Ambulatory Measurement of Foot Kinematics Using Wearable Ultrasonic Sensors

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***Abstract*— In this paper, an ultrasonic-based system for foot parameters measurement has been proposed and investigated. An extended Kalman filtering-based methodology has been developed to extract foot parameters including step length, stride length and cycle time from horizontal displacement during walking. The system comprises of one ultrasonic transmitter (mobile) and four ultrasonic receivers (anchors) with fixed known positions. A Radio Frequency (RF) module is used in our system not only to provide synchronization clock between the mobile and anchors, but also to transmit collected data wirelessly to reduce the wires used. To evaluate the performance of the proposed system, the 2-dimensional foot displacement and the foot parameters were measured and validated against the reference camera motion capture system. These experiment results demonstrate the capability of the proposed system being used as a gait analysis tool for rehabilitation and other medical applications.**

I. Introduction

The most accurate and standard system for tracking of human movement is optical motion analysis using more than one high-speed camera to capture human motion [1]. However, optical tracking system needs high-speed graphic signal processing devices and complex pre-calibration experiments, which are often prohibitive for routine application. In addition, optical system has high requirements for lighting. It is sensitive to changes in lighting, clutter and shadow [2].

Therefore, many wearable sensor systems with easily operation, lower cost and less restrictions to human has attracted more and more attentions in clinical applications [3]. In [4], an unrestrained measurement system of upper-limb motion based on accelerometer only has been proposed. Additionally, the combination of accelerometer and gyroscope is always used to human motion tracking including limb orientation measurement [5], [6], walking feature assessment [7], and daily activity recognition [8]. Using accelerometer and gyroscope combination with other sensors, such as ground reaction force sensor, researchers are introduced some techniques to detect gait phase during walking [3], [9]. As all author stated that it is necessary to rectify a cycle from data of accelerometer or gyroscope for further integration to get the orientation or displacement calculation. This action aims to guarantee a stable and drift-free estimation. However, the initial condition may be difficult to handle, such as special implementation like measurement of walking features, where the heel may never contact the ground. Furthermore, due to the error accumulation over time, long term monitoring maybe another issue for inertial tracking system.

Impulse-Radio Ultra-wideband (IR-UWB) radio is a promising technique for wearable healthcare system to continuously estimate human movement due to its high temporal resolution, low power consumption and multipath immunity [10]. Particularly, wearable UWB radios is well suited for physicians to monitor the degree of motor impairment and to inspect patients response to therapy, since they can provide high ranging and positioning accuracies especially in indoor environment [10]. It is, however, difficult to sample the received signal in real time with current Analog to Digital Converter (ADC) technology due to its large bandwidth of UWB pulse. Furthermore, the clock between transmitter and receiver should be strictly synchronized, because even small clock drift would produce significant measurement error due to its high transmission speed [11].

In this paper, a wireless wearable sensor system based on wearable ultrasonic sensor during treadmill walking is proposed. The objective is to allow patients to be monitored under an unrestrained environment. The proposed approach makes use of the wireless sensor network concept with all the mobile sensor nodes communicating wirelessly with the coordinator. These sensor nodes are light and small for attaching to the human foot. Furthermore, it is low cost as compared to the camera based motion capture system.

A brief overview of the configuration of the wireless wearable ultrasonic system is given in Section II. Section III describes the proposed measurement system using state-space methods to continuously track foot displacement during treadmill walking. Experimental validation is conducted against camera based motion capture system in Section IV. Finally, discussion and conclusion are made in Section V.

II. System Configuration

Fig. 1 shows the general configuration of the system [12]. The system comprises of a coordinator, a data transmission module, anchors, a mobile and a personal computer. The mobile consists of an ultrasound transmitter and RF module. The RF module on the mobile provides synchronization clock between the mobile and anchors. An anchor is composed of an ultrasound receiver, temperature sensor and RF module. Since the speed of light is sensitive to surrounding temperature, the temperature sensor is added. The RF module on the anchor is used to identify the coming ultrasound signal and open the timers to obtain propagation delays of the ultrasound signal.

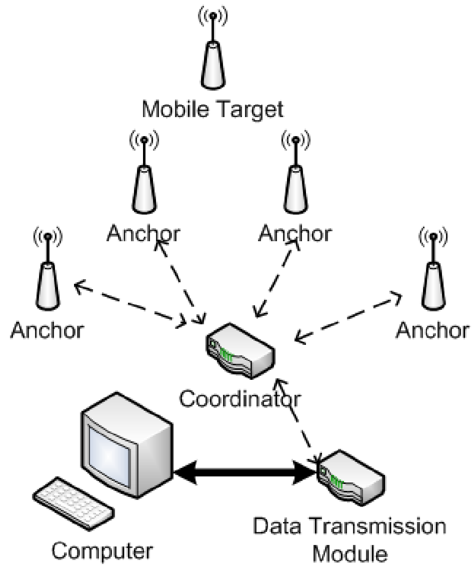

Fig. 1. General configuration of the system

Once upon the necessary data have been collected by the coordinator, they are transferred wirelessly through RF module to data transmission module, and then forward to personal computer through RS232 cable for post-processing.

