Taylor Series-based Tracking Algorithm for Through-Wall Tracking of a Moving Person

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Abstract: Target tracking using time of arrival measurements belongs to the primary tasks solved within radar signal processing. In this paper, the Taylor series-based tracking algorithm that uses time of arrival measurements for through wall tracking of the moving target is introduced. The proposed algorithm is derived from the Taylor series method applied for target localization. In contrast to the Taylor series method, the Taylor series-based tracking algorithm exploits for target positioning not only actual time of arrival measurements, but also the target position estimated in the previous time instant. In order to improve the tracking ability of the proposed algorithm, a suitable weighting of the input data of the algorithm is applied. The performance of the Taylor series-based tracking algorithm will be compared with the performance of the direct calculation method and linear Kalman filtering. For that purpose, two real scenarios of through wall tracking of a moving person will be analysed. The obtained results will show very clearly that the new Taylor series based tracking algorithm introduced in this paper can provide the better estimate of the target trajectory than the other tested localization and tracking algorithms.

Keywords: localization, target tracking, Taylor series, TOA, UWB radar system

1 Introduction

Electromagnetic waves occupying the spectral band below 4-5 GHz show reasonable penetration through most typical building materials, such as brick, wood, dry wall, concrete and reinforced concrete. This electromagnetic wave penetration property can be exploited with advantage by UWB radar systems operating in this frequency band for through wall detection and tracking of moving and breathing persons [3]. There are a number of practical applications where such radar systems can be very helpful, e.g. for through wall tracking of moving people during security operations, through wall imaging during fire, through rubble localization of trapped people following an emergency (e.g.

earthquake or explosion) or through snow detection of trapped people after an avalanche, etc. [3], [7].

Moving target tracking, i.e. determining target coordinates as the continuous function of the time, is a complex process that includes four phases [10]: target detection, the distance estimation between transmitting antenna (*Tx*), target (*T*) and receiving antenna (*Rx*), target localization and finally, tracking itself. The decision of whether the target is or is not present in a scanned area is the detection phase output. If some target is detected, the distance between *Tx*, *T* and *Rx* can be estimated. For that purpose, the measurement of the time of arrival (TOA) corresponding to the target to be tracked and electromagnetic wave propagation velocity between *Tx*, *T* and *Rx* can be used [1]. If the radar system is equipped with more than one receiving antennas, the target position can be estimated by using the suitable localization algorithm exploiting distances between *Tx*, *T* and *Rx* [12], [13]. Tracking is the last phase of the radar signal processing. Target tracking provides a new estimation of the target position based on the actual and foregoing estimations of the target positions. Usually, the target tracking will result in the target trajectory estimation error decreasing, including the smoothing of the target trajectory obtained as the localization phase output.

In the case of through wall tracking of moving targets, the estimation of the moving target position obtained by the localization phase is usually characterized by large estimation error (e.g. [10]). This effect is due to the extremely small power of signals scattered by the moving target and subsequently received by *Rx*, by the increased attenuation of the power of the electromagnetic waves at their transmission through the wall, and at the same time, by the complex and strong clutter due to multiple reflections of the electromagnetic waves emitted by the radar system from static objects located within the scanned area. With regard to these effects, target tracking algorithms must be applied in order to get moving target position estimation with acceptable error.

There are two basic approaches how to track a moving target. The former consists of localization followed by tracking itself. The target locations estimated in consecutive time instants create the target trajectory. Here, several iterative and non-iterative methods can be applied for the target localization [12], [13], [14]. On the other hand, most tracking systems utilize a number of basic and advanced modifications of Kalman filters, such as linear, extended and unscented Kalman filters [6]. In addition to Kalman filter theory, further methods of target tracking have been proposed [8]. These are usually based on smoothing of the target trajectory obtained by the target localization methods.

The latter approach to tracking the moving target is to join the localization and tracking phases into one phase of the radar signal processing. In this paper, a new tracking algorithm of that kind will be introduced for the radar system equipped with one transmitting and two receiving antennas. For the target coordinates estimation in the time instant t, the proposed algorithm exploits the TOA corresponding to the target to be tracked for the actual time instant t and the distance between *Tx*, *T* and *Rx* determined for the previous time instant t-1. Then, these data are used as the target localization inputs for the Taylor series method (TSM) [13]. Because for the target localization, according to the outlined approach, the data concerning the actual position of the target (TOA for the time instant t) as well as the estimation of the previous position of the target (more precisely, the distance between *Tx*, *T* and *Rx* for the time instant $t-1$) are used, the proposed algorithm includes the localization and tracking phases. The proposed algorithm allows for the control of the influence of the reliability of the estimation of the TOA and the previous position of the target to the final estimation of the target position. Here, a weighting matrix $\mathbf{W}$ is used as the controlling parameter. This new algorithm, joining the phases of the target localization and target tracking based on the TSM application, will be referred to as the Taylor Series Based Tracking Algorithm (TST) in this paper.

