Localization of Wearable Ultrawideband Antennas for Motion Capture Applications

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***Abstract*—This letter presents a study of human body localization using ultrawideband (UWB) technology. Various base-station configurations, time of arrival, and first peak detection algorithms are used to estimate the position of the body-worn antennas. Localization error as small as 1–2 cm has been achieved using eight base stations, which is comparable to the measurement accuracy obtained by a complex optical motion capture system to determine the absolute displacement error. The localization error obtained is better by a third in comparison to common commercial system based on UWB technology. The results demonstrate that cuboid-shape configuration with four base stations gives slightly low average percentage error (2%–3%) in comparison to Y-shape (4%). However, the Y-shape configuration is more compact and provides setting-up simplicity, which makes it convenient for various applications ranging from healthcare monitoring to entertainment technologies either laboratory-based or in-home.**

***Index Terms*—Localization, motion capture, ultrawideband.**

I. Introduction

MONITORING and classification of human activity using simple and compact body-worn sensors is emerging as an important research and development area. Impulse-radio ultrawideband (IR-UWB) systems provide promising solutions for high-resolution indoor positioning and ranging applications [1]–[3]. UWB meets the key requirements of human localization in terms of low cost, high data rate, easy implementation, robustness toward multipath, and low energy consumption [2], [3].

Commercial UWB localization systems have reported an accuracy of 10–15 cm with an operating range of around 50 m [4]. Three-dimensional (3-D) motion tracking products based upon miniature (MEMS) inertial sensor technology [5] uses a position aiding system (MVN MotionGrid) that is based on UWB technology enabling 5–8 cm positioning accuracy in an area of 20×20 m^2. Higher accuracy has been reported in the literature for indoor UWB positioning systems. Results presented by Zetik *et al.*, Low *et al.*, and Meier *et al.* indicate that UWB technology has the potential to achieve high centimeter and even millimeter accuracy levels for short-range indoor environment localization [4]–[6]. Submillimeter-range accuracy is possible using carrier-based UWB systems as proposed in literature [7].

In this letter, localization of human body movements is studied using sensors on 12 different locations of the upper body. To the best of the authors' knowledge, very limited work is presented in the open literature in the field of localization of body-worn sensors using UWB technology. The experiments were undertaken in an uncluttered indoor environment in which accurate localization of body-worn sensors was performed using a simple, compact, and efficient UWB localization system. The objective of the work is to achieve accurate localization of the body-worn sensors using time-of-arrival (TOA) positioning techniques. The rest of the letter is organized as follows. The localization measurement setup and scenarios are presented in Section II. Section III briefly describes the techniques and algorithms used. The results are analyzed and discussed in Section IV in terms of accuracy achieved, multipath components for different sensor locations on the body, and base-station (BS) configuration setup. Finally, Section V presents a conclusion of the letter.

II. Localization Measurement Setup

Experiments were performed at the motion capture studio at the University of Kent, Canterbury, U.K. [8]. A real human test subject (1.8 m tall and average male build) was used to assess the localizing sensors placed on the body. Twelve sensor locations were chosen, with six at the joints of the arm and six on the torso. The distance between the human body surface and the antenna was around 5 mm. The subject sat on a chair in the center of a 2×2-m^2 area (see Fig. 1). Compact and low-cost tapered coplanar-waveguide-fed UWB antennas (TSAs) (Fig. 2 [9]) were used as transmitters placed on the body and also as receivers in three different configurations (cuboid shape: eight BSs, cuboid shape: four BSs, Y shape: four BSs) [10]. The TSA (size of 27×16 mm^2) had an excellent impedance matching with a return loss better than 10 dB and good radiation performance in the UWB range with relatively constant gain across the whole frequency band [9]. Due to the presence of the lossy human body (with increased conductivity at high frequencies), the antenna front-to-back ratio is significantly increased to 25–30 dB, and the antenna directivity increases by around 5 dB than in the free-space scenario.

Frequency-domain measurements were performed in the 3–10-GHz band. A vector network analyzer (VNA) was used to capture S_{21} (channel transfer function) parameters between

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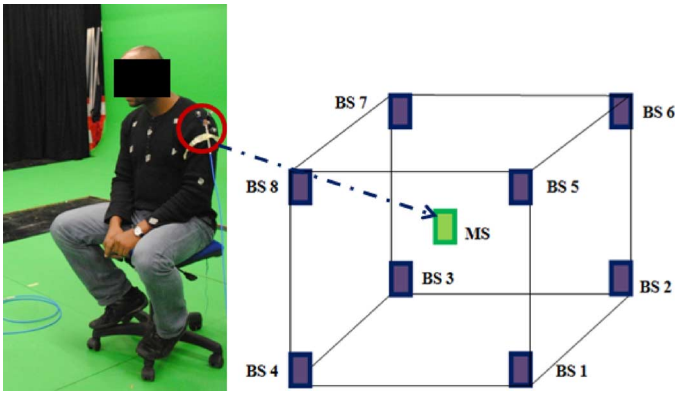