The proposed system measures the Time-of-Arrival (TOA) of the ultrasonic signal from mobile to anchors. Together with the knowledge of the anchor's position, the absolute distance that the signal travels can be computed. Then, the range information defines a circle centered at this anchor with radius equal to the measured distance, and the mobile resides within the intersections of several such circles.

Fig. 2 shows how horizontal displacement is used to estimate step length, stride length and cycle time during treadmill walking. With respect to the j-th gait cycle, the estimator of the temporal foot parameters are as follows.

- Stride length, SL:

$$\begin{aligned} SL(j) &= 2S(j) \\ S(j) &= Max(j) - Min(j) \end{aligned} \tag{1}$$

- Cycle time, CT:

$$CT(j) = Index(Max(j+1)) - Index(Max(j)) \tag{2}$$

- Velocity, V:

$$V(j) = SL(j)/CT(j) \tag{3}$$

III. Displacement Measurement Based on Extended Kalman Filter

To identify the aforementioned foot parameters, the displacement of foot should be estimated, especially in horizontal direction. In two-dimensional space, the distances to four anchors with known positions can be used to compute the position of a mobile (x,y), which is attached to the heel of the foot, using the equation:

$$d_i = \sqrt{(x-x_i)^2 + (y-y_i)^2} \tag{4}$$

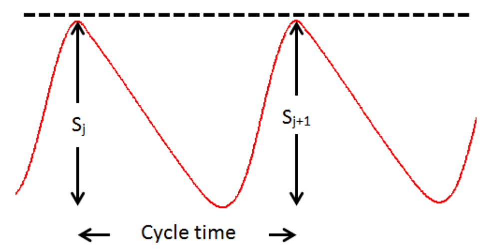

Fig. 2. Schema of Step Length and Cycle Time

where (x_i, y_i) is the coordinates of anchor i (i=1,2,3,4). We design an Extended Kalman Filter (EKF) using a state vector with two cartesian coordinates (x,y). Therefore, the state transition equation from time step $k-1$ to k can be expressed as

$$X_k = X_{k-1} + \boldsymbol{q}_{k-1} \tag{5}$$

where $X_k = [x_k \; y_k]^T$. The process noise is $\boldsymbol{q}_{k-1} \sim N(0, Q_{k-1})$. The covariance matrix Q_{k-1} accounts for the un-modeled factors of the system that will be treated as random noise. It becomes:

$$Q(k-1) = \begin{bmatrix} q_x\mathrm{T} & 0 \\ 0 & q_y T \end{bmatrix} \tag{6}$$

where T is sampling period. In most cases, q_x and q_y can be considered as the velocity in x and y directions, respectively.

Let d_{ik} denote the measured distance at ith anchor using the equation:

$$\begin{aligned} d_{1k} &= \sqrt{(x_k - x_1)^2 + (y_k - y_1)^2} + e_{1k} \\ d_{2k} &= \sqrt{(x_k - x_2)^2 + (y_k - y_2)^2} + e_{2k} \\ d_{3k} &= \sqrt{(x_k - x_3)^2 + (y_k - y_3)^2} + e_{3k} \\ d_{4k} &= \sqrt{(x_k - x_4)^2 + (y_k - y_4)^2} + e_{4k} \end{aligned} \tag{7}$$

where e_{ik} is distance measurement error at anchor i.

Stacking all distance information, we can get

$$D_k = H_k \cdot X_k + E_k \tag{8}$$

where $D_k = [d_{1k} \; d_{2k} \; d_{3k} \; d_{4k}]^T$, $E_k = [e_{1k} \; e_{2k} \; e_{3k} \; e_{4k}]^T$, and H_k is measurement model matrix, which is a Jacobian matrix, defined as:

$$H_k = \begin{bmatrix} \frac{\partial d_{1k}}{\partial x} & \frac{\partial d_{1k}}{\partial y} \\ \frac{\partial d_{2k}}{\partial x} & \frac{\partial d_{2k}}{\partial y} \\ \frac{\partial d_{3k}}{\partial x} & \frac{\partial d_{3k}}{\partial y} \\ \frac{\partial d_{4k}}{\partial x} & \frac{\partial d_{4k}}{\partial y} \end{bmatrix} \tag{9}$$

where

$$\begin{aligned} \frac{\partial d_{ik}}{\partial x} &= \frac{x_k - x_i}{\sqrt{(x_k - x_i)^2 + (y_k - y_i)^2}} \\ \frac{\partial d_{ik}}{\partial y} &= \frac{y_k - y_i}{\sqrt{(x_k - x_i)^2 + (y_k - y_i)^2}} \end{aligned} \tag{10}$$

