UWB Radar Based Localization of a Person Changing the Nature of Their Motion State

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Abstract—In the last decade, it has been shown that short-range ultra-wide band radars can provide the efficient solution to tag-free person localization for line-of-sight and non-line-of-sight scenarios. To localize people correctly using this technology, the corresponding detection methods have to be selected according to the nature of person motion state. On the other hand, people monitored in the case of real-life scenarios are moving by different styles, which are usually changing. It results in the need to develop complex radar signal processing methods allowing to detect and localize people moving with changing the nature of their motion state. Motivated by this finding, we will deal with the problem of person localization for such scenarios in this paper. Firstly, we will introduce a helpful classification of persons according to the character of their motion states. Then, using this classification and already known radar signal processing procedures for moving and static person localization, we will develop a novel concept of radar signal processing procedure for UWB localization of a person changing the nature of their motion state. A finally, good features of this concept will be demonstrated by its application for through-the-wall localization of a single person moving with a short and long stops.

I. INTRODUCTION

In the last years, great efforts have been made to develop methods for the localization of tag-free persons [1], [2]. It has been shown, that for that purpose, ultra-wideband (UWB) sensors (radars) operating in the frequency band DC-5 GHz can be used with advantage. Electromagnetic waves occupying such frequency band can penetrate through most non-metallic materials with a small enough attenuation, and hence persons located behind such obstacles can be detected. On the other hand, due to the employment of the ultra-wide bandwidth, UWB sensors can provide fine range resolution, and hence a high accuracy of the target localization as well [2].

Due to these properties, UWB sensors can be applied with advantage for the person detection and localization e.g. at rescue and security operations, for the critical infrastructures monitoring, for the elderly people monitoring within ambient assisted living programs, for baby monitoring focused on the detection of sudden death syndrome, etc.

In the past, two fundamental approaches for the human beings localization have been studied. The former is intent on the localization of so-called moving persons (MP), i.e. persons moving within the monitored area in such a way, that their coordinates are changing. The latter approach is devoted to the localization of so-called static persons (SP), i.e. persons situated, but not moving (e.g. unconscious persons) within the monitored area (i.e. their coordinates are not changing). Respiration or heart beating could be given as examples of the motion activities of SP. As the result of these studies whole range of methods, algorithms and complex solutions designed to locate either MP or SP have been developed e.g. in [3], [4].

But in the case of real-life scenarios, persons to be located are usually neither perfectly moving nor perfectly static ones. Here, a person walking with short stops, a staying but gesturing person, a sleeping person changing its position, can be given as examples. In addition, the scenarios being analysed could be more complicated if there are more than one person with different kinds of their motions. These real-life scenarios indicate that there is a request for the localization of persons changing the nature of their movements. According to our best knowledge, there are only two papers [5], [6] focused on this problem. The concept of the localization of persons changing the nature of their movement introduced in these papers (in the next "basic concept") consists in the simultaneous application of signal processing method for MP localization and method for SP localization. Then, the results obtained by both methods are simultaneously mapped into the same information space (e.g. a picture visualizing the actual state within the monitored area). Unfortunately, the concept of person localization according to [5], [6] does not solve satisfactorily some specific but often occurring situations that may arise in real-life scenario. For example, the detection and localization of a person walking or running with short stops cannot be successfully processed by the basic concept. Motivated by that fact, we will propose in this paper a new modification of radar signal processing procedure for the detection and localization of a person changing the nature of their movement. Unlike the basic concept, this new approach is capable to detect and localize MP and SP as well as a person moving with short stops. For this purpose, a variance of radargram with subtracted background evaluated along the fast-time-axis will be applied as the indicator of a stop of MP.

This paper is organized as follows. In Section II, a new concept of the localization of a person changing the nature of their motion will be firstly introduced. The core of this concept will consist in the application of radar signal processing procedures for MP and SP localization including a new algorithm applied for detection of a person motion. Some experimental results illustrating the performance of the proposed localization approach will be shown in Section III.
II. A NEW CONCEPT OF PERSON LOCALIZATION

The analyses of the detection and localization of human beings by means of UWB sensors have shown that the fundamental solution of this problem depends on the character of the motion of persons to be detected and localized (e.g. [3]–[6]). The results of the analyses are summarized in Table I. This table suggests a classification of the person types according to the character of their motion and provides a description of the particular kinds of movement. Moreover, motion examples corresponding to the particular types of persons are given in this table too.

