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# Measurement of Knee Flexion/Extension Angle Using Wearable UWB Radios

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*Abstract*— **This paper proposes a wearable system using UWB transceivers to measure the knee flexion/extension angle parameter, who is known to be of clinical importance. First, a pair of very small and light antennas is placed on the adjacent segments of knee joint. Then, the range data between these two antennas is acquired using Time of Arrival (TOA) estimator. We further use the measured distance to compute the flexion/extension angle using the law of cosines. The performance of the method was compared with a flexible goniometer by simultaneously measuring knee flexion-extension angle. The experimental results show that the system has reasonable performance and has sufficient accuracy for clinical applications.**

## I. INTRODUCTION

Tracking of human movement has attracted more and more attentions nowadays due to its widespread applications such as rehabilitation, gait analysis and sports science [1], [2]. In these applications, it is well known that knee flexion/extension angle parameter is of clinical importance for investigating complex gait disorders, monitoring of progress in rehabilitation, and providing the required information for treatment plans [3].

Current methods of knee flexion/extension angle measurement are based on either optical, ultrasonic, magnetic, or inertial tracking [4]. Optical systems employ one or more cameras to track markers positioned at particular anatomical sites on the body segments which are often prohibitive for routine applications because of its cost and complexity. Additionally, they are sensitive to changes in lighting, clutter and shadow [5]. In recent years, advances in micro-electromechanical systems (MEMS) led many research groups to utilize wearable inertial and magnetic sensors to track human movement in and out of a laboratory [6]. The advantages of these wearable sensors (accelerometers, goniometers, gyroscopes) include their small size, little hindrance to natural movement, and capability for long term monitoring [7]. 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 [8].

Impulse-Radio Ultra-wideband (IR-UWB) radio is a promising technique for wearable healthcare system to continuously estimate human joint angles due to its high temporal resolution, low power consumption and multipath immunity [9]. 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 [8].

In this paper, a wearable healthcare system based on UWB radios in indoor environment is proposed. The objective is to allow patients to wear equipments as light and small as possible and to be monitored under a natural environment. The patient only need to wear two antennas with small form factor and light weight. It is low cost compared to the optical system.

The paper is organized as follows: we first give a brief overview of biomechanics of knee joint flexion/extension movement, and describe the proposed joint angle measurement procedure in section II. Then, Section III introduces the TOA estimator for ranging. This is followed by the experimental results from simultaneous knee angle measurements using UWB radios and a flexible goniometer in Section IV. Finally, conclusions are made in Section V.

## II. OVERVIEW OF FLEXION/EXTENSION ANGLE MEASUREMENT SYSTEM

### A. Biomechanics of Knee Flexion/Extension Movement

Knee flexion/extension angle is defined as the relative angle of the knee between two adjacent segments, as shown in Fig. 1. It is well known that knee flexion/extension angle has clinical importance not only in gait analysis, but also in rehabilitation [6]. Actually, other movable joints, such as head, shoulder, elbow, wrist, trunk, finger, hip and ankle, are also able to conduct flexion and extension movement [10]. Flexion is a bending movement which decreases the relative joint angle between the adjacent segments, while extension is a straightening movement in which the relative angle of joint between two adjacent segments increases as the joint returns to the reference anatomical position [7], [10].

### B. Brief overview of Proposed System

The system in this paper is based on wearable UWB radios mounted on body segments, or necessary sewn into clothing to measure distance between two points during human movement. Fig. 1 shows a simplified diagrammatic representation for the placement of transceivers. Accordingly, when a transmitter (Tx) and a receiver (Rx) were attached on human body as in Fig. 1, a triangle is formed by the pair of transceivers and knee joint. Since the two sides of the

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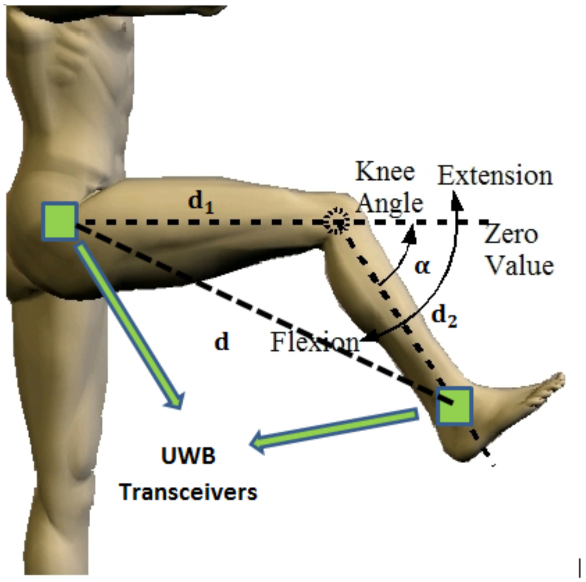


