A Wearable Wireless Ultrasonic Sensor Network for Human Arm Motion Tracking

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Abstract— **This paper introduces a novel method for arm flexion/extension angles measurement using wireless ultrasonic sensor network. The approach uses unscented Kalman filter and D-H kinematical chain model to retrieve the joint angles. This method was experimentally validated by calculating the 2-dimensional wrist displacements from one mobile, placed on the point of subject's wrist, and four anchors. The performance of the proposed ultrasonic motion analysis system was benchmarked by commercial camera motion capture system. The experimental results demonstrate that a favorable performance of the proposed system in the estimation of upper limb motion. The proposed system is wireless, easy to wear, to use and much cheaper than current camera system. Thus, it has the potential to become a new and useful tool for routine clinical assessment of human motion.**

I. INTRODUCTION

Measurement and analysis of arm motion has become more popular for its wide applications including rehabilitation engineering, movement disorders diagnosis, and athletic performance evaluation [1]. The commonly used method is optical system, which uses one or more cameras to captured the reflective markers on the body [2]. Although it is the most common and accurate in human tracking, the optical system is costly, and suffers from light changing, occlusion and shadow [3].

Therefore, there is a need for an easy to use and not costive device to measure the flexion/extension angles of arm. Inertial sensors have emerged to monitor the arm motion in recent days [1]. Although those inertial sensors overcomes such limitations of optical system, it suffers from integration drift caused by noise and a fluctuating offset [4]. Therefore, many studies using such sensors were evaluated either during slow movement [5] or short durations [6] to reduce the integration time, thus reducing error drift.

In this paper, a novel measurement system has been developed for arm motion tracking based on wearable wireless ultrasonic positioning system. The proposed system makes use of the wireless sensor network concept with all the mobile sensor nodes communicating wirelessly with the coordinator, thus reducing wires used in experiments. There is only one ultrasonic sensor attached to human arm, which enables subjects to be monitored under natural environment. Furthermore, only one ultrasonic sensor not only minimizes the discomfort for users, but also avoids complex calibration procedures and synchronization issues [7].

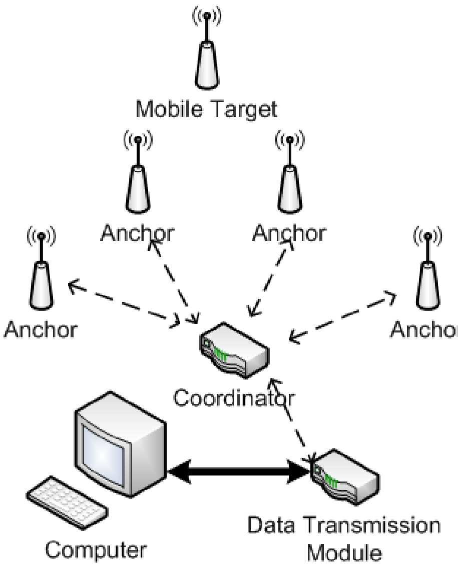

Fig. 1. General configuration of the system

II. SYSTEM CONFIGURATION

Fig. 1 shows the general configuration of the system [8]. The ultrasonic motion analysis system comprises of a coordinator, a data transmission module, four 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. In order to minimize the effect of environment temperature on the speed of sound, a temperature sensor has been used to estimate the velocity of sound real time. Therefore, the velocity of sound can be approximated in the air by [9]

$$v_s = \sqrt{\kappa R T} \approx 20.05\sqrt{T} \tag{1}$$

where κ is the isentropic coefficient which is equal to 1.4 in air, $R = 287.14\ m^2/s^2K$ is the general gas constant, and T is the air temperature in degrees Kelvin.

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

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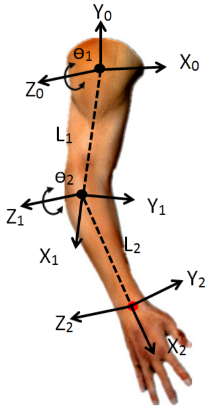

Fig. 2. Simplified kinematical chain of human arm.

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.

III. KINEMATIC MODELING OF ARM

In this study, we pay more attention on the arm flexion/extension angle measurement on sagittal plane. The commonly used method for modeling human rigid body is based on a sequence of links connected by joints. Denavit and Hartenberg (D-H) algorithm is used to assign right-handed orthogonal coordinate frames to each link [10]. The simplified kinematical chain of human upper limb is shown in Fig. 2. Table I shows D-H parameters for the arm kinematics, respectively, which correspond to a kinematic chain comprising of two rigid segments (forearm and upper arm).

