A Joint Localization and Breathing Rate Estimation of Static Persons Using UWB Radar

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Abstract—In the past period, great efforts have been made to develop methods for people detection based on monitoring their respiratory motion using ultra-wide band sensors (radars). The basic principle of these methods consists in the detection of signal components of raw radar data possessing a significant power in the frequency band 0.1 Hz–0.7 Hz (a frequency range of human respiratory rate) for a constant range between the target and radar antennas. In the connection with the localization of people, a new requirement has been appeared. It has been requested not only to localize people, but also to estimate the frequency of their breathing. This finding may indicate health and psychological state of monitored persons. However, the problem of multiple persons localization associated with the estimation of their breathing rate has not been yet studied deeply. In order to fill this gap, a new radar signal processing procedure for a joint localization and breathing rate estimation of persons will be introduced in the paper. The performance of the proposed procedure will be illustrated by an experimental scenario intent on through-the-wall localization and respiratory rate estimation of two static persons using single ultra-wide band sensor employing one transmitting and two receiving antennas.

Keywords—breathing frequency; detection; localization; person; radar; respiration rate; signal processing; UWB sensor

I. INTRODUCTION

In the last decade a great effort has been devoted to the research and development of short-range ultra-wide band (UWB) sensor applications for human being monitoring [2]-[4]. The interest in this UWB radar employment has been motivated by their unique features such as respiration or heartbeat (e.g. [5]). Moreover, the respiratory motion (a form of micro-motion) is the only visible component of respiration that can be applied with an advantage in areas such as e.g. geology, archaeology, non-destructive testing, etc. Among these applications, the detection of unauthorized intrusion [4], for searching for survivors after disasters (e.g. earthquakes, tsunamis, earth slides, building collapses) or as the detectors of emergency events within AAL programs [2].

Because of the outlined features of UWB sensors, it is assumed that these sensors can be used for people monitoring during military and security operations [3], for monitoring of critical environments for the detection of unauthorized intrusion [4], for searching for survivors after disasters (e.g. earthquakes, tsunamis, earth slides, building collapses) or as the detectors of emergency events within AAL programs [2].

In the mentioned applications, different scenarios of person localization have to be solved. To localize people correctly, localization methods should be chosen according to the person movement nature. From this point of view, two basic types of scenarios are referred to as moving and static can be identified [5]. A moving person can be defined as a person moving in such a way that his/her coordinates are changing (e.g. walking persons). On the other hand, a static person is a motionless person situated in the monitored area so that his/her coordinates are not changing (e.g. sleeping persons). Here, the respiratory motion (a form of micro-motion) is the only visible component of the movement. It is well known, that the static persons can be localized based on the detection of their vital signs such as respiration or heartbeat (e.g. [5]). Moreover, in the case of the localization of static human beings at the above mentioned applications, the estimation of their breathing and heartbeat rate could be useful. This finding may indicate health and psychological state of the localized persons.

Motivated by these facts, we will focus on a joint localization and respiratory rate estimation of multiple static persons in this paper. The capability of UWB radar to be used for remote monitoring of patient’s heart activity and respiration has been considered and demonstrated in [6]. Then, the basic idea of the static person detection was introduced e.g. in [7]. A comprehensive description of people localization based on their vital sign detection can be found e.g. in [2]. A method of multiple static persons localization and estimation of their breathing frequency has been proposed in [8]. In this paper, a network of bistatic UWB sensors was used for the static person localization for a line-of-sight scenario.

In contrast to [6]-[8], we will focus on a more complex scenario in this paper. In this contribution, we will deal with a joint localization and breathing frequency estimation of multiple static persons for through-the-wall scenario (i.e. monitoring of persons situated behind a wall) using a single UWB sensor equipped with one transmitting (Tx) and two receiving antennas (Rx). For the solution of that task, we will
introduce a radar signal processing procedure effectively linking methods for static person detection and localization, and power spectrum estimation methods. The performance of the introduced procedure will be illustrated for through-the-wall scenario with two human static targets. The obtained results will show that the proposed procedure allows achieve robust detection and precise localization of human targets simultaneously with a good estimate of their respiration rates.

