Localisation of Motionless Persons in 3D Space by UWB Radar

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Abstract— In this paper, a new method of motionless person localization in 3-dimensional space (3D) by ultra wideband (UWB) radar will be introduced. The presented approach is based on the application of a multistatic UWB radar using one transmitting and four receiving antennas. The novel localization method is based on the approximation of 3D localization problem by solution of two 2D localization tasks. A proper lay-out of the radar antenna system will be introduced for the considered UWB radar applications. The performance properties of the outlined concept of 3D localization system have been evaluated by the experiments intent on indoor line-of-sight and through-the wall localization of motionless person.

1. INTRODUCTION

The current research in the field of human target positioning by radio frequency devices or sensor networks is focused on two types of tasks. The former is to localize persons in order to determine their position and/or navigate them in a known indoor environment. The solution of this task is represented by indoor positioning systems with a fixed infrastructure of sensors spread over the monitored area. Here, two basic approaches have been considered. In the first case, it is assumed that a person to be tracked (or to be navigated) carries an actively transmitting tag (e.g., [1–4]). In contrast to this approach, the second one consists in a tag-free localization of persons (e.g., [5]) using a sensor network with a fixed allocation of the particular sensors over a monitored area only. The comparison of the outlined approaches has shown that the method based on the active-tag employment can provide the higher accuracy of the target localization than that of tag-free approach.

The latter of the mentioned tasks is to provide a support for the emergency event solving by localization of persons of interest. By emergency events we understand either military, law enforcement and security operations or disasters such as earthquakes, fires or hurricanes. Persons of interest in such cases are, e.g., criminals, hostages or survivors. The nature of the described scenarios implies the use of mobile UWB systems. These systems should be able to detect and localize of human targets without any active tags. Several UWB radars that can potentially be used in such applications have been developed recently [6–9]. Usually, they provide a capability of short-range through-wall localization of human beings in 2-dimensional space (2D). A separate category of system able to localize a person in 3D has been presented by [10]. However, the development of this system is aimed towards applications such as gaming, remote control of household appliances, elderly people monitoring and fall detection.

According to security experts, person positioning under emergence events not only in 2D but also in 3D is needful. Following this demand, this paper is focused on a problem of motionless human being localization by a handheld UWB radar in 3D space.

The motionless target localization is a challenging task, especially in a realistic environment. In this paper, a new method of motionless person localization in 3D will be introduced. The presented approach is based on the application of a multistatic UWB radar using one transmitting and four properly distributed receiving antennas. The novel localization method is based on the approximation of 3D localization problem by solution of two 2-dimensional localization tasks. More precisely, the target localization by a multilateration method is substituted by a double application of a trilateration method.

The paper is organized as follows. In the Section 2, the problem of target localization in 3D based based on a multilateration method is set up. The Section 3 introduces a novel method of target localization in 3D based on time-of-arrival (TOA) estimates and a trilateration method. The performance of the novel approach for motionless human being localization in 3D by a short-range UWB radar is illustrated in the Section 4. Here, the results of person localization for indoor line-of-sight and through-the wall scenarios are presented. Section 5 contains concluding remarks.

2. PROBLEM STATEMENT

Let us assume a single multistatic UWB radar with 1 transmitting antenna Tx and N receiving antennas $Rx_i\,(i = 1, 2, \ldots, N)$ with known positions. The coordinates of the transmitting and receiving antennas will be labeled as $Tx = [x_t, y_t, z_t]$ and $Rx_i = (x_{r,i}, y_{r,i}, z_{r,i})$. The target coordinates, labeled as $T = [x, y, z]$, are unknown.

Let us consider the target localization by the multilateration method using TOA estimates. Let TOA_i be the measured propagation time of the UWB signal transmitted by Tx, reflected by the target T and received by Rx_i. Then, the distance between Tx, unknown target position T and Rx_i can be expressed as

$$d_i = c \cdot TOA_i \quad i = 1, 2, \ldots, N \tag{1}$$

where c is the velocity of the propagation of the electromagnetic waves emitted by the radar. In our consideration, c is set to the electromagnetic wave propagation velocity in air, i.e., $c = 3 \times 10^8\,\mathrm{ms}^{-1}$. The Euclidean distance between the points Tx, T and Rx_i can be expressed as

$$d_i = r_i + e_i = \|Tx, T\| + \|T, Rx_i\| + e_i \quad i = 1, 2, \ldots, N \tag{2}$$

In this expression, the symbol e_i represents the additive noise component expressing the random errors of the TOA estimation.