Fig. 1. The configuration of knee flexion/extension angle $\alpha$. $d_1$ and $d_2$ denote the distance between knee joint and transceivers respectively; d is the ranging data required in the proposed system.

triangle , i.e. $d_1$ and $d_2$, are constant during human movement with transceivers fixed on body, the law of cosines enables the knee flexion/extension angle to be calculated using the measured distance.

Range data, $d$, are acquired between Tx and Rx while the subject is moving through TOA of the first received pulse, which is then converted to angle estimation using the law of cosines. During segment movement, modelling the variation of the knee yields

$$\cos\alpha = -\frac{d_1^2 + d_2^2 - d^2}{2d_1 d_2} \tag{1}$$

where $d_1$ and $d_2$ have been measured in initial or static phase, $d$ is the Tx-Rx separation distance. Hence, equation (1) has only one variable, i.e. $d$, and the angle $\alpha$ is calculated using the anti-cosine rule.

## III. RANGING BASED ON TOA ESTIMATION

Ranging in a wireless system involves the collection of distance information from radio signals travelling between a Tx and a Rx [11]. A flow chart of the classical correlator-based TOA estimator is shown in Fig. 2. A common model for the received signal is given by

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

where $s(t)$ is the transmitted pulse, $\alpha_i$ and$\tau_i$ is the attenuation and the propagation delay of $ith$ path, and $n(t)$ is thermal noise.

A number of techniques can be used for TOA estimates, such as energy detection, maximum envelope searching, peak detection, and correlation with local template [12], [13]. Because of the limitations of accuracy, we choose correlation-based technique to estimate the TOA of the first received pulse at the receiver.

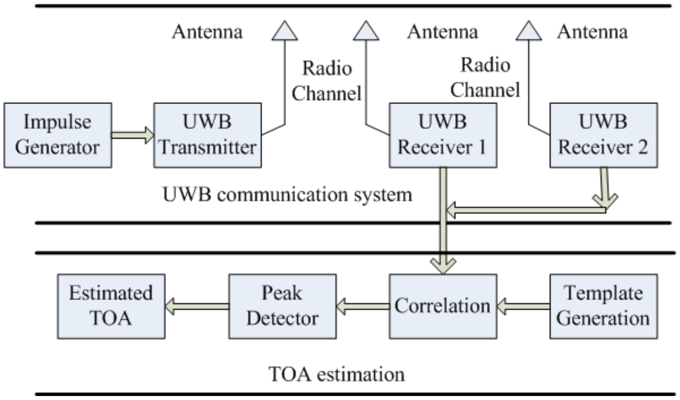


Fig. 2. Conventional correlator-based TOA estimator.

The normalized cross-correlation of the template and received waveforms is expressed as follows:

$$\phi_{rp}(\tau) = \frac{1}{\sqrt{E_r E_p}} \int_{-\infty}^{\infty} r(t)p(t-\tau)dt \tag{3}$$

where $E_r$ is the energy of received waveform, and $E_p$ is the template energy. Therefore, the corresponding TOA estimator is calculated by finding the maximal argument of the aforementioned cross-correlation, which is indicated in the following equation [13]:

$$\tau = \underset{max}{arg}\{\phi_{rp}(\tau)\} \tag{4}$$

where $\tau$ is the propagation delay that maximizes the argument $arg\{\phi_{rp}\}$. In the estimation of TOA, it is apparent that the separation distance $d$ between the Tx and Rx can be measured by the following equation:

$$d = (\tau - \tau_0) \times c \tag{5}$$

where $\tau_0$ is the time when transmission begins, i.e. system delays, and $c = 299792458 m/s$ is the speed of light.

## IV. MEARSUREMENT RESULTS

In order to investigate the performance of the proposed approach, on-body UWB measurements were conducted in indoor environment. Two antennas that specially designed for UWB application, as shown at the bottom of Fig. 3, were attached to the thigh and shank of the test subject with the purpose of measuring the distance between these two points.