Before we will start discussing the problem of detecting people classified by Table I, it will be useful to define the term an observation time interval. An observation time interval associated with the observation time instant \( \tau \) is defined as the interval \( (\tau - \Delta T_{SP}, \tau) \). Then, the length of this interval is \( \Delta T_{SP} \). The importance of this notion will be shown later.

In the next, we will assume that raw radar signals (data) are represented by a set of the impulse responses of the environment through which the electromagnetic waves emitted by the radar are propagated from transmitting to receiving radar antenna. This set of impulse responses is usually referred to as radargram. In this paper, the radargram will be denoted as \( h(t, \tau) \), where \( t \) and \( \tau \) are set for propagation time (fast-time) and observation time (slow-time), respectively. Moreover, sampling periods along the axes \( t \) and \( \tau \) will be denoted as \( t_S \) and \( \tau_S \), respectively.

Now, we can return to Table I and to discuss basic principles of the detection of persons of the particular categories shown in this table. Following the papers [5], [6] and Table I, a new concept of localization of the person changing the nature of its motion state can be summarized as follows:

1) For the detection and localization of MP-I and MP-II, the radar signal processing procedure for moving person detection, localization and tracking (MPL) introduced in [3] can be used. MPL consists of the set of five basic signal processing phases such as background subtraction, target detection, TOA estimation and target localization. For the implementation of these phases, exponential averaging method (background subtraction phase), band-pass filtering along the fast-time axis and low-pass filtering along slow-time axis (target echo enhancement), trace connection method (TOA estimation phase) and direct computation method (localization phase) are recommended. For the detection, two-stage detector consisting of power spectrum estimator (implemented e.g. by Welch periodogram), OS-CFAR detector and simple threshold detector can be applied. The deeper discussion and description of MPL is also behind this paper. The additional information concerning this topic can be found e.g. in [4].

A basic principle of SPL consists usually in the detection of the person’s respiratory motion. It is well-known (e.g. [7], [8]), that depending on the age, health and a mental condition of the person, the frequency of its respiration motion takes the value from the interval \((0.2 \text{ Hz}, 0.7 \text{ Hz})\), whereby the pick-to-pick value of the chest motion due to the respiration in adults is about 0.4-1.2 cm. If we ignore for a moment the small changes between the person chest and antenna array of the radar system due to the breathing, then the bistatic range of the person and radar system (i.e. the distance transmitting antenna-person-receiving antenna) can be considered as the constant one.

Then, SP can be detected based on the identification of periodical components of the radargram with subtracted background with the fundamental harmonic component from the interval \((0.2 \text{ Hz}, 0.7 \text{ Hz})\) for a constant instant of the propagation time \( t = t_0 \). Then, the target bistatic range is \( d_0 = c.t_0 \), where \( c = 3.10^8 \text{ ms}^{-1} \) is the velocity of the electromagnetic wave propagation in the air.

It is well-known, that for the signal power spectrum estimation, a sufficiently long record of the analysed signal has to be used. In the case of periodical signals, there is a rule of thumb, according to which if the period of an analysed signal is \( T_p \), then for its power spectrum estimation, a record of the signal with the length of \( 10T_p \) should be employed. Because the fundamental harmonic of the human respiratory motion is usually from interval \((1.4 \text{ s}, 5.8 \text{ s})\), then for the detection of respiratory motion, the components of the radargram \( h(t_0, \tau) \) gathered during observation time interval \((\tau - \Delta T_{SP}, \tau)\) for \( \Delta T_{SP} = 50 \text{ s} \) should be used. Our practical experiences with SPL based on Welch periodogram application for radargram power spectrum estimation have shown that \( \Delta T_{SP} = 30 \text{ s} \)
is usually sufficient for SP detection. Unfortunately, if \( \Delta T_{SP} < 30 \text{ s} \) then the target probability detection is decreasing rapidly.

