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Review

Basic gait analysis based on continuous wave radar

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ABSTRACT

A gait analysis method based on continuous wave (CW) radar is proposed in this paper. Time–frequency analysis is used to analyze the radar micro-Doppler echo from walking humans, and the relationships between the time–frequency spectrogram and human biological gait are discussed. The methods for extracting the gait parameters from the spectrogram are studied in depth and experiments on more than twenty subjects have been performed to acquire the radar gait data. The gait parameters are calculated and compared. The gait difference between men and women are presented based on the experimental data and extracted features. Gait analysis based on CW radar will provide a new method for clinical diagnosis and therapy.

1. Introduction

Gait is one of the most basic human movements. The current methods of gait analysis are mostly based on camera systems [1], for example, using infrared camera with infrared ray transmitter and several markers which can reflect infrared light. During experiments, cameras are set at different positions laboratory, and reflective markers are stuck on the different parts of the human body such as the pelvis, knees, ankles, and the camera records the motion trajectory of the markers on the human body, and those data will be used to perform an analysis of the gait. Some other gait analysis methods use cameras to get the image of human walking or using acceleration sensors on a human body to measure gait motion parameters [2–4]. The main problems of current gait measurement methods include: (1) for a camera system, the irregular shape and color changes in the video makes it difficult to track the human body, the video processing algorithms are relatively computationally intensive, and relatively high cost of the systems. (2) The sensors attached to the human body may affect the normal walking behavior.

This paper introduces a low-cost all-weather CW radar system for gait analysis. The gait analysis is realized through detecting the micro-Doppler frequency signal caused by a human moving [5]. Gait radar is getting more attention by military and security departments since radar can detect a human target at a distance from hundreds meters to several kilometers in all weather condition. This paper will focus on the possibility of the medical application of gait analysis based on CW radar. For observing humans, radar has advantages over other sensors: the radar transmitted electromagnetic wave signal is insensitive to day and night, while smoke, dust and fog only slightly reduce the signal. Radar signals can also penetrate most clothing, preventing disguises from being effective. It is possible to obtain the gait signal and measure the gait parameters of a person in his/her natural walking state without him/her being aware of it, and we can obtain some gait parameters such as stride time and speed of torso directly.

The aim of this investigation was twofold. First, a new system for gait analysis is introduced and the methods for measuring the gait parameters are discussed. Second, different gait states and parameters are investigated by CW radar.

2. Method

2.1. The principle of gait analysis based on CW radar

Radar transmits an electromagnetic wave to an object, the object reflects the wave back to the radar receiver, and the return signal contains information that represents some kinds of the features of the object. If the object or some parts of it have some kind of slow rotation or vibration, each moving part will result in a modulation of the Doppler frequency shift, this phenomenon is called the micro-Doppler effect, and we can extract certain kinds of features of the observed object from the micro-Doppler signal. When radar illuminates the human body, the different echo signals contain micro-Doppler feature caused by irregular movement of the limbs and torso. Those Doppler features reflect the human gait motion characteristics [6].

The CW radar system used for this experiment works with a single antenna, and transmits a stable continuous wave signal and directly converts the echo signal to base band. The basic principle of the system is shown in Fig. 1(a). Fig. 1(b) shows the operating state of radar. The base-band output frequency of the system is the

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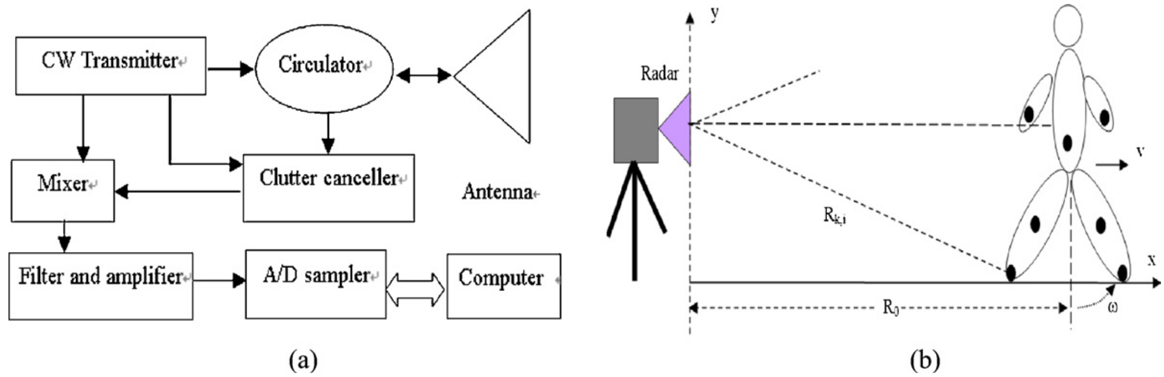

Fig. 1. The principle of the system (a) and the operating diagram of the gait CW radar (b).

Doppler frequency corresponding to the speed of moving targets. The Doppler frequency of an object which moves with angle θ to the radial direction of the radar can be written as:

$$f_d = 2 f_0 \frac{v(t)}{C} \cos\theta \quad (1)$$

where f_0 = 10.525 GHz is the operating frequency of the radar, $v(t)$ is the velocity of the human motion, so the Doppler frequency and velocity of objects are directly related. In this experiment we used a commercial data sampling card to convert the base band analog signal to a digital signal and stored the converted data on to a computer. The base-band digital signal was Short-time Fourier Transform (STFT) analyzed and parameters were extracted in the computer.