II. DETECTION OF RESPIRATORY MOTION OF PERSON

Let us consider a problem of static person detection by monostatic UWB radar for a line-of-sight scenario. Let the person be at a distance of $d_0$ from the radar antenna. During the radar performance, its antenna converts the signal $p(t)$ into an electromagnetic wave that is transmitted at the time instant $t$ toward the body of a person. There, it will be partially reflected and travels back to the antenna. The received signal converts the wave back into signal $h(t, \tau)$. Because, a static person is assumed in this scenario, the respiratory motion of the person is the only visible form of his/her movement. Then, a theoretical analysis of this scenario has shown that the raw radar signals can be expressed as follows [2], [10]:

$$h(t, \tau) = \sum_{i=1}^{N} A_i p(t-t_i) + A_0 p(t-t_d(\tau)) + n(t, \tau)$$

$$= h_{on}(t, \tau) + h_{o}(t, \tau) + n(t, \tau)$$

(1)

In this expression, $h(t, \tau)$ represents an impulse response (IR) of the environment, through which the electromagnetic wave is propagated from a transmitting to receiving antenna of the radar. The time variables $\tau$ and $t$ are set for slow-time and fast-time, respectively. It is well known, that the set of these IRs is usually referred to as a radargram. The constants $A_i$ for $i=1,2,\ldots,N$ express amplitudes of the transmitted signal reflected by static objects and received by the radar. On the other hand, the constant $A_0$ represents amplitude of backscattering of a signal from a person. The variable $t_d(\tau)$ is time delay corresponding to a time-of-arrival (TOA) of a monitored person. And finally, $n(t, \tau)$ is a white Gaussian noise due to radar antenna and analogue circuits.

Taking into account the analysed scenario, $t_d(\tau)$ can be expressed as follows

$$t_d(\tau) = 2d(t_0, \tau) / c$$

where $c = 3\times10^8 \text{ms}^{-1}$ is the electromagnetic wave propagation velocity in the air. The term $d(t_0, \tau)$ expresses the exact distance between the radar antennas and the person at the time instant $\tau$. This distance is slowly changing as a result of person breathing. Using the expression (2), a distance of a person from the radar antenna can be estimated as

$$d_0 = ct_0 / 2$$

(3)

Taking into account the meaning of the mentioned quantities, variables and constants, a clutter $h_{on}(t, \tau)$ and the IR component due to a static person denoted as $h_o(t, \tau)$ can be expressed using the following expressions:

$$h_{on}(t, \tau) = \sum_{i=1}^{N} A_i p(t-t_i)$$

$$h_o(t, \tau) = A_0 p(t-t_0) + A_0 p'(t-t_0) \left[ -m_b \sin(2\pi f_b \tau) \right]$$

(4)

(5)

Here, $p'(t)$, $m_b$ and $f_b$ is the first derivative of $p(t)$, the amplitude of the chest motion and a human breathing frequency. The amplitude of the chest motion due to respiration in adults ranges from 0.2 to 0.6 cm. The frequency range of human breathing signal is $B \approx 0.1 \text{Hz}, 0.7 \text{Hz} > 10]$

Taking into account the above mentioned findings, the basic principle of the static person detection can be summarized as follows. As follows from (5), the components of the IR due to person breathing $(h_o(t, \tau))$ can be regarded as periodic signal with the fundamental harmonic $f_b \in B$. Then, a static person can be detected based on the detection of the periodical components of the radargram with a frequency $f_b \in B$ with regards to the slow-time variable $\tau$ for a constant fast-time instant $t = t_0$. If the time instant $t = t_0$ is estimated, then the distance between a person and the radar antenna can be evaluated according (3). Moreover, a respiration rate estimation of a human target can be obtained by the spectrum analyses of the signal $h(t, \tau)$ in the vicinity of the fast-time instant $t = t_0$, i.e. for $t \in (-t_0 - \Delta t, t_0 + \Delta t)$ and $\tau \in 0, \tau_{\max}$. Because the thorax is a part of the human body executing the most significant respiratory movements, the most significant backscatters during a static person monitoring will be due to just the motion of his/her thorax [13]. Because an average size of the human thorax is approximately of $s = 60 \text{cm}$, the distance $Tx$–person thorax–$Rx$ can take on values from the interval $d \in (-ct_0 - s/2, ct_0 + s/2)$. If a person is considered as a single point target, then the expression $ct_0$ represents the distance $Rx$-person-$Tx$. And hence, if $s \approx c\Delta t / 2$, then $\Delta t \approx 1 \text{ns}$.

