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Localization of Wearable Ultra Wideband Antennas for Motion Capture Applications

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Localisation of Wearable Ultra Wideband Antennas for Motion Capture Applications

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***Abstract*—This paper presents a study of human body localisation using Ultra Wideband (UWB) technology. Various base station configurations, time of arrival and first peak detection algorithms are used to estimate the position of body-worn antennas. Localisation error as small as 1-2 cm has been achieved using 8 base stations which is comparable to the measurement accuracy obtained by complex optical motion capture system to determine the absolute displacement error. The localisation 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 4 base stations gives slightly low average percentage error (2 to 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*—Ultra Wideband, Localisation, Motion Capture**

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 Ultra Wideband (IR-UWB) systems provide promising solutions for high resolution indoor positioning and ranging applications [1-3].UWB meets the key requirements of human localisation in terms of low cost, high data rate, easy implementation, robustness towards multipath and low energy consumption [2, 3].

Commercial UWB localisation systems such as Ubisense, Multispectral Solutions Inc, have an accuracy of 10 – 15 cm with an operating range of around 50 m [4]. Xsens offers 3D motion tracking products based upon miniature (MEMS) inertial sensor technology [5]. This motion capture product uses a position aiding system (MVN MotionGrid) that is based on UWB technology enabling 5-8 cm positioning accuracy in an area of 20 X 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 cm and even mm accuracy levels for short range indoor environment localisation [4-6]. Sub-millimetre range accuracy is possible using carrier based UWB systems as proposed in literature [7].

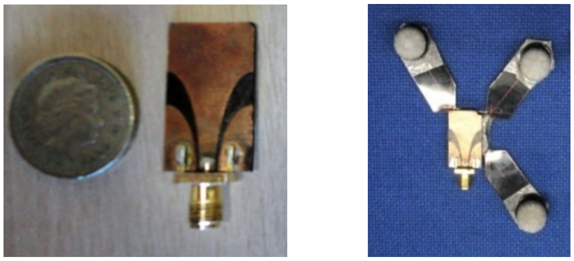
In this paper, localisation of human body movements is studied using sensors on 12 different locations of the upper body. To the best of the authors' knowledge, very limited work is presented in the open literature in the field of localisation of body worn sensors using UWB technology. The experiments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

II. LOCALISATION MEASUREMENT SET UP

Experiments were performed at the motion capture studio at University of Kent, UK [8]. A real human test subject (1.8 m tall and average male built) was used to assess the localising sensors placed on the body. Twelve sensor locations were chosen with 6 at the joints of the arm and 6 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 centre of a 2×2 m^2 area (see Fig. 2). Compact and low cost Tapered co-planar waveguide fed UWB antennas (TSA) (Fig.1 [9]) were used as transmitters placed on the body and also as receivers in three different configurations (Cuboid shape: 8 BS's, Cuboid shape: 4 BS's, Y shape: 4 BS's) [10]. The TSA antenna (size of 27 mm × 16 mm) 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].

Frequency domain measurements were performed in the 3 to 10 GHz band. A vector network analyzer (VNA) was used to capture S_{21} (channel transfer function) parameters between each transmitter antenna location on the body and the receiver antenna. The antennas were mounted on plastic frames with 3 markers each to allow estimation of position of antennas in 3D space through VICON motion capture system [8]. The system consists of 8 cameras giving high accuracy in range of 1 to 2 cm.

The motion capture system was used to compare with the UWB localisation 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 base station (BS) and mobile station (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 pass-band 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).



(a) (b)

Fig. 1.Tapered slot co-planar (a) ultra wideband (UWB) antenna used in the 3D localisation measurements and analysis. (b) TSA antennas placed on a plastic base with reflective markers.