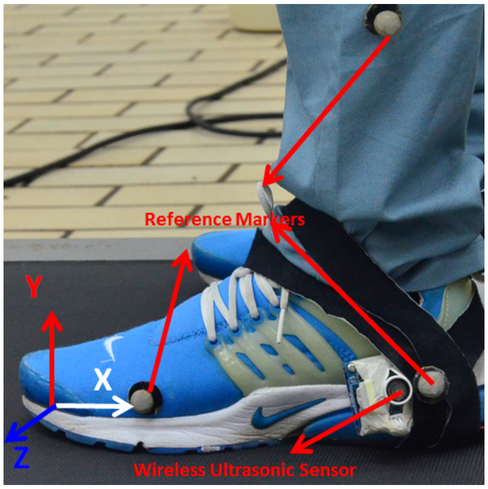

Fig. 3. Wireless unit with embedded ultrasonic transmitter attached on foot, and three reflective markers fixed on toe, heel and shank for reference camera based motion capture system.

We have made an assumption that the distance measurements of each anchor is independent among the four anchors. This will provide a diagonal measurement noise matrix, $R_k = diag(e_1^2, e_2^2, e_3^2, e_4^2)$. e_i is always considered as the standard deviations of the measurement error of anchor i.

Using the measurement model, the position of mobile is determined by following EKF algorithm.

- Prediction:

$$\begin{aligned} \hat{X}_k &= X_{k-1} \\ \hat{P}_k &= P_{k-1} + Q_{k-1} \end{aligned} \tag{11}$$

- Update:

$$\begin{aligned} K_k &= \hat{P}_k H_k^T (H_k \hat{P}_k H_k^T + R_k)^{-1} \\ X_k &= \hat{X}_k + K_k (D_k - H_k \hat{X}_k) \\ P_k &= (I - K_k H_k) \hat{P}_k \end{aligned} \tag{12}$$

where $\hat{x}_k$ and $\hat{P}_k$ are the predicted mean and covariance of the state, respectively, for time step k before getting measurement result; X_k and P_k are the estimated mean and covariance of the state, respectively for time step k after getting measurement result; K_k is the Kalman filter gain.

IV. Measurement Results

The proposed method was tested in measurement of 2-dimensional foot displacement during treadmill walking, as shown in Fig. 3. A mobile node constructed by an ultrasound transmitter and RF module is attached to the subjects's heel and is fixed by elastic strap on the left foot. Since all the data were transmitted to data transmission module wirelessly, there is no additional equipments mounting on the body of subjects in our system.

1) Experiment Setup: The measurement was conducted in a motion analysis lab with eight high speed cameras in the School of Mechanical and Aerospace Engineering at Nanyang Technological University. The eight camera analysis system was used to provide independent reference

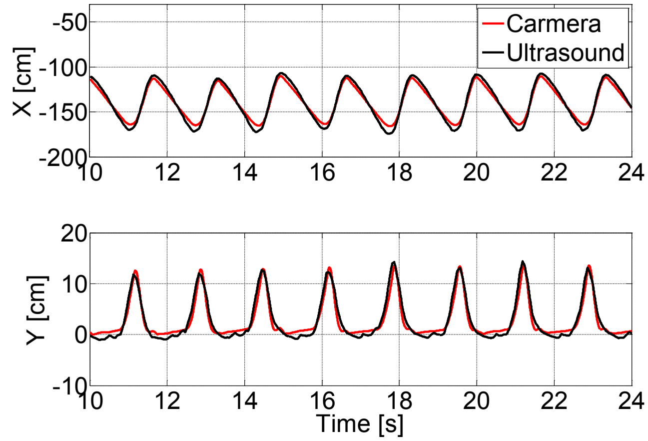

Fig. 4. Foot trajectory during walking in 2-dimensional space (a) Horizontal displacement, and Vertical displacement (foot clearance) is compared with camera based reference system by using ultrasonic sensors.