TABLE I
DENAVIT-HARTENBERG PARAMETERS OF THE ARM MODEL

Joint	θ_k	d_k	a_k	α_k
Shoulder (q_1)	θ_1	0	l_1	0
Elbow (q_2)	θ_2	0	l_2	0

The transformation matrix between two adjacent links $k-1$ and k is defined by the following expression [10]

$$T_{k-1}^{k} = \begin{bmatrix} C\theta_k & -C\alpha_k S\theta_k & S\alpha_k S\theta_k & a_k C\theta_k \\ S\theta_k & C\alpha_k C\theta_k & -S\alpha_k C\theta_k & a_k S\theta_k \\ 0 & S\alpha_k & C\alpha_k & d_k \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

where $Sx = sinx$ and $Cx = cosx$. In order to compute the arm matrix, we can multiply the transformation matrixes in turns: [10]:

$$T_0^2(q) = T_0^1(q_1) \cdot T_1^2(q_2) \tag{3}$$

The final homogeneous transformation matrix of arm coordinate system 2 with respect to base coordinate system 0 is given by,

$$T_0^2(q) = \begin{bmatrix} C\theta_{12} & -S\theta_{12} & 0 & l_2 C\theta_{12} + l_1 C\theta_1 \\ S\theta_{12} & C\theta_{12} & 0 & l_2 S\theta_{12} + l_1 S\theta_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4}$$

where $\theta_{12} = \theta_1 + \theta_2$, θ_1 and θ_2 are shoulder and elbow extension/flexion angle, respectively.

IV. INVERSE KINEMATIC MODEL

As mentioned in section III, the forward kinematic model can be used to determine the position and orientation of the wrist with given joint angles. On the other hand, we can estimate joint angles with desired or known the position of wrist, where the inverse kinematic model is used. For convenience, we refer to the position and orientation of wrist as the wrist configuration vector (WCV).

The WCV is a vector that represents of the position and orientation of wrist, which is defined:

$$w(q) = \begin{bmatrix} w^1 \\ w^2 \end{bmatrix} = \begin{bmatrix} p \\ [\exp(\frac{q_n}{\pi})]\, r^3 \end{bmatrix} \tag{5}$$

where w^1,the first three components of WCV, represents the wrist position, $p = [x\ y\ z]^T$. w^2, the next three components of WCV, represents the wrist orientation. As in our system, we are only interested in the shoulder and elbow joint flexion/extension angles, therefore, only the position information is used to the inverse kinematic model.

Equating the first elements of the last column of matrix in equation (4) and (5),

$$\begin{aligned} x &= w_1 = l_2 C\theta_{12} + l_1 C\theta_1 \\ y &= w_2 = l_2 S\theta_{12} + l_1 S\theta_1 \\ z &= w_3 = 0 \end{aligned} \tag{6}$$

Squaring and adding x and y, we can get the elbow angle,

$$\theta_2 = \cos^{-1}\left(\frac{x^2 + y^2 - l_1^2 - l_2^2}{2 l_1 l_2}\right) \tag{7}$$

As the θ_2 has been solved by equation (7), we need to isolate the $C\theta_{12}$ and $C\theta_{12}$ using sum of sines and cosines. Write into matrix form,

$$\begin{bmatrix} l_1 + l_2 C\theta_2 & -l_2 S\theta_2 \\ l_2 S\theta_2 & l_1 + l_2 C\theta_2 \end{bmatrix} \begin{bmatrix} C\theta_1 \\ S\theta_1 \end{bmatrix} = \begin{bmatrix} x \\ y \end{bmatrix} \tag{8}$$

Then, the shoulder angle is computed as

$$\theta_1 = \tan^{-1}\left(\frac{l_1 + l_2 C\theta_2 - l_2 S\theta_2 x}{(l_1 + l_2 C\theta_2)x + l_2 S\theta_2 y}\right) \tag{9}$$

V. DISPLACEMENT MEASUREMENT

In order to solve the equations of (7) and (9), the displacements in vertical and horizontal direction should be estimated first. Unscented kalman filter has been implemented for the wrist position tracking in this paper. The filter state space comprises of the position of wrist, which is given by the equations

$$\begin{aligned} X_{k+1} &= X_k + q_k \\ Y_k &= h(X_k) + v_k \end{aligned} \tag{10}$$

where

$$\begin{aligned} X_k &= \begin{bmatrix} x_k & y_k \end{bmatrix}^T \\ q_k &= \begin{bmatrix} q_k^x & q_k^y \end{bmatrix}^T \\ v_k &= \begin{bmatrix} v_k^1 & v_k^2 & v_k^3 & v_k^4 \end{bmatrix}^T \\ h_i(X_k) &= \sqrt{(x_k - x_i)^2 + (y_k - y_i)^2} \end{aligned} \tag{11}$$

where (x_i, y_i) is the coordinates of anchor i (i=1,2,3,4), X_k is the state vector to be estimated, Y_k is the measured vectors, q and v are the system and measurement noises with covariance matrices of Q and V.

