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Using Wearable UWB Radios to Measure Foot Clearance During Walking

Yongbin Qi, Cheong Boon Soh, Erry Gunawan, Kay-Soon Low, Arash Maskooki
School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798
Email: qiyo0001@e.ntu.edu.sg, ecbsoh@ntu.edu.sg, egunawan@ntu.edu.sg, ekslow@ntu.edu.sg

Abstract— **Foot clearance above ground is a key factor for a better understanding of the complicated relationship between falls and gait. This paper proposes a wearable system using UWB transceivers to monitor the vertical heel/toe clearance during walking. First, a pair of very small and light antennas is placed on a point approximating to the heel/toe of the foot, acting as a transmitter and receiver. Then, the reflected signal from ground is captured and propagation delay is detected using noise suppressed Modified-Phase-Only-Correlator (MPOC). The performance of the UWB-based system was compared with an ultrasound system for stationary movements. The experimental results show that an overall mean difference between these two systems is about 0.634mm with correlation coefficient value of 0.9604. The UWB-based system is then used to measure foot clearance during walking which shows promising results for gait events detection.**

I. INTRODUCTION

Falls in the old population are serious healthcare issues due to their financial cost and associated mortality and morbidity rates [1]. With the annual increasing percentage of the elderly population in the world, more and more occurrence of falls is expected [2]. This expected increase requires higher health-care cost. Some research has investigated some basic gait variables such as stride length and walking speed [3] while others have studied joint kinematics to evaluate the ageing effects on gait [4]. It is reported that most falls in older adults result from inappropriate foot placement and clearance over the ground while walking [5]. It is therefore necessary to devise a way to measure foot clearance, which helps to improve understanding of falls, monitor rehabilitation progress, and further enhance rehabilitation strategies [6].

Foot clearance can be measured using a wide variety of techniques and sensors. Optical tracking system uses one or more cameras to track reflective markers positioned at particular anatomical sites on the foot [7]. However, it is often prohibitive for routine applications because of its cost and complexity. Additionally, they are sensitive to changes in lighting, clutter and shadow [8]. Advances in micro-electromechanical systems (MEMS) enable many research groups to use wearable inertial and magnetic sensors to measure foot clearance in and out of a laboratory [9], [1]. These wearable sensors (accelerometers, goniometers, and gyroscopes) are used due to their small size, little hindrance to natural movement, and low power consumption which is capable of providing long term monitoring [10]. However, the estimation of orientation and position is done by double integrating of measured angular acceleration or integrating of angular velocity respectively, which produces high probability to error accumulation over time caused by noise and a fluctuating offset [7], [11].

It is therefore of interest to design an accurate system to overcome such problems as mentioned before. Impulse-Radio Ultra-wideband (IR-UWB) radio is a promising technique for wearable healthcare system to continuously estimate foot clearance due to its high temporal resolution, low power consumption and multipath immunity [12]. Particularly, they can provide high ranging and positioning accuracies especially in indoor environment [11]. In this paper, a wearable tracking system based on UWB radios is proposed and investigated. The objective is to allow subjects to wear equipments as light and small as possible and to be monitored under a natural environment. Actually, the subject only needs to wear two antennas with small form factor and light weight.

The paper is organized as follows: we give a brief overview of the UWB-based foot clearance measurement system and Time-of-Arrival (TOA) detection procedure in Section II. We then investigate the performance of our tracking system by comparing the estimated clearance to those obtained from an ultrasound reference system in Section III. Finally, conclusions are made in Section IV.

II. OVERVIEW OF FOOT CLEARANCE MEASUREMENT SYSTEM

The proposed foot clearance measurement approach uses a pair of wearable UWB transceivers because of its high ranging and positioning capacity. As shown in Fig. 1, foot clearance is defined as the vertical distance between a foot and the ground during walking. The distance during walking is widely used in many fields extending from gait analysis to rehabilitation. General requirements for gait analysis are that the device attached to human body should be as small and as light as possible. Any bulky devices heavier than about 1-2 percent of the subject's mass may potentially disturb normal gait [13].

The proposed system acquires the distance between the transmitter and receiver by multiplying signal velocity to the TOA estimation of first reflected pulse. Classical TOA estimation can be achieved by finding the maximum correlation between received signal and local template [14], which can also be computed in frequency domain. We can also use the spectral phase information alone to estimate TOA. As concluded in [15], Phase-Only-Correlator (POC) has a better performance for resolving closely-spaced signals than conventional correlator because of its impulse-like output.