In order to illustrate the TST performance, two real scenarios of through wall tracking of a moving person by the UWB radar system will be analyzed. Within both scenarios the M-sequence UWB radar system equipped with one transmitting and two receiving antennas will be used [4], [11]. The first scenario will focus on the comparison of the tracking ability and accuracy of the new TST with the traditional approach of the target localization and tracking represented by the direct calculation method [1], [13] and linear Kalman filtering [6]. The results obtained for this scenario will show that the TST is able to provide a better estimation of the target trajectory than the mentioned traditional approach. On the other hand, the latter scenario is devoted to bringing out the dependence of the TST tracking accuracy on the mentioned weighting matrix $\mathbf{W}$. In this case, the obtained results will outline how to choose the weighting matrix $\mathbf{W}$ for the different reliability of the estimation of the TST input quantities.

The structure of the paper is as follows. The problem statement concerning the target localization by the UWB radar system will be outlined in the next Section. Then, in the Section 3, the TST for the join target localization and tracking will be introduced. The illustration of the TST properties will be given in the Section 4. For that purpose, two scenarios of through wall tracking of a moving person will be used. Finally, conclusions and final remarks to this contribution are drawn in Section 5.

2 Target Localization: Problem Statement

Let us consider a UWB radar system equipped with one transmitting antenna *Tx* and two receiving antennas Rx_i, i = 1,2. The antenna positions are known and they are given by $Tx=(x_t,y_t)$ and $Rx_i=(x_i,y_i)$ for i=1,2. Let $TOA_i(t)$ for i=1,2 represent the estimation of TOA of the electromagnetic wave transmitted by *Tx*, reflected by the target and received by the *i*-th *Rx* in the time instant *t*. The goal is to determine the unknown target coordinates $T(t)=(x(t),y(t))$ in 2D for every observed time instant *t*.

In the next, the function

$$D\left(A,B,C\right)=\left\|AB\right\|+\left\|BC\right\| \tag{1}$$

will be used. In this expression, the symbol $\left\|XY\right\|$ is set for the Euclidean distance between the points X and Y.

The unknown target coordinates $T(t)=(x(t),y(t))$ for every observed time instant *t* can be computed by using the distances $d_i(t)$ given by

$$d_i\left(t\right)=D(Tx,T(t),Rx_i)=c.TOA_i\left(t\right),\quad i=1,2 \tag{2}$$

where *c* is the electromagnetic wave propagation velocity. In our consideration, *c* is set to the electromagnetic wave propagation velocity in air, i.e. c = 3.10^8 ms^{-1}.

Under the real conditions, the distances $d_i(t)$ are estimated with an error represented by the additive noise components $e_i(t)$. Then, the estimated distances $d_i(t)$ can be modeled as

$$\begin{aligned}d_i\left(t\right)&=r_i\left(t\right)+e_i\left(t\right)=D(Tx,T(t),Rx_i)+e_i\left(t\right)=\left\|Tx\,T(t)\right\|+\left\|T(t)\,Rx_i\right\|+e_i\left(t\right)=\\&=\sqrt{\left(x(t)-x_t\right)^2+\left(y(t)-y_t\right)^2}+\sqrt{\left(x(t)-x_i\right)^2+\left(y(t)-y_i\right)^2}+e_i\left(t\right)\end{aligned} \tag{3}$$

where $r_i(t)$ are true distances $D(Tx,T(t),Rx_i)$. Then, the target localization task consists in determining the target coordinates $x(t)$ and $y(t)$ by the solution of the nonlinear equation set (3). For that purpose, the TSM and the direct calculation method can also be used [13].

The target localization by the TSM was originally proposed for one way propagation time measurements in [5]. Then in [13], the original TSM was modified for the target localization based on $TOA_i(t)$ estimation. However, this method gives for the radar system equipped with one transmitting antenna and two receiving antennas the same results as simple localization based on the direct calculation method [1], [13]. For a radar system of that kind, the direct calculation method determines the target position under the condition that $e_i(t)\equiv 0$. This means that, according to the direct calculation method, the target coordinates correspond to the intersections of two ellipses defined by (3) for $i=1,2$.