Using the system model, the position of wrist is determined by following algorithm.

- For each step k, start from $\overline{X}_{k/k}$ and $P_{k/k}$, do
- Generate sigma points:

$$\begin{aligned} B_{k/k} &= \sqrt{(n+\lambda)P_{k/k}} \\ \chi_{k/k} &= \begin{bmatrix} \bar{X}_{k/k} & \bar{X}_{k/k} + B_{k/k} & \bar{X}_{k/k} - B_{k/k} \end{bmatrix} \in R_{n\times(2n+1)} \end{aligned} \tag{12}$$

- Prediction:

$$\begin{aligned} \chi^*_{k+1/k} &= \chi_{k/k} \\ \bar{X}_{k+1/k} &= \sum_{i=0}^{2n} W_i^m \chi^*_{i,k+1/k} \\ P_{k+1/k} &= \sum_{i=0}^{2n} W_i^c [\chi^*_{i,k+1/k} - \bar{X}_{k+1/k}][\chi^*_{i,k+1/k} - \bar{X}_{k+1/k}]^T \end{aligned} \tag{13}$$

- Update:

$$\begin{aligned} B_{k+1/k} &= \sqrt{(n+\lambda)P_{k+1/k}} \\ \chi_{k+1/k} &= \begin{bmatrix} \bar{X}_{k+1/k} & \bar{X}_{k+1/k} + B_{k+1/k} & \bar{X}_{k+1/k} - B_{k+1/k} \end{bmatrix} \\ Y_{k+1/k} &= h(\chi_{k+1/k}) \\ \bar{Y}_{k+1/k} &= \sum_{i=0}^{2n} W_i^m Y_{i,k+1/k} \end{aligned} \tag{14}$$

- Compute the Kalman gain:

$$\begin{aligned} P_{yy} &= \sum_{i=0}^{2n} W_i^c [Y_{i,k+1/k} - \bar{Y}_{k+1/k}][Y_{i,k+1/k} - \bar{Y}_{k+1/k}]^T \\ P_{xy} &= \sum_{i=0}^{2n} W_i^c [\chi_{i,k+1/k} - \bar{X}_{k+1/k}][Y_{i,k+1/k} - \bar{Y}_{k+1/k}]^T \\ K_{k+1} &= P_{xy} P_{yy}^{-1} \end{aligned} \tag{15}$$

- Measurement update:

$$\begin{aligned} \bar{X}_{k+1/k+1} &= \bar{X}_{k+1/k} + K_{k+1}(Y_{k+1} - \bar{Y}_{k+1/k}) \\ P_{k+1/k+1} &= P_{k+1/k} - K_{k+1} P_{yy} K_{k+1}^T \end{aligned} \tag{16}$$

- End

where λ is the scaling factor. W is the associated weight matrix.

VI. MEASUREMENT RESULTS

The purpose of this part was to provide experimental validation of the accuracy of the proposed ultrasonic system against camera based system. Various experiments have been conducted using the hardware system described in section II. The platform comprises of a wireless ultrasonic sensor network with four anchors and one mobile equipped with ultrasonic transmitter/receiver board. The wrist 2-dimensional displacements are estimated using unscented Kalman filter. Together with the inverse kinematic model, the joint extension/flexion angles can be estimated.

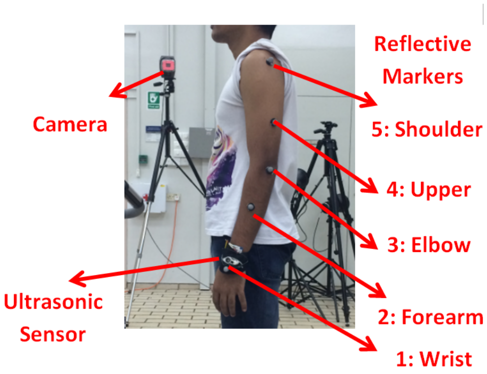

Fig. 3. Wireless unit with embedded ultrasonic sensor attached on wrist, and five reflective markers fixed on wrist, forearm, elbow, upper arm, and shoulder for reference camera based motion capture system.

1) Experiment Setup: As shown in Fig. 3, a wearable ultrasonic sensor was placed on the wrist of subject. The validation experiments have been conducted in a motion analysis lab with eight high speed cameras in the School of Mechanical and Aerospace Engineering at Nanyang Technological University. The subject was asked to perform flexion and extension of his forearm for 2 mins. Then the motion is repeated five times. The camera system tracked the position of five reflective markers placed on wrist, forearm, elbow, upper arm, and shoulder of subject according to Fig. 3.