III. STATIC PERSON LOCALIZATION

The raw radar signal complexity illustrated by (1) and the basic principle of the static person detection outlined in the previous section indicate, that a static person cannot be localized using a simple localization method only, but a complex radar signal processing procedure should be used. A procedure of that kind has been introduced e.g. in [9]. It consists of a set of phases of signal processing such as background subtraction, target echo enhancement, target detection, TOA estimation and TOA association, and target localization, where each phase is implemented by proper methods of signal processing. A detailed description of the procedure and its particular phases can be found in e.g. in [9], [11] and [12]. In the next paragraphs, the mentioned procedure
for multiple static human target localization by UWB sensor equipped with one transmitting (Tx) and two receiving (Rx1, Rx2) antennas will be briefly described.

A. Background Subtraction

As has been shown in the previous section, a raw radar signal consists of a target echo (the IRs components due to static persons), clutter and noise. Unfortunately, the target echo-to-clutter and noise ratio (ECNR) is very low. In order to improve this ratio before the detection phase, a background subtraction is applied for stationary clutter suppression. For this purpose, the exponential averaging method can be used with the advantage [12].

B. Target Echo Enhancement

The ECNR can be improved using not only a background subtraction method but also by methods of low-level target echo enhancement. An interesting approach for such improvement of ECNR has been presented in [13]. Here, the analysis of the IR obtained at monitoring of a static person has shown that the target echo is located within frequency band 0.4–1.4 GHz. Then, range filtering along the fast-time axis by a band-pass filter can be used for a low-level echo enhancement.

As we mentioned in Section II, a static person can be detected based on the detection of the periodical components of the radargram due to person breathing. It is well known that detection of periodic signals in noise depends on ECNR. Therefore, it would be helpful to increase this ratio before the spectrum estimator application. Following this idea, we propose to filter the radargram with the subtracted background by a low-pass or band-pass filter along the slow-time axis. The passband of this filter should be properly selected taking into account the frequency band of human respiratory motion ($B = \langle 0.1 \text{Hz}, 0.7 \text{Hz} \rangle$). In the next, a filter applied for this purpose will be referred to as a slow-time filter.

C. Target Detection

Detection methods analyse the radargram with the subtracted background processed by range and slow-time filters to reach the decision whether a backscatter is present or absent in the analysed radargram. As we have shown in the previous section, the detection of a static person can be based on the identification of the periodical components of the radargram located in the interval $B = \langle 0.2 \text{Hz}, 0.7 \text{Hz} \rangle$ for a constant fast-time instant. A two-stage detector employing this idea has been proposed in [9]. This detector consists of the power-spectrum estimator employing Welch periodogram [14], order statistic constant false alarm rate detector (OS-CFAR) [15] and a simple threshold detector. Because of the complexity of the discussed two-stage detector, its detailed description is beyond this paper, and hence, it will not be presented here. The reader can find its comprehensive description in [11].

D. TOA Estimation and TOA Association

TOA can be defined also as a time interval that electromagnetic waves need to overcome the distance Tx-target-Rx. Then, TOA corresponding to a target can be estimated as the fast-time instant at which a target is detected. The efficient method of TOA estimation referred to as the trace connection method has been introduced in [16]. This algorithm provides not only TOA estimation, but also the association of the received data from both radar receiving channels. Because TOA association provides a deghosting operation as well, it is the key algorithm allowing to localize more than one person. A basic principle and detailed description of the trace connection method are quite complex, and hence, they are beyond of this paper. More details concerning this method can be found e.g. in [16]. The output of TOA estimation and association method is represented by the pairs of TOA associated with the same targets obtained for both Rx of the radar.