If the above mentioned simplification is not correct or at least acceptable, a large error in the target position estimation usually arises for the direct calculation method. In order to improve the target coordinates estimation accuracy, the simplified assumption $e_i(t) \equiv 0$ cannot be accepted. It could be done only if the number of the equations of (3) is greater than two. If this condition is fulfilled, the TSM can be used with advantage for the solution of this equation set. Then, improved accuracy of the target localization can be reached by an extension of the equation set (3) by new suitable equations and subsequently by the application of the TSM for the solution for such a set of nonlinear equations. By extending this fundamental idea, the TST can be derived, which is done in the next section of this contribution.

3 Taylor Series-based Tracking Algorithm

As was outlined in the previous sections, the key idea of the TST is the combination of the TSM and the extension of (3) by new equations. The conventional TSM uses for the target localization in the time instant t, $TOA_i(t)$ or the estimated distances $d_i(t)$. In contrast to the TSM, the TST is based on the idea that for the target localization in the time instant t, $TOA_i(t)$ or $d_i(t)$ as well as $\hat{T}(t) = (\hat{x}(t\text{-}1), \hat{y}(t\text{-}1))$ i.e. the target coordinates estimated for the time instant $t-1$, will be used. Just the application of $\hat{T}(t) = (\hat{x}(t\text{-}1), \hat{y}(t\text{-}1))$ enables us to extend the equation set (3) by two new equations. Then, the TST applied for the calculation of $\hat{T}(t) = (\hat{x}(t), \hat{y}(t))$ i.e. the estimation of the target coordinates in the time instant t, consists of the following steps:

1 Let $\hat{d}_i(t\text{-}1) = D(Tx, \hat{T}(t-1), Rx_i)$. Then, the following equations can be obtained by using (1):

$$\hat{d}_i(t\text{-}1) = \sqrt{\left(\hat{x}(t\text{-}1) - x_t\right)^2 + \left(\hat{y}(t\text{-}1) - y_t\right)^2} + \sqrt{\left(\hat{x}(t\text{-}1) - x_i\right)^2 + \left(\hat{y}(t\text{-}1) - y_i\right)^2}, \quad i = 1, 2. \tag{4}$$

It can be found very easily, that for the distances $d_i(t)$ expressed by the target position $\hat{T}(t\text{-}1)$ estimated in the previous time instant *t*-1, the expression

$$d_i(t) = \hat{d}_i(t\text{-}1) + \varepsilon_i(t), \quad i = 1, 2 \tag{5}$$

holds. In this expression, $\varepsilon_i(t)$ is the difference between $d_i(t) = D(Tx, T(t), Rx_i)$ and $\hat{d}_i(t-1) = D(Tx, \hat{T}(t-1), Rx_i)$. For a relatively slowly moving target, the approximation

$$d_i(t) \approx \hat{d}_i(t-1), \quad i = 1,2 \tag{6}$$

can be accepted. Then, the distances $\hat{d}_i(t-1)$ can be expressed by using (3) and (6) as

$$\begin{aligned}\hat{d}_i(t-1) = &\sqrt{\left(x(t)-x_t\right)^2 + \left(y(t)-y_t\right)^2} + \\ &\sqrt{\left(x(t)-x_i\right)^2 + \left(y(t)-y_i\right)^2} + \sigma_i(t), \quad i = 1,2\end{aligned} \tag{7}$$

where $\sigma_i(t)$ is caused by the errors $e_i(t)$ from the equations (3) and $\varepsilon_i(t)$ from the equations (5).
The connection of the equations (3) and (7) gives a new set of the four non-linear equations with the unknown target coordinates $T(t) = (x(t), y(t))$ in the time instant t:

$$\begin{aligned}d_i(t) \quad &= \sqrt{\left(x(t)-x_t\right)^2 + \left(y(t)-y_t\right)^2} + \sqrt{\left(x(t)-x_i\right)^2 + \left(y(t)-y_i\right)^2} + e_i(t), \\ \hat{d}_i(t-1) &= \sqrt{\left(x(t)-x_t\right)^2 + \left(y(t)-y_t\right)^2} + \sqrt{\left(x(t)-x_i\right)^2 + \left(y(t)-y_i\right)^2} + \sigma_i(t), \\ &i = 1,2.\end{aligned} \tag{8}$$

The unknown coordinates of the target $(x(t), y(t))$ are estimated from the equations (8) by the TSM where the $e_i(t)$ and $\sigma_i(t)$ are unknown components.