The distance d_i can also be expressed by means of the antenna and target coordinates as follows:

$$d_i = \sqrt{(x - x_t)^2 + (y - y_t)^2 + (z - z_t)^2} + \sqrt{(x - x_{r,i})^2 + (y - y_{r,i})^2 + (z - z_{r,i})^2} \; i = 1, 2, \ldots, N \tag{3}$$

Then, the target localization problem can be defined as the estimation of the target coordinates, $T = (x, y, z)$, based on a solution of the set of nonlinear Equation (3). As it follows from this equation set, $N = 3$ represents the minimum number of equations and therefore the minimum number of receiving antennas necessary for target localization in 3D. The target localization based on the solution of (3) is usually referred to as the multilateration method.

From the mathematical point of view, each of the Equation (3) defines a rotational ellipsoid with foci placed in Tx and Rx_i positions. To obtain the target position, it is necessary to find an intersection at least of 3 ellipsoids. However, considering that distances d_i are estimated with the measurement errors e_i, such joint intersection does not always exist. Therefore, the TOA based multilateration method cannot be directly used in most real life scenarios.

3. A NOVEL 3D LOCALIZATION METHOD

The number of radar antennas and their lay-out are limited by the expected radar applications. In the scenarios described in this paper, we assume that the radar should be implemented as a small, lightweight device, proper for handheld usage. To be able to operate in real life situations, the radar should utilize small antenna array while providing reliable data about presence and position of persons.

Taking into account the mentioned requirements, we have proposed to use the radar antenna system according to Figs. 1–3. The proposed antenna system consists of one transmitting and four receiving antennas located in the same plane. The receiving antennas are located in the vertex of the square (rectangle), whereas the transmitting antenna is put in the intersection of the diagonals of the same square (rectangle). Such lay-out enables to approximate the 3D localization problem by two 2D localization tasks. This is achieved by processing the signals received by the pair of horizontally placed antennas separately (i.e., independently) from the signals received by the pair of vertically placed antennas. This will produce the estimate of target coordinates $[x, y_1]$ in the plane x-y parallel to the ground as well as the estimate of target coordinates $[y_2, z]$ in the plane y-z perpendicular to the ground.

Summarizing the obtained results, the target coordinates can be estimated as follows:

$$T(x, y, z) = T\left(x, (y_1 + y_2)/2, z\right) \tag{4}$$

4. EXPERIMENTAL RESULTS

The performance of the proposed approach for montionless person localization in 3D is demonstrated by processing of signals acquired by measurements with the multistatic UWB radar. The particular measurements were focused on line-of-sight and through-the-wall localization of tag-free motionless persons. As the radar device, the 4-receiving channel M-sequence UWB radar has been used [7]. The clock frequency of the system is 6.95 GHz, which results in the operational bandwidth of approximatelly DC-3.5 GHz. The M-sequence order is 12, i.e., the impulse response covers 4095 samples regularly spread over 585 ns. This corresponds to an observation window of 585 ns leading to an unambiguous range of about 88 m in free space. In both measurements, horn-type antennas with vertical polarity were used, transmitting antenna placed in the center of "+"-shape.

The radar and target placement and measurement scenario for the line-of-sight measurement are shown in Fig. 1. Target was sitting motionlessly on the last of the series of stairs, in front of the transmitting antenna. The distance from the transmitting antenna to the edge of the stair was 3.75 m. The height of the transmitting antenna was 1.1 m above ground level. The height of the stair on which the target was located was 1.38 m above ground level.

(a) (b)

Figure 1: Line-of-sight scenario: (a) front view, (b) side view of a target and the antenna array setup.