E. Target Localization

The aim of the target localization phase is to determine the target coordinates in a defined coordinate system. Because the UWB sensor considered in this section is equipped with one Tx and two Rx, the target coordinates can be obtained using a direct computation method (e.g. [12]) applied to the particular pairs of TOA associated with the same target. The estimates of the target coordinates represent the output of this phase and the final output of the radar signal procedure as well.

IV. RESPIRATION RATE ESTIMATION

A person respiration rate can be estimated using the radargram with the subtracted background processed by range- and slow-time filters. In the next, this data set will be referred to as $h_{be}(t, \tau)$ . Let us assume that TOA of a person to be detected has been estimated as the fast-time instant $t_0$ . Taking into account the fact that a human body represents so-called distributed target, there may be several backscatters due to a human target located in the vicinity of $t_0$ . According to our analyses introduced in Section II, the TOAs corresponding to these backscatters should be located especially within the interval $T_b \in \langle t_0 - \Delta t, t_0 + \Delta t \rangle > \Delta t \approx 1 \text{ns}$ . In the next, the subset of $h_{be}(t, \tau)$ for $t \in T_B$ will be denoted as $h_B(t, \tau)$ . Because $h_{be}(t_k, \tau)$ for a fast-time instant $t = t_k$ represents a row of $h_{be}(t, \tau)$ , $h_B(t, \tau)$ can be considered as a set of the rows of $h_{be}(t, \tau)$ in which a person could be detected.

In order to estimate the person breathing frequency, a power spectrum density (PSD) of each row of $h_B(t, \tau)$ is evaluated using Welch periodogram [14]. Let, the estimated PSD of the row of $h_B(t_k, \tau)$ is denoted as $H_B(t_k, f)$ . Then, the person breathing frequency $f_p(t_k)$ can be obtained as

$$f_p(t_k) = \arg \max_{f \in B} H_B(t_k, f)$$

(i.e. $f_p(t_k)$ is obtained as a dominant frequency component of $H_B(t_k, f)$ in the frequency range of human breathing signal $B$ ). Unfortunately, the ECNR in each row of $h_B(t, \tau)$ may not be high enough to allow a good estimate of the breathing frequency. Taking into account this assumption, it
will be appropriate to choose from the set $h_B(t, \tau)$ those rows that could possess the high ECNR. Let us assume that $h_B(t, \tau)$ is modelled according to (5) as an additive mixture of a harmonic signal and noise. If we assume that the breathing frequency is estimated according to (6), then the peak-to-average power ratio (PAPR) of $H_B(t_k, f)$ can be evaluated as follows

$$PAPR(t_k) = H_B(t_k, f) / \text{rms}^2(H_B(t_k, f))$$

(7)

where $\text{rms}(\cdot)$ is the root mean square operator. Taking into account the relation between ECNR and PAPR for the considered model of $h_B(t_k, \tau)$, as the rows of $h_B(t, \tau)$ appropriate for the breathing frequency estimation can be selected those satisfying the conditions

$$PAPR_n(t_k) = \frac{PAPR(t_k)}{\text{arg max}_{t_1 \in T_B} PAPR(t_k)} \geq \gamma$$

(8)

In this expression, $PAPR_n(t_k)$ and $\gamma \in (0,1)$ are the normalized $PAPR(t_k)$ and a constant threshold, respectively. The threshold $\gamma$ should be set high enough (e.g. $\gamma \geq 0.8$), to get $h_B(t, \tau)$ rows with the appropriate ECNR. Let us consider now, that the set $K = \{h_B(t_1, \tau), \ldots, h_B(t_l, \tau)\}$ consists of the rows of $h_B(t, \tau)$ satisfying (8). Then, the final estimate of the person breathing frequency denoted as $f_b^*$ can be obtained as

$$f_b^* = \text{arg max}_{f \in B} H_K(f)$$

(9)

where $H_K(f)$ is a new Welch periodogram evaluated using the set of $h_B(t, \tau)$ rows denoted as $K$.

V. EXPERIMENTAL RESULTS

The performance of the proposed approach for the joint localization and respiratory rate estimation of static persons has been tested experimentally for through-the-wall scenario with two static human targets. The measurement scheme is shown in Fig. 1. The monitored area was represented by a school canteen. The UWB sensor was situated behind a brick wall of thickness 0.35 m. The targets were represented by two persons sitting on chairs at the positions P1 and P2 (Fig. 1). The length measurement was about 35s.