Fig. 1. Human subject sitting with TSA as sensor with three markers placed on left arm. Eight-base-station configuration with sensors placed at the vertices in a $2 \times 2 \times 0.45$-m^3 volume with mobile station (MS) in the center. Four–base-station configuration: BS(1, 6, 3, 8) for cuboid-shape and BS(1, 2, 4, 5) for Y-shape configuration. The subject is facing BS(1, 4, 5, 8), showing higher probability of line-of-sight (LOS) situation between MS–BS link.

(a) (b)

Fig. 2. (a) Tapered slot coplanar UWB antenna used in the 3-D localization measurements and analysis. (b) TSA antennas placed on a plastic base with reflective markers.

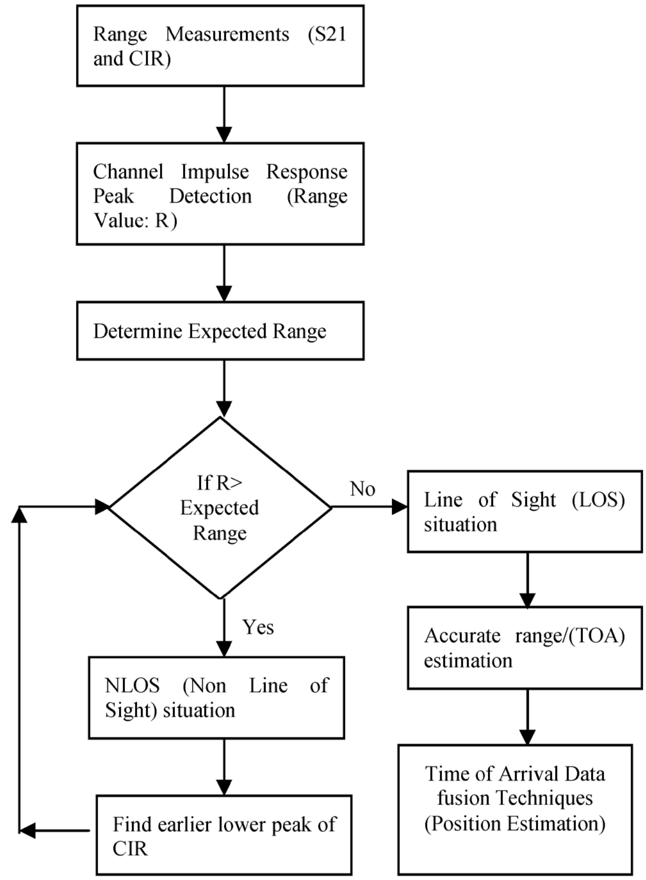

Fig. 3. Proposed localization scheme for UWB localization in realistic environment with multipath and non-line-of-sight (NLOS) situations.

each transmitter antenna location on the body and the receiver antenna. The antennas were mounted on plastic frames with three markers each to allow estimation of position of antennas in 3-D space through the VICON motion capture system [8]. The system consists of eight cameras giving high accuracy in the range of 1–2 cm. The motion capture system was used to compare against the UWB localization results and also to obtain exact coordinates of the base stations (receiver antennas). The channel impulse response was obtained from the S_{21} parameters collected from the VNA for each BS and MS. The ranges were obtained by use of the fast Fourier transform technique and, because of the carrier-less nature of IR UWB systems, the real passband method was applied. Furthermore, the data-fusion time-of-arrival positioning technique was applied to obtain coordinates of the sensor with respect to the reference (BS1).

III. Position Estimation Algorithms

The range-based TOA approach is one of the most suitable approaches for localization in UWB sensor networks because of the high accuracy obtained due to the high time resolution of the applied signals [1], [11]. Fig. 3 shows a flowchart of the proposed localization algorithm that is based on channel impulse response (CIR) and time-of-arrival localization estimation technique. The time of arrival between the mobile and base stations is estimated by CIR and peak detection techniques. First, the S_{21} parameters are measured, and inverse fast Fourier transform is then applied to obtain the channel impulse response of the measured channels. The channel impulse response [11], [12] is given by

$$h(\tau, t) = \sum_{k=1}^{K} a_k(t)\, \delta(\tau - \tau_k) e^{j\theta_k(t)} \tag{1}$$

where δ is the Dirac delta function, K is the number of resolvable multipath components, τ_k are the delays of the multipath components, a_k are the path amplitude values, and θ_k are the path phase values.