The following equipments were used in our experiment: Impulse Generator 3500D by Picosecond Pulse Labs, Agilent Real Time Oscilloscope DSO80804B and two antennas SMT-3TO10M by Skycross with very small size ($12.2mm \times 18.5mm \times 1mm$), as shown in Fig. 3.

To benchmark the performance of the proposed system, we compare with a goniometer probe (PS-2137 from PASCO) attached on a human leg. The test subject wearing UWB antennas and goniometer probe was allowed to perform flexion and extension of his shank for 15s while keeping the rest of body still. Goniometer was mounted on the lateral

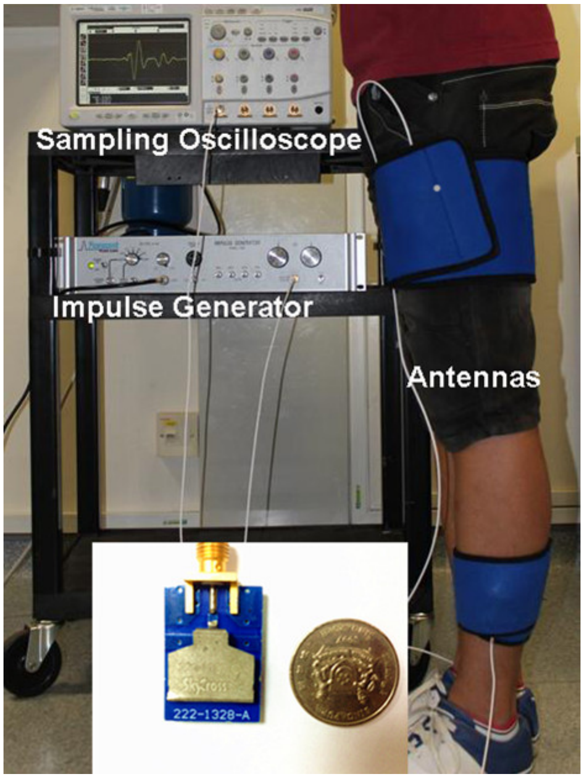


Fig. 3. Sagittal view of attachment of antennas on thigh and shank, and an embedded photograph of a skycross antenna and a 20 cent Singapore coin.

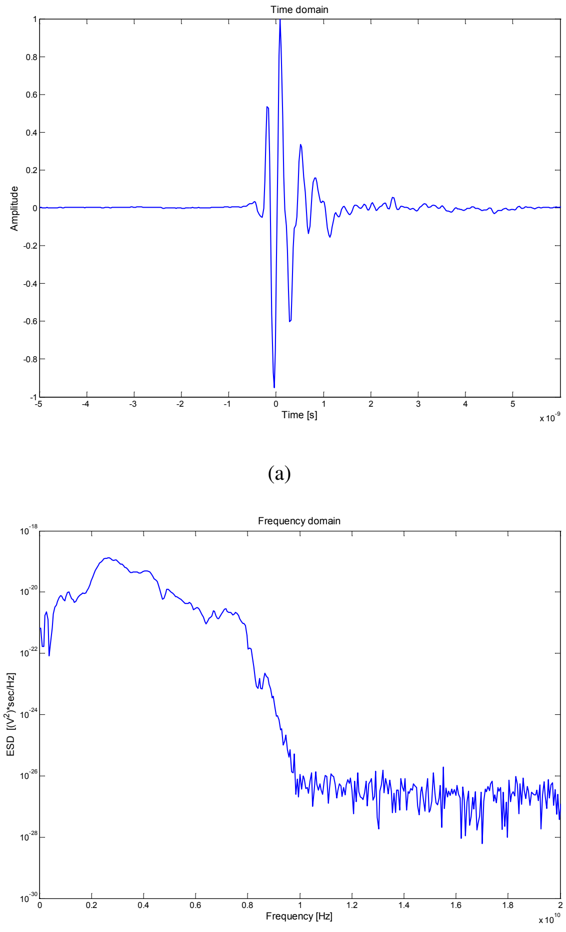
side of the leg centred at knee joint. Simultaneously, the received pulse is sampled by the real time oscilloscope with sampling frequency 40GHz. The synchronization between goniometer system and UWB system was done by maximizing the correlation between the angle. An example of received waveform in time domain is shown in Fig. 4(a), and the single-sided Energy Spectral Density (ESD) is also shown in Fig. 4(b). The average power of the received pulse is about -31.5 dBmW.