The raw radar data were acquired by M-sequence UWB radar system equipped with one $Tx$ and two $Rx$ antennas [1]. The system clock frequency of the radar device is about 4.5 GHz, which results in the operational bandwidth of about DC-2.25 GHz. The order of the M-sequence emitted by the radar is 9, i.e., the IR covers 511 samples regularly spread over 114 ns. This corresponds to an observation window of 114 ns, leading to an unambiguous range of about 17 m. In our measurement, the rate of measurement was 22.4 IR per second. The total power transmitted by the particular radars was about 1 mW.

Some partial results of the proposed procedure of signal processing illustrating the process of the person localization and the final results as well are given in Fig. 2 -Fig. 7. Firstly, the radargrams with the subtracted background are shown in Fig. 2. Then, radargrams processed by the slow-time filter (a band-pass filter with cut off frequencies 0.1Hz and 0.7Hz was applied) are depicted in Fig. 3. Here, it can be seen that the target located on the position P2 is clearly visible. On the other hand, the target on the position P1 is not well-visible in Fig. 2 and Fig. 4. It could be due to the environment properties and the antenna pattern. The similar results can be seen in Fig. 4, where the PSD estimates for each row of $h_B(t, \tau)$ are presented. In these figures, two significant signal components with the frequencies 0.33 Hz and 0.26 Hz can be seen. The input signals of the OS-CFAR detector are successfully eliminated within TOA association process using the trace connection methods [16]. And finally, the true and estimated positions of the targets including a sketch of the target tolerance area (red circle with the radius of 35 cm) are given in Fig. 7. Because a person is not a point but a distributed target with a non-zero size, the tolerance area is used to illustrate the accuracy of the target localization. It can be seen from the Fig. 7 that the both persons were localized within their tolerance areas what confirms the good performance of the proposed methods of the static person localization.

Some quantities and signals illustrating the process of the person breathing frequency estimation are shown in Fig. 8 and Fig. 9. Firstly, $PAPR_n(t_k)$ for $Rx1$ is given in Fig.8. Then, in Fig. 9, the rows of $h_B(t, \tau)$ and $H_B(t, f)$ selected for the different PAPR and TOA are presented. This figure illustrates very clearly, that the rows $h_B(t, \tau)$ with higher value of PAPR are more appropriate for breathing frequency estimation than those with smaller value of PAPR. Finally, Welch periodograms $H_K(f)$ for the 1st person (for $Rx1$ and $Rx2$) are drawn in Fig. 10. The values of the person breathing frequencies estimated using $H_K(f)$ and (8) are given in Fig. 7.
The reference measurements of the breathing frequencies of both targets were done indirectly using laser rangefinders with the range resolution 0.1 mm. The signal measured by the laser rangefinder is given in Fig. 11. The time-variations of this signal express the time changes of the distance between the person and the laser rangefinders due to the breathing. The time-waveform of this signal clearly indicate that it contains a periodical component. This conclusion is also confirmed by its PSD (Fig. 11). The frequency of this periodical component can be estimated as a frequency corresponding to the maximum value of the computed PSD. This frequency is also equal to the frequency of the respiratory motion of the monitored person. Then, using the outlined approach, we found that the breathing frequencies of the persons at the positions P1 and P2 are 0.25 Hz and 0.33 Hz, respectively. A comparison of the person breathing frequencies estimated by UWB sensor and by the laser rangefinders have shown, that the application of UWB sensor can provide a good accuracy of the breathing frequency estimation.

VI. CONCLUSION

In this paper we have dealt with the problem of localization and breathing rate estimation of static persons. Following state-of-the-art focused on the studied problem, we introduced a novel efficient method for a joint localization and respiratory
rate estimation of static persons. The experimental results have confirmed its good performance properties. Key engineering contribution of this work we can see in a possibility to apply the proposed solution also for challenging and complex scenarios such as monitoring of multiple human targets situated behind non-metallic obstacles.

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