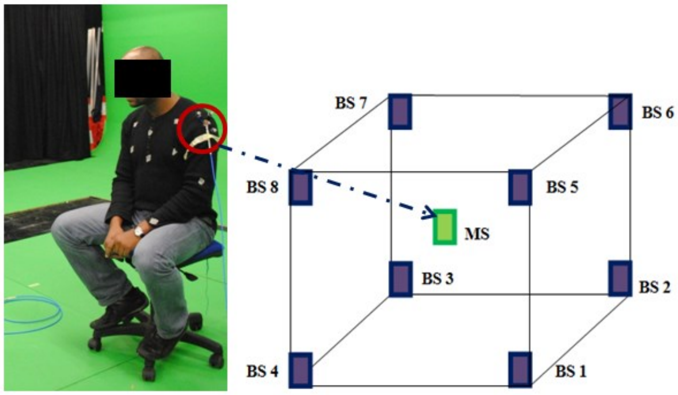

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Fig. 2. Human subject sitting with TSA antenna as sensor with three markers placed on left arm.8 Base Station Configuration with sensors placed at the vertices in a 2×2×0.45 m^3 volume with Mobile Station (MS) in the centre. 4 Base station configuration: BS(1,6,3,8) for cuboid-shape and BS(1,2,4,5) for Y-shape configuration.

III. POSITION ESTIMATION ALGORITHMS

The range-based time of arrival (TOA) approach is one of the most suitable approach for localisation 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 flow chart of the proposed localisation algorithm which is based on Channel Impulse Response (CIR) and time of arrival localisation estimation technique.The time of arrival between the mobile and base stations is estimated by CIR and peak detection techniques. Firstly, 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:

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

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.

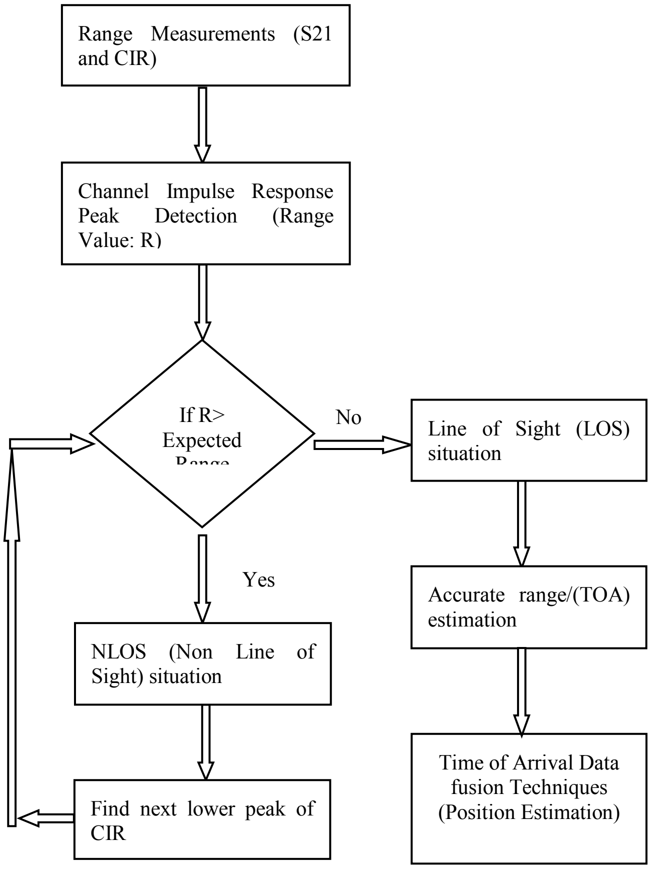
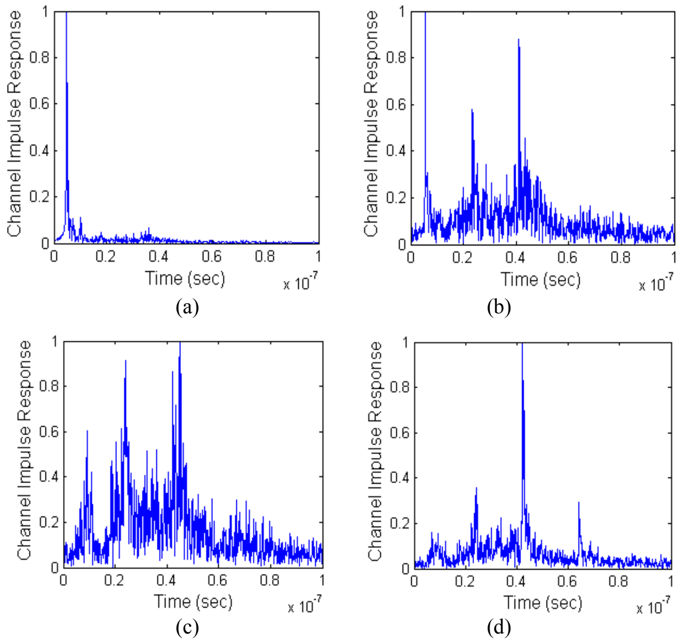