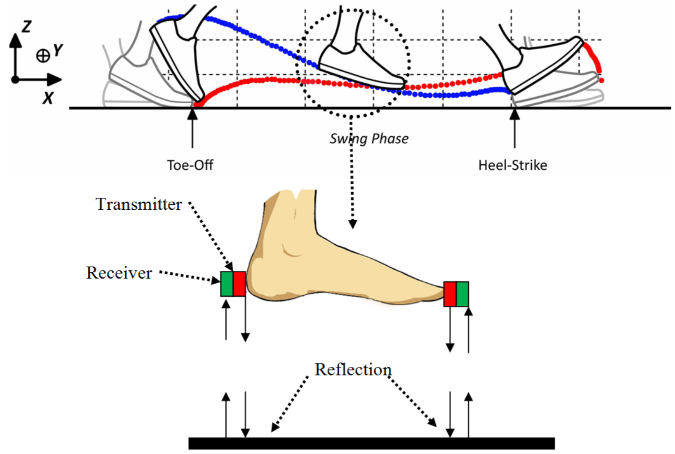


Fig. 1. The prototype of foot clearance measurement during gait.

In our measurement, the reflected signal is weak, and it is easily affected by other noise components. To mitigate this problem, we apply a kurtosis-based noise suppression module, as described in [16], into our measurement system.

In multipath channel, a common used model for received signal is:

$$r(t) = s(t|\tau_i) + n(t) \tag{1}$$

where

$$s(t|\tau_i) = \sum_{i=1}^{n} \alpha_i s(t-\tau_i) \tag{2}$$

is the received pulse, α_i is the attenuation, τ_i is the propagation delay of ith arrival path respectively, and $n(t)$ is thermal noise. The Fourier spectrum $R(\omega)$ of the received signal can be expressed as follows:

$$R(\omega) = \sum_{i=1}^{N} \alpha_i S(\omega) e^{-j\omega\tau_i} + N(\omega) \tag{3}$$

where N is the total number of paths in the channel, $S(\omega)$ is spectrum of transmitted signal and $N(\omega)$ is the noise spectrum.

In MPOC [15], both $R(\omega)$ and the conjugate of $S(\omega)$ are first normalized by the amplitude of $S(\omega)$ and then multiplied together:

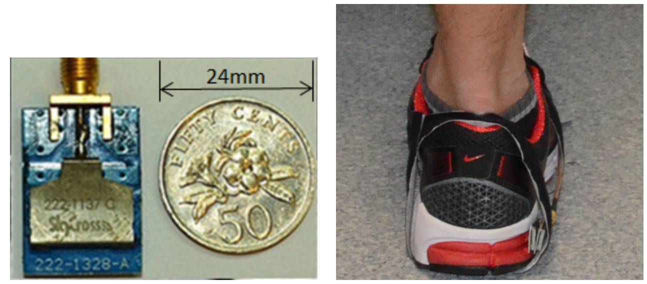
$$P(\omega) = \frac{R(\omega)}{|S(\omega)|} \cdot \left[\frac{S(\omega)}{|S(\omega)|}\right]^* = \frac{R(\omega)}{S(\omega)} \tag{4}$$

where$[\cdot]^*$ denotes complex conjugate.

Substituting (3) into (4), we can get the following equation by simplifying:

$$P(\omega) = \sum_{i=1}^{N} \alpha_i e^{-j\omega\tau_i} + \frac{N(\omega)}{S(\omega)} \tag{5}$$

In equation (5), the first term is the channel frequency response, and the corresponding propagation delay τ_i, i.e. TOA, can be estimated by maximizing the argument of correlator output, which can be achieved by implementing Inverse Fast Fourier Transform (IFFT) on $P(\omega)$. The second term is the noise spectrum divided by the known local template spectrum. Hence, the noise component can be suppressed by setting the high peak values of $N(\omega)/S(\omega)$ in the out-of-band frequencies to zero [15].



(a) (b)

Fig. 2. (a) UWB antennas manufactured by the Skycross corporation, and (b) foot clearance measurement setup.

Suppose the reflected signal of interest is denoted by τ, then we have:

$$\tau = \arg_{\max}\{IFFT(P(\omega))\} \tag{6}$$

Then, the detected propagation delay can be converted to foot-to-ground clearance by the given expression:

$$d = \frac{(\tau - \tau_0) \times c}{2} \tag{7}$$

where τ_0 is the time when transmission begins, and $c = 299792458m/s$ is the speed of light in free space.