2 The non-linear equations (8) are linearized by their expanding in the Taylor series [2] around the point corresponding to the target position, which is subsequently estimated within the particular iterations of the iteration process and keeping only terms below second order. Let us set the initial estimate (x_v, y_v) of the target coordinates for the time instant t as the target position estimated in the time instant t-1, i.e. $(x_v, y_v) = (\hat{x}(t-1), \hat{y}(t-1))$ and define new functions

$$\begin{aligned}f_i(x(t), y(t)) = &\sqrt{\left(x(t)-x_t\right)^2 + \left(y(t)-y_t\right)^2} + \\ &\sqrt{\left(x(t)-x_i\right)^2 + \left(y(t)-y_i\right)^2}, \quad i = 1,2.\end{aligned} \tag{9}$$

Then, (9) can be rewritten as

$$f_i\left(x(t),y(t)\right)=d_i(t)-e_i(t),$$
$$f_i\left(x(t),y(t)\right)=\hat{d}_i(t-1)-\sigma_i(t),\quad i=1,2. \tag{10}$$

If x_v and y_v are the initial estimates of the target coordinates, then

$$x=x_v+\delta_x,\quad y=y_v+\delta_y \tag{21}$$

where x and y are the true coordinates of the target in the time instant t and δ_x and δ_y are the target localization errors to be determined.

Expanding f_i in the Taylor series and retaining the first two terms produces

$$f_{iv}+a_{i1}\delta_x+a_{i2}\delta_y\approx d_i(t)-e_i(t),$$
$$f_{iv}+a_{i1}\delta_x+a_{i2}\delta_y\approx \hat{d}_i(t-1)-\sigma_i(t),\quad i=1,2 \tag{32}$$

where

$$f_{iv}=f_i(x_v,y_v),$$
$$a_{i1}=\frac{\partial f_i}{\partial x}\mid x_v,y_v=\frac{x_v-x_t}{r_{tv}}+\frac{x_v-x_i}{r_{iv}},$$
$$a_{i2}=\frac{\partial f_i}{\partial y}\mid x_v,y_v=\frac{y_v-y_t}{r_{tv}}+\frac{y_v-y_i}{r_{iv}}, \tag{43}$$
$$r_{tv}=\sqrt{(x_v-x_t)^2+(y_v-y_t)^2},$$
$$r_{iv}=\sqrt{(x_v-x_i)^2+(y_v-y_i)^2}.$$

Then, (12) can be rewritten in the matrix form as

$$\mathbf{A}\delta=\mathbf{D}+\mathbf{e} \tag{54}$$

where

$$\mathbf{A}=\begin{bmatrix}a_{11}&a_{12}\\a_{21}&a_{22}\\a_{11}&a_{12}\\a_{21}&a_{22}\end{bmatrix},\quad \delta=\begin{bmatrix}\delta_x\\\delta_y\end{bmatrix},\quad \mathbf{D}=\begin{bmatrix}d_1(t)-f_{1v}\\d_2(t)-f_{2v}\\\hat{d}_1(t-1)-f_{1v}\\\hat{d}_2(t-1)-f_{2v}\end{bmatrix},\quad \mathbf{e}=\begin{bmatrix}e_1(t)\\e_2(t)\\\sigma_1(t)\\\sigma_2(t)\end{bmatrix}. \tag{65}$$

3 The set of the linear equations written by the matrix form (14) is solved by the weighted least-squares method [2][1] to produce a new estimate of the target coordinates to be applied in the next iteration of the iteration process. The iteration process continues until a pre-defined criterion is satisfied. Then δ obtained as the weighted least-squares solution of (14) with a weighting matrix $\boldsymbol{W}$ can be expressed in the form

$$\delta = \left[\mathbf{A}^T \mathbf{W} \mathbf{A} \right]^{-1} \mathbf{A}^T \mathbf{W} \mathbf{D}. \tag{76}$$

For the new estimate of the target position, the updated coordinates of the target according to

$$\begin{aligned} x_v &\leftarrow x_v + \delta_x \\ y_v &\leftarrow y_v + \delta_y \end{aligned} \tag{87}$$

is used, where δ_x and δ_y are given by (16). The iteration process is repeated until δ is sufficiently small.

Generally, the TSM and the TST require a good initial guess of the target coordinates. If the initial guess is not close to the true solution, divergence of the iteration process may occur. However, the divergence of the iteration process is easily detectable. For that purpose, we must check if $||\delta||$ at current iteration is larger than that of $||\delta||$ in the previous iteration. If this is the case, the iteration process does not converge and it must be started once again with a new initial guess of the target coordinates.