Suppose that the transmitter signal of the radar is

$$S_T(t) = A\cos(2\pi f_0 t) \quad (2)$$

When scattering from the total human body is considered, the radar return becomes a summation of the different moving parts: torso, arms, legs and feet. Each part has a different velocity and acceleration, if K different parts of the body are considered, the received echo signals from different parts of human body can be written as:

$$\begin{aligned} S_R(t) &= \sum_{i=1}^{K} A_i \cos(2\pi f_0 (t - \tau_i)) \\ &= \sum_{i=1}^{K} A_i \cos(2\pi (f_0 + f_{di}(t))t) \end{aligned} \quad (3)$$

where $\tau_i = 2R_i(t)/C$ is the two-way transmission time delay from the radar antenna to the object, C is the speed of light, $R_i(t)$ is the distance variation between the radar and the different parts of the human body, $f_{di}(t)$ is the Doppler frequency caused by ith part of the body. Fig. 2(a) shows a radar echo signal from a man who walked back and forth two times in the radial direction of the radar.

2.2. The Short-time Fourier transform of gait radar signal

Normally for analyzing a time-stationary signal, the most useful method is the Fourier Transform (FT). Using a FT we can obtain the frequency spectrum which reflects the signal features in the frequency domain. But for a walking human, the torso and limbs have different motion velocity and acceleration, and will cause time-varied Doppler frequency shifts, so radar echoes from walking human are non time-stationary in the time domain. Therefore if we use a FT for analyzing gait radar signals, we will lose the time-varying Doppler frequency information. Time–frequency signal representation techniques are good tool for revealing the features of non-stationary signal in the time frequency domain [6]. In order to introduce time dependency in the Fourier transform, a simple and intuitive solution consists of pre-windowing the signal $S(t)$ around a particular time t, calculating its FT, and doing that for each time instant t. The resulting transform is called the Short-time Fourier Transform (STFT) [7]. The spectrogram, i.e. a representation of the frequency content of the signal as a function of time, can be represented as the power of STFT.

Here we use STFT to get the time–frequency distribution of a radar gait signal. The STFT of a signal $S_R(t)$ can be defined as:

$$F_s(t, f) = \int_{-\infty}^{+\infty} S_R(u) h^*(u - t) e^{-j2\pi f u}\, du \quad (4)$$

where h is the short-time analysis window function. Here we choose a small Hamming window to time–frequency analyze the real radar gait signal. The radar signal is digitized at 1500 samples per second. The length of the Hamming window is 128 samples. We perform a FT on the echo Doppler signal in the time window for each time instant t to obtain the time–frequency spectrogram. An example time–frequency spectrogram of gait signal is shown in Fig. 2(b), the horizontal axis represents the time in the figure and the vertical axis represents the Doppler frequency caused by body motion. From the figure we can see the Doppler frequency change caused by the human arms, legs and torso movement. Since the different parts of the human body do not move with constant radial velocity, the small micro-Doppler signatures of the human body are time-varying and therefore STFT analysis techniques are a good tool to reveal more gait characteristics from time-varying gait signals.

2.3. Data analysis

2.3.1. The envelope of time–frequency spectrogram

The envelope of the time–frequency spectrogram is very useful for analyzing the feature of time frequency features of gait signals [8]. The highest Doppler frequency at each time bin makes up a high-frequency envelope. Since there may be noise

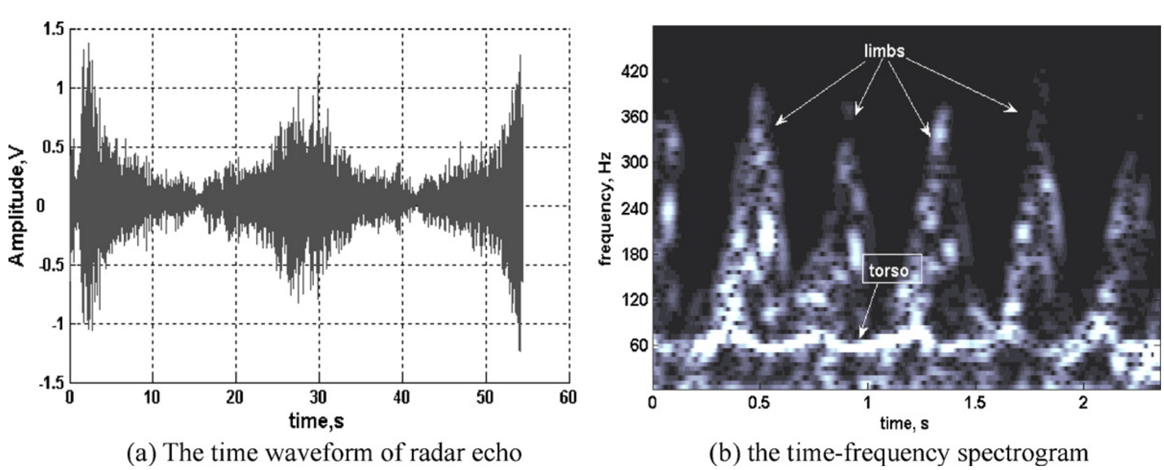

Fig. 2. The time wave (a) of and time-frequency spectrogram (b) of human gait radar echo.