The peak detection algorithm gives an estimate of time of arrival of the UWB signal between Tx and Rx. For a LOS situation [Fig. 4(a) and (b)], the TOA is easily estimated by the detection of the strongest peak of the CIR. In situations where the strongest peak does not give an estimate of the expected TOA [as shown in Fig. 4(c) and (d)], threshold-based algorithms such as search-back technique and leading edge detection methods [12], [13] are used to find the expected time of arrival. The search-back method first finds the strongest path (SP), and then looks for a peak arriving before the strongest path that has greater power than a detection threshold level. Few iterations are required in order to obtain the peak value nearest to the expected value or within the localization range based on the selected threshold level. For a situation [Fig. 4(d)] where the expected peak value of the target is quite low (i.e., below

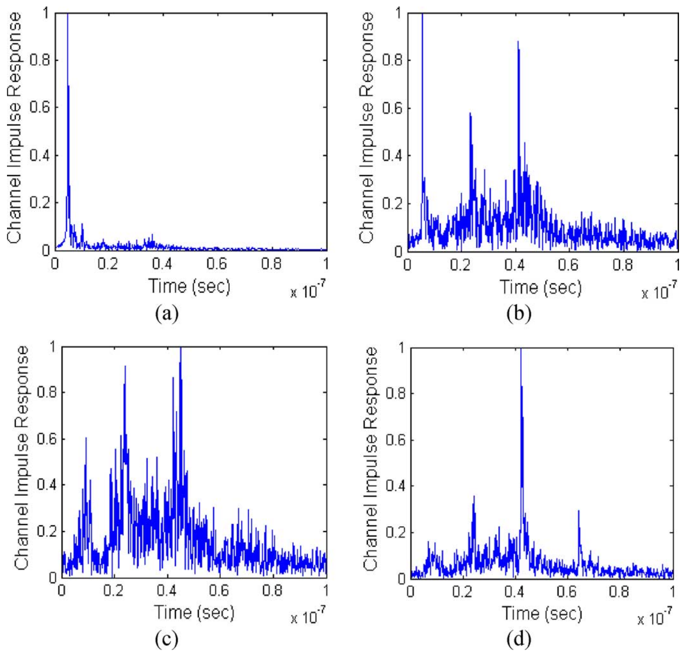

Fig. 4. Different kinds of channel impulse response observed: (a) line-of-sight direct path; (b) line of sight with high multipath; (c) detectable non-line-of-sight path (I); (d) detectable non-line-of-sight path (II).

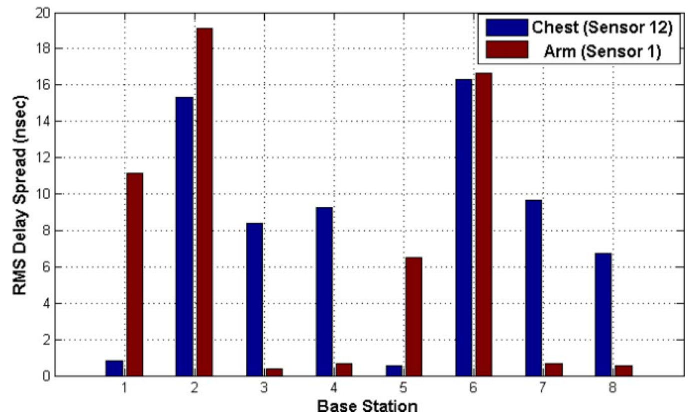

Fig. 5. RMS delay spread for various receiver positions for sensor location 1 placed on right arm and 12 placed on chest.

TABLE I
LOCALIZATION ERROR FOR DIFFERENT BASE-STATION CONFIGURATIONS

Average Localisation Error		
	x axis (cm)	y axis (cm)
8 Base Stations	1.74	2.32
4 Base Stations		
Cuboid shape	2.51	2.82
Y shape	3.72	3.79

20% of the maximum peak magnitude), threshold-based algorithms [12] (e.g., leading edge detection) can be used in order to distinguish between the noise and the information regarding the range values in the channel impulse response measurements. To obtain the expected value of range, study of the environment in which localization is taking place is very important. By obtaining such information, one can discard peaks in the CIR that may be occurring due to presence of objects like reflection from metallic objects in the room, presence of a large solid object in the indoor environment, etc.