3) Let us consider detection and localization of MP-SP-I and MP-SP-II. The method of determining the position of the person depends on whether the person is detected at the time of observation \( \tau \) as MP or SP. If the person to be detected in the observation time \( \tau \) is in the role of MP, he/she can be detected and localized by MPL. If the person to be detected in the observation time \( \tau \) is in the role of SP and \( \Delta T_{SP} > 30 \text{ s} \) (MP-SP-II), he/she can be detected and localized by SPL. On the other hand, if the person to be detected in the observation time \( \tau \) is in the role of SP and \( \Delta T_{SP} \leq 30 \text{ s} \) (MP-SP-I), the person in the role of SP will be neither detected by SPL nor by MPL. Then, in order to get some estimate of the position of this person, we can employ the following procedure. Firstly, the time instant of the stopping of the person will be found. Then, the person coordinates at the time instants of the person stopping will be computed by MPL. In the next time instants, the person is in the role of SP, but their coordinates will be those obtained in the time instant of the person stopping.

4) If no MP or SP is detected, then the monitored area is empty.

Because it is not usually known a priori if MP or SP is located in the monitored area, the algorithm described below can be used to determine whether a person is moving or static at the observation time instant \( \tau \). According to this finding, MPL or SPL should be used for the person localization. In the case of target detection at the observation time instant \( \tau \), the raw radar signals at least from the observation time interval \( \langle \tau - \Delta T_{MP}, \tau \rangle \) and \( \langle \tau - \Delta T_{SP}, \tau \rangle \) can be processed for MP and SP detection and localization, respectively.

As follows from the outlined approach for handling detection and localization of MP and SP, an algorithm for detection of a motion has to be used. For that purpose, the monitoring of the variance \( \sigma^2(\tau) \) of the impulse responses for the particular observation time instants \( \tau \) can be employed. The mentioned variance can be estimated for the every observation time instant \( \tau = \tau_0 \) as

\[
\sigma^2(\tau_0) = E \left\{ \left[ h_b(t, \tau_0) - h_b(t, \tau_0) \right]^2 \right\},
\]

where \( h_b(t, \tau_0) \) is a component of the radargram with subtracted background and

\[
h_b(t, \tau_0) = E \left\{ h_b(t, \tau_0) \right\}
\]

is the mean of \( h_b(t, \tau_0) \) for the constant time instant of the observation time \( \tau_0 \). It will be shown in the next section that \( \sigma^2(\tau) \) possesses the following useful property. If MP is presented in the monitored area in the observation time instant \( \tau = \tau_0 \), then \( \sigma^2(\tau_0) \) is relatively high. On the other hand, if \( \sigma^2(\tau_0) \) is relatively small, then no MP is located in the monitored area in the observation time instant \( \tau = \tau_0 \). From the above is obvious, that \( \sigma^2(\tau) \) could be employed to detect the presence or absence of MP in the monitored area. For that purpose, the following simple algorithm can be used.

Firstly, the variance \( \sigma^2(\tau) \) of the impulse responses for the particular observation time instants \( \tau = \tau_0 \) is estimated according to (1). As it will be shown in the next section, the variance \( \sigma^2(\tau_0) \) consists not only of a slowly changing DC component, but also of some random components. In order to smooth \( \sigma^2(\tau) \), the variance estimated by (1) is filtered by median filter, what is expressed as follows:

\[
\sigma^2_{F}(\tau) = \text{filter} \left( \sigma^2(\tau) \right).
\]

Now, let us define a variance range as

\[
\Delta \sigma^2_F = \max_{\tau} \{ \sigma^2_{F}(\tau) \} - \min_{\tau} \{ \sigma^2_{F}(\tau) \}. \tag{2}
\]

Then MP is detected in the monitored area at the observation time instant \( \tau_0 \), if

\[
\sigma^2_{F}(\tau_0) \geq 0.05 \Delta \sigma^2_F. \tag{3}
\]

On the other hand, if

\[
\sigma^2_{F}(\tau_0) < 0.05 \Delta \sigma^2_F, \tag{4}
\]

then no MP is located in the monitored area in the observation time instant \( \tau_0 \). Note that the threshold used in (3) and (4) is set to 5% of the variation range given by (2).