16 periods of collected signal are real-time averaged by the Agilent oscilloscope so as to reduce the effect of high frequency noise. Using TOA, the distance *d* can be estimated using equation (5) which enables the corresponding flexion/extension angle to be computed. The measured distance and extracted knee flexion/extension angles of different test subjects are shown in Fig 5 and Fig 6.

TABLE I

MEAN DIFFERENCE (MD), STANDARD DEVIATION(SD) AND CORRELATION COEFFICIENTS (CC) BETWEEN GONIOMETER- AND UWB-BASED ANGLE MEASUREMENT SYSTEM

| Speed | MD(°) | SD(°) | CC |
|---|---|---|---|
| Slow | 0.2433 | 1.27 | 0.9931 |
| Normal | 1.0026 | 2.16 | 0.9817 |
| Fast | 2.0493 | 3.07 | 0.9700 |



(a)

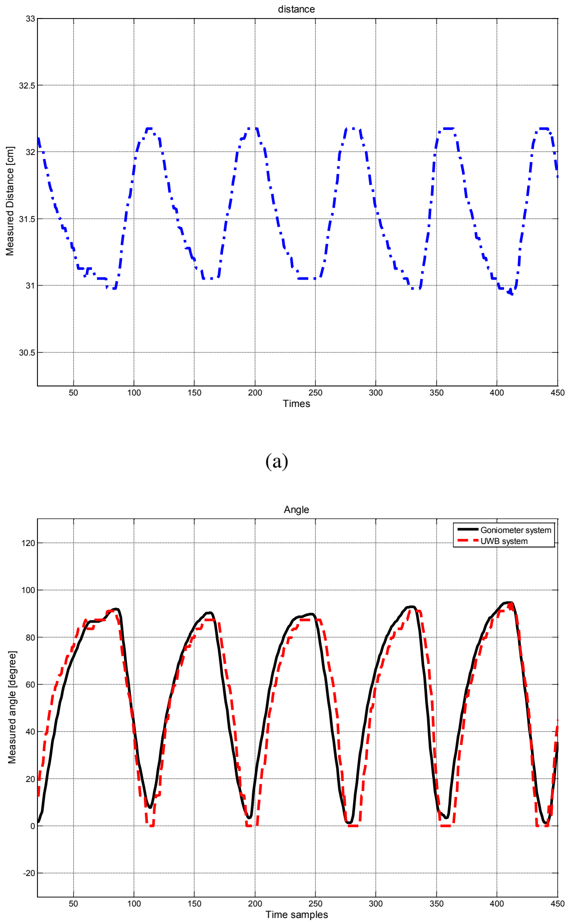
(b)

Fig. 4. Normalized received pulse. [a] Time domain. [b] Frequency domain.

One subject was instructed to perform knee flexion/extension task with three angular velocities (slow, normal, fast), repeating each velocity three times. The data were recorded concurrently by Goniometer and UWB-based system. The correlation coefficients between the angle estimates from the UWB-based system and estimates from the reference goniometer system are shown in Table I. Although the correlation shows slight decrease with the increase of moving speed, the results show that the proposed measurement system has very good correlation ($\geqslant 0.97$) with reference goniometer-based system.

## V. CONCLUSION

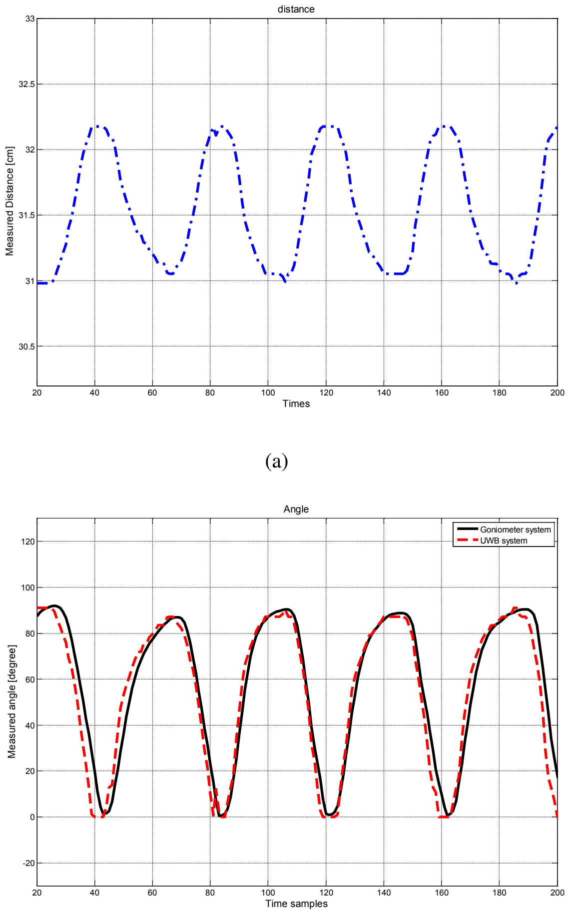
In this paper, we present an wearable system based on on-body UWB radios for tracking human motion. Experiments were conducted with different subjects. The tracking ability of the UWB-based knee flexion/extension system has been shown to be as accurate as a goniometer-based system. The proposed UWB-based flexion/extension angle measurement system can be applied not only to knee joint, but also to other joints such as elbow, etc.. This system is capable of taking indoor and outdoor measurements, thus it is well-suited for healthcare applications which allow the patients