III. Measurement Schemes

A. Study A: TOA estimation based on MPOC

In order to demonstrate the performance of the proposed system, on-body UWB measurements are conducted in indoor environment. Two UWB transmitting and receiving antennas, manufactured by the Skycross corporation, are attached on the heels of test subject, as shown in Fig.2. The reflected signal is sampled by Agilent Real Time Oscilloscope DSO80804B with sampling rate of 40 GHz/s and post-processed by Matlab. It is worthy to note that the received pulse comprises of direct path component from transmitter to receiver. To reduce the effects of direct path and other channel multipath on the reflected signal, we conduct one more measurement before the experiment begins. The additional measurements should be done far away from the floor. The measurement waveform during walking is then subtracted by the initial measurement, and finally the residue of the signal is the purely reflected pulse from ground.

The whole process of Modified-POC-based TOA estimation has been shown in Fig. 3. Fig. 4 shows the reflected signal and outputs of different correlators. From Fig. 4, both the classical correlator and MPOC are able to detect the reflection from ground. However, the signal-to-noise-rate (SNR) will be further attenuated during walking. Therefore, MPOC with noise suppression procedure is used in the UWB-based system.

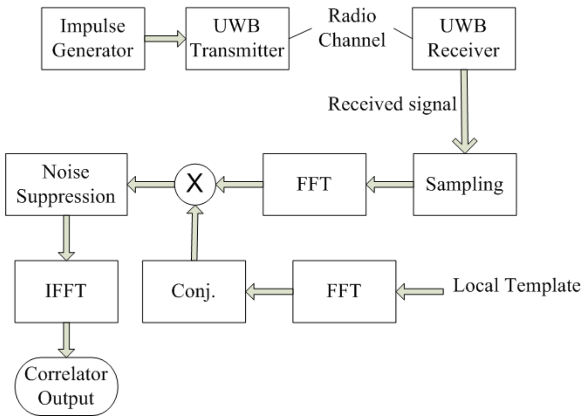
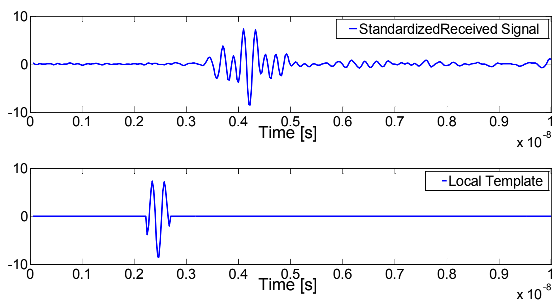
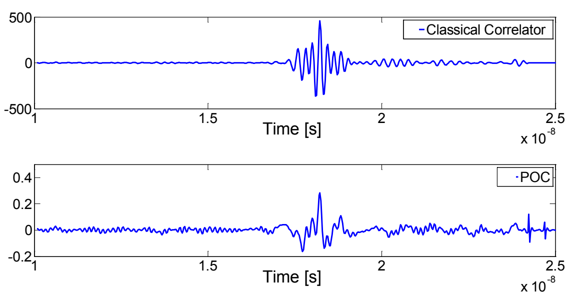


Fig. 3. The block diagram of TOA estimation based on MPOC with noise suppression.



(a)



(b)

Fig. 4. (a) The standardized reflected signal and local template, and (b) normalized classical correlator and Modified-POC outputs collected from the reflected signal.

B. Study B: Stationary Foot Movement

In the experiment, a pair of UWB transceivers is mounted on the subject's shoe using elastic straps and tape at a point approximating to the heel of the foot, as shown in Fig. 2. To benchmark the performance of the proposed system, we compare with the readings from a motion sensor (PS-2103 from PASCO). The motion sensor transmits a burst of 16 ultrasound pulses with a frequency of about 49 kHz. The equipment has a resolution of $0.001m$ at the sampling rate of $50Hz$. However, the sensor is too heavy and large to attach on human body or foot. Therefore, we put the sensor directly under the subject's foot on the ground to calculate the distance or velocity. Then, the subject is allowed to move his leg up and down. The process is repeated 5 times with total of 500 trials used for analysis. The data are collected concurrently from motion sensor and proposed UWB system. The synchronization between these two system is done by maximizing the correlation between the measured distance.