Fig. 3. Proposed localisation scheme for UWB localization in realistic environment with multipath and NLOS situations

The peak detection algorithm gives an estimate of time of arrival of the UWB signal between Tx and Rx. For Line-of-sight (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 which 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 localisation range based on the selected threshold level. For situation of almost undetectable peak (Fig. 4 (d)) where the expected peak value of the target is quite low, 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 localisation is taking place is very important. By obtaining such information one can discard peaks in the CIR which may be occurring due to presence of objects like reflection from metallic object in room, presence of 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 i^{th} 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:

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



(a) (b)

(c) (d)

Fig. 4. Different kind 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)

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 position. 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 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 senor 12) which is attributed to NLOS situation between the sensor position on the body and the base stations.

Some of the factors affecting localisation accuracy are precise estimation of time of arrival between the MS and BS, operating bandwidth, antenna efficiency and presence of 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. Table 1 lists the average localisation 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 8 base-stations configuration showing high accuracy position estimation.

The calculation showed that there is less error (approx. 1 to 2 cm) in the estimation of the position of the target when all 8 base stations are used for localisation of the sensors. The localisation error obtained is similar to that of the motion capture system with 8 cameras. As the number of base stations is increased, the area under localisation is better covered and also because of the usage of trilateration technique to estimate unknown locations, additional sensors will enhance the least square solution accuracy. For the configurations considering 4 base-stations, the error is increased by 0.5 cm to 1 cm for the Cuboid shape configuration. For the Y-shape configuration, which is more compact and easily set-up, 1 to 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 localisation in comparison to the two other configurations applied.

TABLE I.
LOCALISATION 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

The accuracy achieved for the different configurations can be analysed 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 8 BS configuration is 0.8 which is excellent accuracy. For 4 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 to 2 which are considered to give high accuracy localisation results.

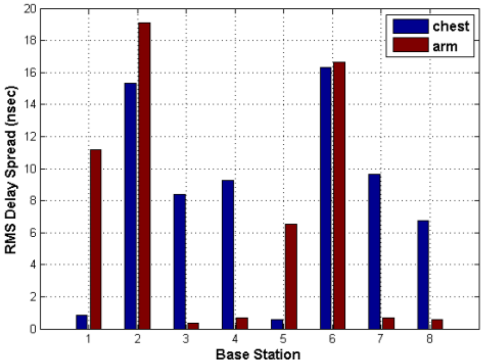


Fig. 5 RMS delay spread for various receiver positions for sensor location 1 placed on right arm and 12 placed on chest.

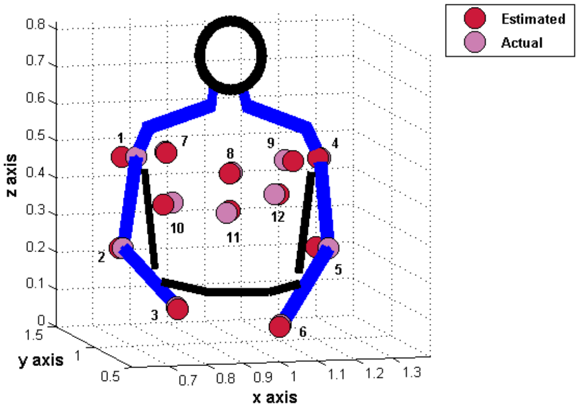


Fig. 6. UWB localisation: Estimated and Actual positions of the sensors placed on the body for 8 base station configurations.

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 localisation of human movements. Sufficiently accurate 2D localisation with reasonable resolution for the intended application is achieved using a compact and low cost antenna (TSA). Average localisation 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 1.5% (0.5 cm to 1 cm) for Cuboid-shape configuration with 4 base stations. By confining the base-stations into a smaller area such as the Y-shape configuration, the error is increased by 2.5% (1 cm to 1.5 cm) due to the limited coverage area and also the simplicity of the detection algorithm used. However, the compact set up 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 localisation applications. Generally, the localisation error obtained is less than a third in comparison to the common available generic commercial systems based on UWB technology.

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