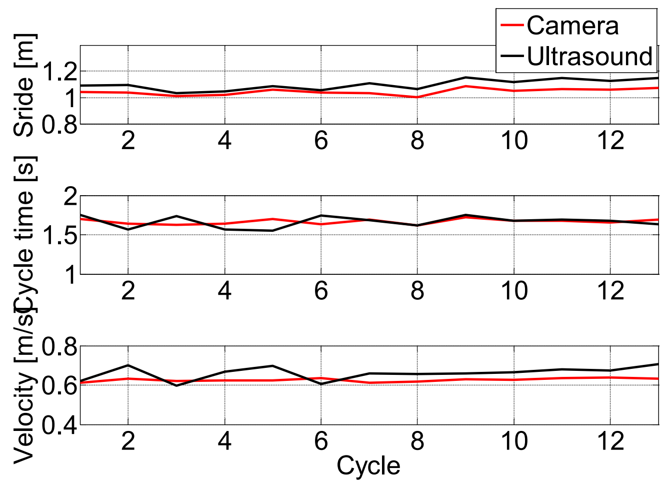

Fig. 5. The foot kinematics (Stride length, Cycle time, and Velocity) obtained from both ultrasonic and optical system during treadmill walking.

measurements and used for the validation of the ultrasonic system. The subject was required to walk on treadmill without shoes or wear regular shoes without high heels, and repeat several times at a specific speed. The camera system tracked the position of three reflective markers placed on toe, heel and shank extremities of subject's foot or shoe according to Fig. 3. Actually, one reflective marker on heel was enough to provide a reference data for validation. The other two reflective markers were used to create a template for better tracking in camera based motion capture system.

TABLE I

Mean Difference, Standard Deviation (STD), and Agreement (PCC) of the Proposed Ultrasonic System for Displacement Measurement During Treadmill Walking

	Mean (mm)	STD (mm)	PCC
Horizontal displacement	0.16	40.44	0.997
Vertical displacement	0.25	11.30	0.965

TABLE II

MEAN DIFFERENCE AND STANDARD DEVIATION BETWEEN ULTRASONIC AND OPTICAL MEASUREMENT SYSTEM

	Camera		**Ultrasound**		**Difference**	
	Mean	STD	Mean	STD	MD	STD
SL (cm)	104.4	2.42	109.8	4.08	-5.42	2.35
CT (s)	1.67	0.033	1.67	0.073	0.0015	0.074
V (cm/s)	62.63	0.88	66.05	3.45	-3.41	3.31

2) Results: To verify the accuracy of the proposed system, the mean and standard deviation value of the difference between parameters extracted with camera based reference system were computed. The accuracy of the 2-dimensional displacement was also compared in terms of Pearson's correlation coefficient (PCC). Good correspondence of foot displacements between proposed system and the reference camera based system is shown in Fig. 4. Table I lists the numerical comparison of the displacements in horizontal and vertical direction. Horizontal displacement was obtained with an error of 0.16 ± 40.44 mm (expressed as the mean $\pm$ STD of the set of difference with the reference system) for kalman filter, together with high PCC value of 0.997. The mean difference and STD of the vertical displacement was 0.25 ± 11.30 mm, which had high similarity of 0.965 with the results of reference system. These displacements were estimated using extended Kalman filter, which is robust and not sensitive to the distributed geometry of anchors.

The experimental results for foot kinematics (Stride length, Cycle time, and Velocity) are shown in Fig. 5. Table II lists the comparison between proposed ultrasonic system and reference camera based system for walking speed, cycle time and stride length, respectively. As shown in Table II, foot kinematics obtained from the test shows that mean values of all foot parameters are very close. For all the collected data, the cycle time of interest were estimated with a mean difference from the reference camera based system of less than 0.074s. For all these three estimated foot parameters, stride length had the relatively high error. It is possible that the attachment of the ultrasonic sensor and reflective markers is not strictly on the same point, therefore, the mean error may be a little bit large in our system, thus introducing errors in the velocity calculation.

V. DISCUSSION AND CONCLUSION

We use state-space methods to estimate the 2-dimensional displacements of foot during treadmill walking using one ultrasonic transmitter and four receivers. To estimate the 2-dimensional displacements of foot, we use the EKF which is more computationally efficient compared to other filters like Unscented Kalman Filter (UKF). This is because the EKF estimates for our system are as accurate as the estimates obtained with more complicated filters like UKF.

In our experiments, the subject is instructed to walk over several minutes period. Other researchers [4] have also investigate foot kinematics using inertial sensors (accelerometers, gyroscopes or both). Their experiments were conducted under slow movements or a limited number of consecutive strides to eliminate the error accumulation over time, since the displacements are estimated by either integrating the velocities or double integrating the measured accelerations. However, our proposed system does not have such limitations and does not have error accumulation even for prolonged measurement durations.

In summary, this study proposes a novel measurement system using wearable ultrasonic sensor to measure the foot kinematics continuously during walking. To evaluate the performance of the proposed system, the foot kinematics was measured and validated against the reference camera based motion capture system. These experiments demonstrate that the results from the proposed ultrasonic measurement system have high correspondence with the results from camera based motion capture system over long walking period. Additionally, the proposed system is easy to wear and to use. It does not restrict the movement of patients or subjects with bulky cables.

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