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**Table I: A classification of the person types according to the character of their motions.**

<table>
<thead>
<tr>
<th>Person type</th>
<th>Description of person motion character</th>
<th>Example</th>
</tr>
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<tbody>
<tr>
<td>1. Moving person I (MP-I)</td>
<td>Person is continuously moving within the monitored area in such a way that their coordinates are changing.</td>
<td>Walking, running or crawling person.</td>
</tr>
<tr>
<td>2. Moving person II (MP-II)</td>
<td>Not motionless person but their coordinates are not changing. Person is still on the same place, but their limbs (legs, hands, head) or trunk are in motion.</td>
<td>Person swinging their arms.</td>
</tr>
<tr>
<td>3. Static person (SP)</td>
<td>&quot;Motionless&quot; person situated in the monitored area. Person’s respiration motions are the only visible form of their movement. Their coordinates are not changing.</td>
<td>Sleeping person, unconscious person.</td>
</tr>
<tr>
<td>4. Person changing nature of their movement I (MP-SP-I)</td>
<td>The same person may be once regarded as MP and once again as SP. Person is continuously in the role of SP over an observation time interval with the length ( \Delta T_{MP} \leq 30 \text{ s} ).</td>
<td>Person walking with a stop/stops. The duration of the stop (in the next referred to as ( T_{SP} )) is maximally 30 s. (i.e. ( T_{SP} \leq 30 \text{ s} ).</td>
</tr>
<tr>
<td>5. Person changing nature of their movement II (MP-SP-II)</td>
<td>The same person may be once regarded as MP and once again as SP. Person is continuously in the role of SP over an observation time interval with the length ( \Delta T_{SP} &gt; 30 \text{ s} ).</td>
<td>The duration of a stop is minimally 30 s (i.e. ( T_{SP} &gt; 30 \text{ s} ).</td>
</tr>
</tbody>
</table>
| 6. Empty monitored area | There is no person in the monitored area. | Empty room.
If MP is detected by (3) for every observation time instants \( \tau \), then MPL should be used for person localization during the whole observation time. If SP is detected by (4) for every observation time instants \( \tau \), then SPL should be used for person localization during the whole observation time. And vice versa, by comparing the equations (3) and (4), the areas where the person is moving or static can be determined. According to the detected of the person motion, MPL or SPL will be applied in these stated areas.

The method of person localization described in the paragraphs 1) - 4) combined with the algorithm for detection of person motion will be referred as radar signal processing procedure for localization of person changing the nature of their motion state. In the next section, some experimental results illustrating the performance of the proposed localization approach will be shown.

### III. EXPERIMENTAL RESULTS

The performance of the introduced procedure of radar signal processing for person localization has been experimentally tested for through-the-wall localization of a single person (in the next “experimental scenario”). The measurement scheme is shown in Fig. 1. The particular positions of the person to be localized within the experimental scenario can be divided into following nine phases:

A The person entered the empty room through the position P11.
B The person walked along the trajectory P11-P10-P9-P6-P1-P3-P5.
C The person was sitting on a chair situated at the position P5 for about 30 s.
D The person stood up. Then the person walked along the positions P5-P8-P9-P10-P11. Finally, the person left the monitored area through the position P11.
E The monitored area was remaining empty for about 10 s. Then the person entered again the empty room through the position P11. Then the person walked along the trajectory P11-P10-P9-P8-P5. At the position P5 the person sat on the chair.
F The person was sitting on the chair (position P5) for 30 s.
G The person stood up and then walked along the trajectory P5-P8-P9-P10-P11.
H The person left the monitored area through the position P11.
I The target (person) was monitored by the M-sequence UWB radar system equipped with one transmitting antenna (Tx) and two receiving antennas (Rx). The parameters of the radar are stated in Table II. The radar system was situated behind a brick wall of thickness 0.5 m. The total measurement time was 115 s.