2) Performance Analysis: The mean and standard deviation value of the difference between parameters extracted with camera based reference system were used to validate the performance of the proposed system. Good correspondence of foot displacements between proposed system and the reference camera based system is shown in Fig. 4, which is one radomly selected trial. Table II lists the numerical comparison of the displacements in horizontal and vertical direction. Horizontal displacement was obtained with an error of 0.10 ± 1.18 cm for unscented Kalman filter. The mean difference and STD of the vertical displacement was 0.14 ± 2.10 cm. These displacements were estimated using unscented Kalman filter, which is robust and not sensitive to the distributed geometry of anchors.

The experimental results for joint angles (shoulder and elbow) are shown in Fig. 5. Table II lists the comparison between proposed ultrasonic system and reference camera based system for shoulder and elbow joint angles respectively. For all the recorded exercises, the joint angles of interest were estimated with a mean difference from the reference camera based system of less than 3^o.

Several factors could be attributed to the errors or difference. In this paper, we are only interested in the flexion/extension of the arm, therefore, the motion is assumed in a sagittal plane. However, there are also some other move-

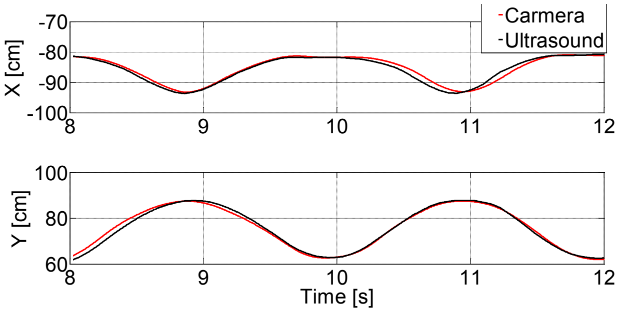

Fig. 4. Wrist position in 2-dimensional space (a) Horizontal displacement, and Vertical displacement (foot clearance) is compared with camera based reference system by using ultrasonic sensors.

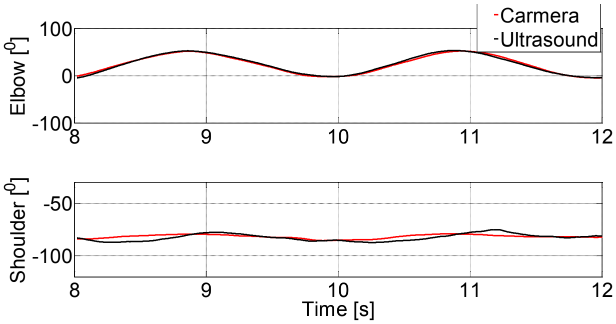

Fig. 5. The joint flexion/extension angles obtained from both ultrasonic and camera system.

ments like rotation of shoulder, which will introduce some errors. Some of the estimation errors might also be attributed to the vibrations of reflective markers or sensors mounted on body. Marker occlusion is one factor that affects the results of camera based motion capture system. The recording of the marker will be discarded when a significant percentage of markers has not been detected by more than 3 cameras. When one of the three markers is nonvisible, the position of such marker will be estimated from the other two markers by interpolation. In summary, the proposed method leads to the estimates of not only the vertical, horizontal displacement, but also the shoulder and elbow joint flexion/exension angles that are similar to those obtained from camera based system.

TABLE II

MEAN DIFFERENCE (MD) AND STANDARD DEVIATION (STD) OF THE PROPOSED ULTRASONIC SYSTEM FOR ARM FLEXION/EXTENSION ANGLE TRACKING

	MD	**STD**
Horizontal (cm)	0.10	1.18
Vertical (cm)	0.14	2.10
Shoulder(deg)	0.88	2.58
Elbow(deg)	-1.51	1.78

VII. CONCLUSION

This study has demonstrated that one ultrasound transmitter (attached to human body) and four receivers are used to obtain high accuracy shoulder and elbow joint flexion/extension angles estimates. Unscented Kalman filter is applied to estimate the displacements in vertical and horizontal direction of the ultrasonic sensor and the recorded displacements, together with inverse kinematic model are used to estimate joint angles. We use state-space methods to estimate the 2-dimensional displacements of wrist during sagittal plane moving of arm. The optical tracking reference system was used to benchmark the performance of the proposed ultrasonic motion analysis system. It demonstrates that the accuracy of this system is sufficiently good for clinical applications, such as rehabilitation, pervasive healthcare, and sports surveillance. Additionally, the proposed system is easy to wear, to use and much cheaper than current camera system. It does not restrict the movement of patients or subjects with bulky cables. Thus,it has the potential to become a new and useful tool for routine clinical assessment of human motion.

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