Furthermore, the range estimates obtained from all the base stations are used to obtain position of the sensors through time-of-arrival data-fusion technique [14], [15]. Let (x_i, y_i, z_i) represent the position of the ith base station, and r_i is the range value obtained from the TOA measurement. The following four equations are solved jointly by using least-square solution in order to estimate the position of the target (x_m, y_m, z_m) via trilateration:

$$r_i^2 = (x_i - x_m)^2 + (y_i - y_m)^2 + (z_i - z_m)^2 \qquad i = 1, 2, 3, 4. \tag{2}$$

IV. DATA ANALYSIS

Root mean square (RMS) delay spread, which is a measure of delay time extent of multipath channel, is calculated for each BS and MS (body-worn sensor) pair. This gives an estimate of which sensor locations have high multipath leading to higher chances of delay and NLOS situations. As shown in Fig. 5, more multipath is generally observed for the situation when sensors are placed on the chest (e.g., sensor 12) in comparison to the sensors placed on the arm (e.g., sensor 1). The reason for the increase in multipath is due to the fact that the sensors are present on the torso region, which causes interference. Low RMS delay spread is observed for BS1 and BS5 for sensor 12 as it is in the LOS situation with the two base stations. High RMS delay spread is observed for BS2 and BS6 for both the sensor locations mentioned in the graph (sensor 1 and sensor 12), which is attributed to the NLOS situation between the sensor position on the body and the base stations.

Some of the factors affecting localization accuracy are precise estimation of time of arrival between the MS and BS, operating bandwidth, antenna efficiency, and presence of a human body, which acts like an obstacle causing delay and interference. The accuracy of the positioning system also depends on the number of base stations used and the distribution of the base stations. The antennas should have sufficient spacing between each other in order to keep minimum interference and coupling between the antennas. Around 0.5 m distance between the antennas, which is five times the wavelength at the lower frequency in the band (3 GHz), is sufficient.

Table I lists the average localization error achieved for the different base-station configurations studied for finding the unknown positions of the body-worn sensors. The estimated and actual positions of the sensors are shown in Fig. 6 for eight-base-stations configuration, showing high accuracy position estimation.

The calculation showed that there is less error (approximately 1–2 cm) in the estimation of the position of the target when all eight base stations are used for localization of the sensors. The localization error obtained is similar to that of the motion capture system with eight cameras. As the number of base stations is increased, the area under localization is better covered, and also because of the usage of trilateration technique to estimate unknown locations, additional sensors will enhance the

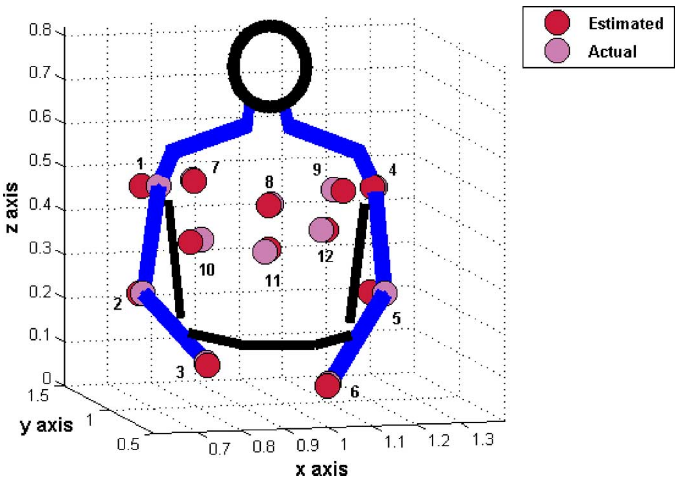

Fig. 6. UWB localization: estimated and actual positions of the sensors placed on the body for eight-base-station configurations.

least-square solution accuracy. For the configurations considering four base stations, the error is increased by 0.5–1 cm for the cuboid-shape configuration. For the Y-shape configuration, which is more compact and easily set up, 1–1.5 cm increase in average error is obtained. This configuration has the substantial advantage of using fewer base stations and requiring less coverage area for localization in comparison to the two other configurations applied.

The accuracy achieved for the different configurations can be analyzed theoretically using geometric dilution of precision [16], which shows the effectiveness of the placement of the base stations. As expected, the average horizontal dilution of precision (HDOP) achieved for the eight-BS configuration is 0.8, which is excellent accuracy. For four-base-station configurations, the average HDOP values achieved are 1.3 and 1.9 for cube- and Y-shape configuration, respectively. All the base-station configurations are in the range of DOP values 1–2, which are considered to give high-accuracy localization results.

V. Conclusion

A comparative study has been made using 12 sensors placed at different locations on the upper body of a human subject in an indoor environment to enable accurate localization of human movements. Sufficiently accurate two-dimensional (2-D) localization with reasonable resolution for the intended application is achieved using a compact and low-cost antenna (TSA). Average localization accuracy as small as 1–2 cm has been achieved, which is comparable to common commercial optical systems. This accuracy reduces by a slight error of 0.5–1 cm for cuboid-shape configuration with four base stations. By confining the base stations into a smaller area such as the Y-shape configuration, the error is increased 1–1.5 cm due to the limited coverage area and also the simplicity of the detection algorithm used. However, the compact setup and cost-effectiveness provide a compromise for the small degradation in detection accuracy and a space for a wider range of laboratory-based and in-home localization applications.

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