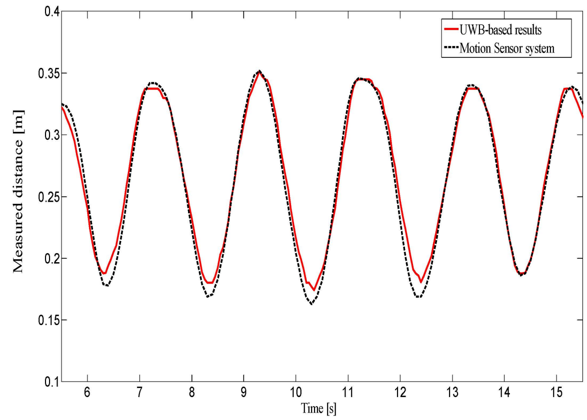


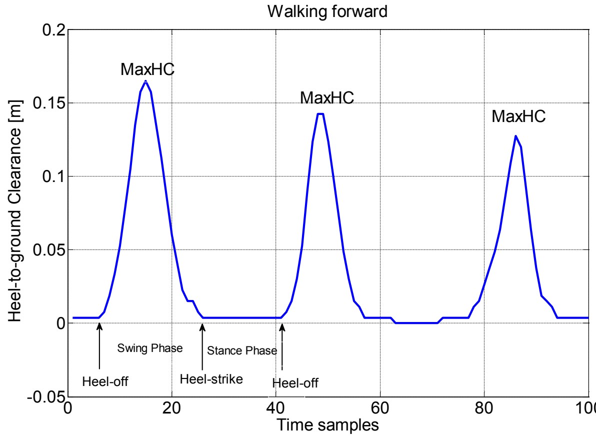
Fig. 5. Vertical distance measurement with motion sensor and UWB radios.

The stationary experiment demonstrates a very good level of agreement between motion sensor and UWB-based systems with correlation coefficient value of 0.9604. The mean difference in distance between these two system was about 0.634 mm. Fig. 5 shows the recorded distance from both systems, the output of UWB-based system shows a strong agreement with the ultrasound system.

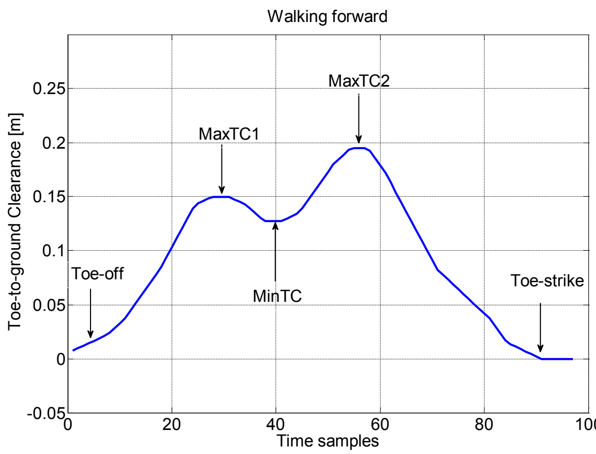
C. Study C: Measurement During Gait

As discussed in section B, the UWB-based foot clearance measurements are as good as those obtain by ultrasound system. Then we conduct measurements with allowing the subject walking forward over 5 meters walkway at normal speed, repeated 3 times. To mitigate interference, the subject is instructed to walk far away from the wall and some large objects. Fig. 6 show the measured foot-to-ground clearance data using UWB radios mounted on the heel and toe of subject's foot respectively.

It is well known that normal gait of healthy person consists of two major phases: swing phase and stance phase. Some researchers have studied specific features of foot clearance during gait [6], such as Minimum Toe Clearance (MinTC),Maximum Toe Clearance (MaxTC) and Maximum Heel Clearance (MaxHC) which are defined as the minimal/maximal vertical distance between the toe/heel and the ground during the swing phase. Swing phase during gait is the transition from toe/heel-off to toe/heel-strike point, and stance phase is from toe/heel-strike to toe/heel-off. In order to demonstrate the feasibility of the proposed system, we use these two phases and specific points to discuss the measurement result. In our experiment, it is easy to detect these gait events (Toe-off, Toe-strike, Heel-strike, Heel-off), as illustrated in Fig. 6.



(a)



(b)

Fig. 6. (a) Heel-to-ground clearance, and (b) Toe-to-ground clearance.

IV. Conclusion

In this paper, we present an wearable system based on on-body UWB radios for foot-to-ground clearance measurement. Estimated foot clearance is computed from detected UWB pulses using noise suppressed MPOC correlator. The feasibility of the proposed approach has been investigated by comparing with an ultrasound system which has correlation value of 0.96. The UWB-based system is then used to measure foot clearance during walking and gait events needed for gait analysis can be detected.

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