustic waves. In air, the resolution of the system will be approximately 9 mm and 1 mm at 40 kHz and 340 kHz respectively, for which commercial

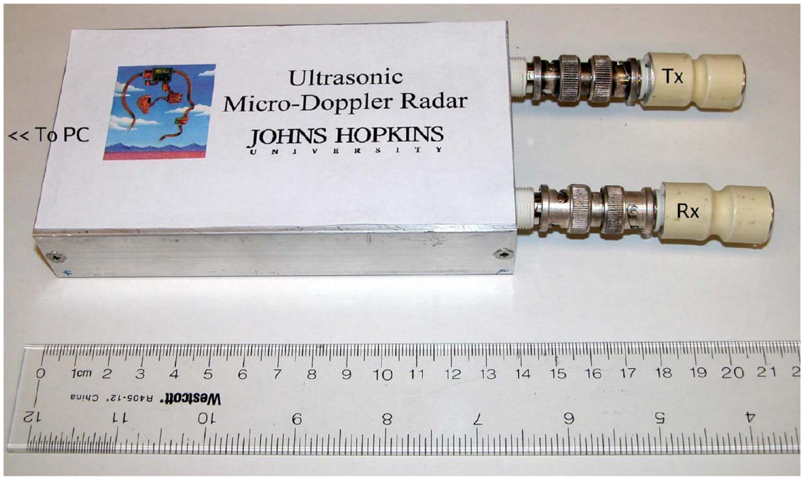

Fig. 2. (Color online) Photograph of the acoustic micro-Doppler radar system.

off-the-shelf transducers are available. Analytical expressions are available to calculate the absorption of sound in still air, given the acoustic frequency, atmospheric pressure, temperature, and relative humidity. (Evans *et al.*, 1972; Bass *et al.*, 1990) For frequencies above 10 kHz, the absorption of sound in dry air can be approximated as a linear function of the square of the frequency. (Crocker, 1998) For the frequencies of interest here, the attenuation is about 1.3 dB/m at 40 kHz and 20 dB/m at 340 kHz, therefore the range of a 340 kHz system is inherently determined to be 15 times smaller than that of a 40 kHz system.

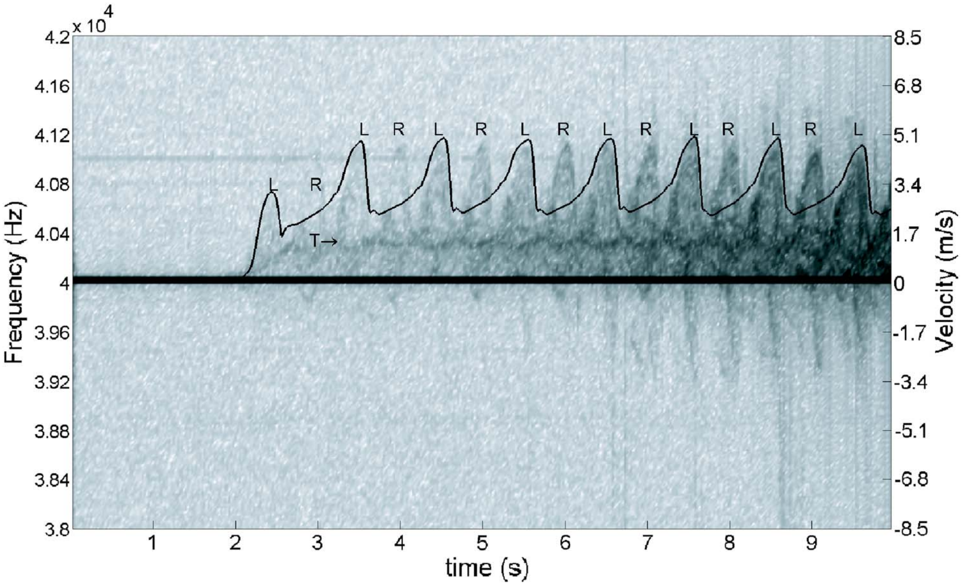

Fig. 3. Micro-Doppler spectrogram of a person walking towards the radar. An accelerometer is attached to the left leg and the velocity derived from the accelerometer signal is superimposed on the spectrogram. The letters 'L' and 'R' mark regions of the spectrogram representing the motion of the left and right legs, respectively. The right arrow 'T' points to a region of the spectrogram around 40.35 kHz, corresponding to a strong Doppler return due to the motion of the torso (walking speed approximately 1.5 m/s). The features below 40 kHz are Doppler shifts caused by arms swinging away from the transducers.

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The velocity resolution is determined by the sampling rate of the ADC and the window size of the STFT. Given a sampling rate of 1 Msamples/s and a window size of 50 000 samples in our system, the frequency resolution is 20 Hz, corresponding to a velocity resolution of 0.085 m/s when 40 kHz transducers are used.

5. Conclusion

A continuous-wave ultrasound micro-Doppler radar system for human gait analysis is reported in this paper. The use of ultrasound rather than microwaves makes the data acquisition and signal processing tasks easier to perform with standard audio frequency digital signal processing hardware and provides immunity from electromagnetic interference sources. The system is simple and can operate in natural environments that are complementary to microwave micro-Doppler radars, such as underwater. The micro-Doppler system can also be used in robotics for intelligent mapping of dynamic environments.

Preliminary experimental data (not shown in this paper) suggest that we are also able to detect multiple humans walking in the observation field. It is also worthwhile noting that each volunteer in our study had a somewhat unique gait signature, suggesting that human gait signatures may provide useful information in biometric identification systems.

Acknowledgments

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