The particular positions of the person were estimated by the methods described in Section II. At the beginning, the algorithm for the detection of person motion was used. In Fig. 2 the radargram with subtracted background for the first Rx is given (the similar results can be achieved for the second Rx). The variance \( \sigma^2(\tau) \) of the particular impulse responses computed by (1) is also depicted here. It is clearly visible from Fig. 2, that the values of the variance are relative high, if the person was moving. On the other side, the values of the variance are relatively small, if the person was sitting on the chair or was outside of the monitored area. In Fig. 3, the variance \( \sigma^2(\tau) \), the smoothed variance filtered by median filter \( \sigma^2_{\text{med}}(\tau) \) and the treshold \( 0.05\Delta \sigma^2_{\text{med}} \) are depicted. By comparing the filtered variance and threshold for every observation time instant \( \tau \), eight changes in motion of the person were found. Based on these changes in motion of the person, nine areas were stated (Fig. 4). These stated areas (denoted from A to I) corresponds to the areas in which the monitored person performed the different character of movement A-I described at the beginning of this section. In these areas a person performed the same motion character. Further signal processing for person localization was different in these individual stated areas A-I.

Depending on whether the person was detected by the algorithm for the detection of person motion in the investigated area as MP, their positions were localized by MPL. On the contrary, when no MP was located in the stated area and the time interval of the investigated area was at least \( T_S > 30 \, \text{s} \),
then SPL was performed.

The final target coordinates estimated by MPL or SPL are depicted in Fig. 5. Area A corresponding to the movement phase A has no estimated target coordinates. Here, no MP or SP was detected. In the areas B, D, F and H corresponding to the movement phases B, D, F and H was MP detected, respectively (Fig. 5(b), 5(d), 5(f) and 5(h)). By MPL estimated target trajectories depicted by red circles correspond to the true target trajectories quite well. In the areas C and G corresponding to the movement phases C and G SP was detected and their positions depicted by blue crosses were estimated by SPL, respectively (Fig. 5(c), 5(g)). Both estimated positions are near to the true target positions (green crosses) and inside the tolerance area (black circles). In the areas E and I corresponding to the movement phases E and I no MP was detected. Because the time interval of the investigated area was less than 30 s the position of the person was estimated by MPL at the time instant of the person stopping (Fig. 5(e), 5(i)).

IV. Conclusion

In this paper, we have dealt with the UWB radar signal processing procedure for the localization of a person moving with the changing nature of their motion. Based on analysis of the problem of person detection under such scenario, we have introduced a novel approach for person localization. The proposed solution is based on the combination of MPL and SPL supplemented with the algorithm allowing to detect of person motion. The core of this algorithm consists in the determination of the variance of radargram with subtracted background along fast-time axis. The experimental results obtained for through-the-wall localization of a single person summarized in Fig. 5 indicate, that the proposed solution could be a good candidate for the localization of person moving with the changing nature of their motion.

As is shown in Fig. 4, the algorithm of person motion detection can be very helpful to illustrate the problem of detection of a person moving with the changing nature of their motion. The deeper analyses of the algorithm allowing to detect the person motion based on the determination of the variance has shown, that this algorithm can provide good and robust performance only in the case of a single person localization. Unfortunately, this algorithm in the presented form cannot be applied in the case of multiple person localization. In such scenarios, a new algorithm for person moving detection has to be used. Such algorithm can be created by a combination of a modification of multiple target tracking system with algorithm of associating the results of MPL and SPL. Here, the modification of multiple target tracking system should be focused on the algorithm responsible for target tracks maintenance. On the other hand, the mentioned associating algorithm should solve the problem point-to track-association where the particular points and tracks are represented by the results provided by MPL and SPL, respectively. A detail solution of this task will be studied within our follow up research.

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Figure 5: Partial tracking results according to the person movement: (a) area A (empty room), (b) area B (MP - trajectory estimated by MPL), (c) area C (SP - position estimated by SPL), (d) area D (MP - trajectory estimated by MPL), (e) area E (SP - position estimated by MPL at the time instant of the stopping), (f) area F (MP - trajectory estimated by MPL), (g) area G (SP - position estimated by SPL), (h) area H (MP - trajectory estimated by MPL), (i) area I (SP - position estimated by MPL at the time instant of stopping). Estimated target trajectories are depicted by red circles for MP or blue crosses for SP.