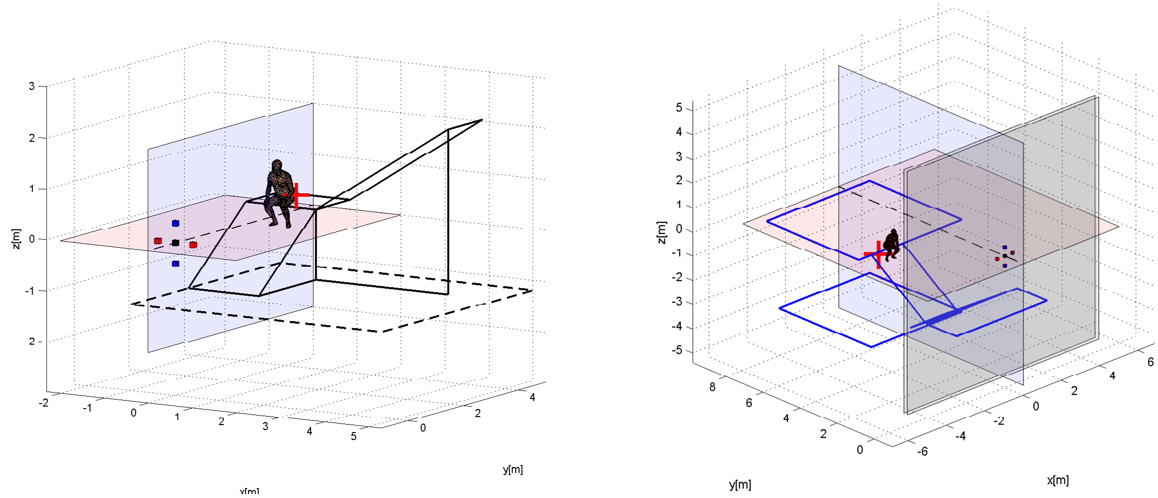
Through-the-wall measurement setup shown in Fig. 2 was very similar to line-of-sight measurement. The radar was placed behind 18 cm thick wall of unknown material. Transmitting antenna was placed 0.77 m above ground level. The target was located in the 4.8 m distance (wall thickness included), shifted 1.5 m to the left side from the radar point of view.

(a) (b)

Figure 2: Through-the-wall scenario: (a) front view, (b) back view of a target and the antenna array setup.

For the TOA estimation corresponding to the particular pairs of $Tx - Rx_i\,(i = 1, 2, 3, 4)$, the procedure of raw radar signal processing consisting of the phases such as background subtraction (exponential averaging method [11]), estimation of the total energy of radar signals with the subtracted background in the frequency band 0.2–0.5 Hz corresponding to human beings breathing (integration method), target detection (CFAR detector application) and TOA estimation based on CFAR detector outputs [12] was used. Then, by using the estimated TOA_i for $i = 1$, 2, 3, 4, the target co-ordinates were finally estimated by the method described in the previous section.

The estimated positions of the target obtained for both scenarios are depicted in Fig. 3 as a red cross. The receiving antennas depicted by the red color were used to obtain the target position estimate in the x-y plane, which is outlined by the transparent red color. On the other hand, the antennas depicted by the blue color were used to compute the target position estimate in the y-z plane, outlined by the transparent blue color. In Fig. 3, the staircase borders and an appropriate



(a) (b)

Figure 3: Experimental results: (a) indoor line-of-sight localization, (b) through-the wall localization.

human body model are also drawn to create a model of measurement environment for the easier visual evaluation of the obtained results.

For the purpose of the evaluation of the localization error, we have defined the mid-point of the human thorax to be the true target position. Then, the difference between the estimated and true target position can be considered to be the target localization error. Taking into account this assumption, we have found that estimation error for the line-of-sight scenario and through-the-wall scenario was about 30 cm and 50 cm, respectively. Taking into consideration the true size of the target and the computational complexity of the novel localization method, it can be concluded that the new method of the motionless person localization in 3D can provide target position with an acceptable accuracy at low computational complexity.

5. CONCLUSION

In this paper, we have presented a simple method of the person localization by using short-range UWB radar in 3D, based on the approximation of 3D localization problem by the solution of two 2D localization tasks. The experiments intent on line-of-sight and through-the-wall localization of motionless persons have proved, that this method provides fairly good estimates of the target position while being of very low computational complexity. This localization method can be used as described, or as a part of more complex method (e.g., to calculate initial condition in localization based on Taylor series).

Although, the theoretical minimum number of receiving antennas for 3D localization is 3, we believe that using 4 receiving antennas can be of great advantage in harsh real life conditions and especially in search for motionless living persons. That is mainly because of the fact, that using a higher number of receiving antennas increases the probability of the true detection of the target. However, in the situations where radar system fails to detect the person presence in data acquired by one of the receiving channels, information from other 3 channels is still sufficient to obtain a rough estimate of the target position by TOA based multilateration method. In the case of failure of two receiving channels, the target position estimate can be still obtained in 2D space.

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