(a)

(b)

Fig. 5. [a] Distance variation during the shank movement of subject A. [b] relative flexion/extension angle for goniometer and UWB system.



(a)

(b)

Fig. 6. [a] Distance variation during the shank movement of subject B. [b] relative flexion/extension angle for goniometer and UWB system.

to be monitored in a unrestrained environment instead of a specialized laboratory in the hospital.

## REFERENCES

[1] H. Zhou and H. Hu. Human motion tracking for rehabilitationła survey. *Biomedical Signal Processing and Control*, 3(1):1–18, 2008.

[2] D. Fitzgerald, J. Foody, D. Kelly, T. Ward, C. Markham, J. McDonald, and B. Caulfield. Development of a wearable motion capture suit and virtual reality biofeedback system for the instruction and analysis of sports rehabilitation exercises. In *Engineering in Medicine and Biology Society, 2007. EMBS 2007. 29th Annual International Conference of the IEEE*, pages 4870–4874. IEEE, 2007.

[3] A.H. Myriam, G. Salim, E. David, and K. Mohammad. An automated method for analysis of gait data to aid clinical interpretation. In *Biomedical Engineering (MECBME), 2011 1st Middle East Conference on*, pages 119–121. IEEE, 2011.

[4] G. Welch and E. Foxlin. Motion tracking: No silver bullet, but a respectable arsenal. *Computer Graphics and Applications, IEEE*, 22(6):24–38, 2002.

[5] S. Bamberg, A.Y. Benbasat, D.M. Scarborough, D.E. Krebs, and J.A. Paradiso. Gait analysis using a shoe-integrated wireless sensor system. *Information Technology in Biomedicine, IEEE Transactions on*, 12(4):413–423, 2008.

[6] J. Favre, BM Jolles, R. Aissaoui, and K. Aminian. Ambulatory measurement of 3d knee joint angle. *Journal of biomechanics*, 41(5):1029–1035, 2008.

[7] G.X. Lee, K.S. Low, and T. Taher. Unrestrained measurement of arm motion based on a wearable wireless sensor network. *Instrumentation and Measurement, IEEE Transactions on*, 59(5):1309–1317, 2010.

[8] H.A. Shaban, M.A. El-Nasr, and R.M. Buehrer. Toward a highly accurate ambulatory system for clinical gait analysis via uwb radios. *Information Technology in Biomedicine, IEEE Transactions on*, 14(2):284–291, 2010.

[9] C.C. Chong, F. Watanabe, and M.Z. Win. Effect of bandwidth on uwb ranging error. In *Wireless Communications and Networking Conference, 2007. WCNC 2007. IEEE*, pages 1559–1564. IEEE, 2007.

[10] J. Hamill and K.M. Knutzen. *Biomechanical Basis of Human Movement with Motion Analysis Software*. Lippincott Williams & Wilkins, 2006.

[11] M.G. Di Benedetto and G. Giancola. *Understanding ultra wide band radio fundamentals*. Prentice Hall, 2004.

[12] S.I. Nikolov and J.A. Jensen. Precision of needle tip localization using a receiver in the needle. In *Ultrasonics Symposium, 2008. IUS 2008. IEEE*, pages 479–482. IEEE, 2008.

[13] M. Abou El-Nasr, H.A. Shaban, and R.M. Buehrer. Low-power ir-uwb coherent toa estimators with suboptimal sinusoidal templates for uwb-based body area networks. *Wireless Networks*, 17(7):1641–1648, 2011.