Generally, the particular weights of the weighting matrix ***W*** can be used to characterize the reliability of $TOA_i(t)$ and $\hat{T}(t-1)$ estimations. According to this idea, the more accurate measurements are placed with larger weights to stress the importance of the more reliable observations. In the TST, the weighting matrix ***W*** used in (16) is set to

$$\mathbf{W} = diag\left\{1, 1, w, w\right\} \tag{98}$$

where $w \epsilon R$ is the weighting factor. That matrix ***W*** is used to weight the actual estimated distances $d_i(t)$ with the added distances $\hat{d}_i(t-1)$ estimated based on using the target position at the time instant $t-1$. If $w < 1$, then $d_i(t)$ are used by the TST with greater reliability than that of $\hat{d}_i(t-1)$. In contrast, if $w > 1$, then $d_i(t)$ are used with lesser reliability than that of $\hat{d}_i(t-1)$. If $w = 1$, then $d_i(t)$ and $\hat{d}_i(t-1)$ are used by the TST with the same level of reliability.

4 When the iteration process has finished, the estimated position of the target in the actual time instant t is

$$\hat{T}(t) = \left(\hat{x}(t), \hat{y}(t)\right) = \left(x_v, y_v\right). \tag{109}$$

The computation flow of the TST is shown in the Fig. 1.

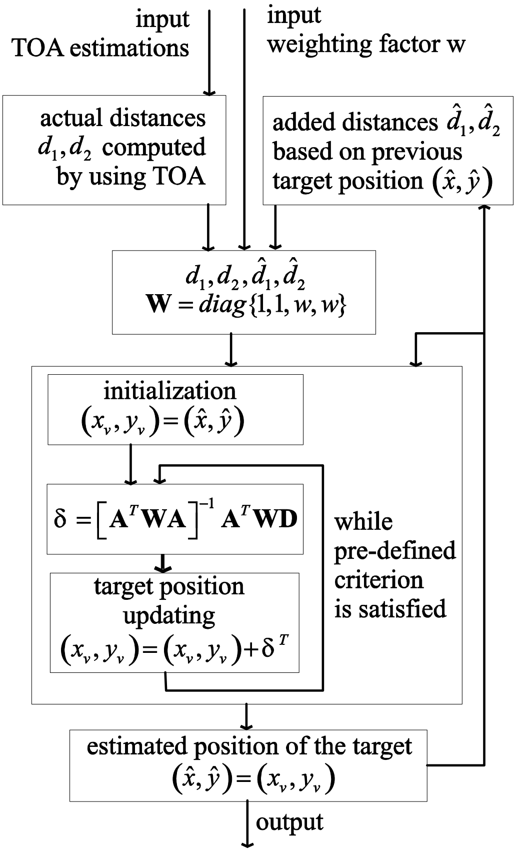

Figure 1

The TST computation flow

4 Performance of TST

In order to illustrate the TST performance, the TST has been applied for the target localization at two scenarios of through wall tracking of a moving person. In the both scenarios, the raw radar data analyzed in this contribution were acquired by means of the M-sequence UWB radar system with one transmitting and two receiving channels [3], [9], [11]. The system clock frequency for the radar device is about 4.5 GHz, which results in an operational bandwidth of about DC-2.25 GHz. The order of the M-sequence emitted by the radar is 9 [4], i.e. the impulse response covers 511 samples regularly spread over 114 ns. This corresponds to an observation window of 114 ns leading to an unambiguous range of about 16 m.

256 hardware averages of the environment impulse responses are always computed within the radar FPGA to provide a reasonable data throughput and to improve the SNR by 24 dB. The basic software of the radar device can provide the additional software averaging. In our measurements, the radar system was set in such a way as to provide approximately 10 impulse responses per second. The total power transmitted by the radar was about 1mW. The radar was equipped by the three double-ridged horn antennas placed along line. At the particular measurements, the transmitting antenna were located in the middle of two receiving antennas.

In order to get $TOA_i(t)$ estimation, raw radar data were processed by the radar signal processing procedure consisting of such signal processing phases as raw radar data pre-processing, background subtraction, detection and trace estimation. Then, $TOA_i(t)$ estimation was obtained as the output of the trace estimation phase. A detailed description of the mentioned radar signal processing procedure is beyond this contribution. It can be found e.g. in [10].

4.1 Scenario 1. Comparison of the TST with the Direct Calculation Method and Linear Kalman Filtering

This scenario was focused on the comparison of the tracking ability and accuracy of the new TST with the traditional approach to the target localization and tracking represented by the combination of the direct calculation method [13] and linear Kalman filtering [6].

The scheme of the analyzed scenario is outlined in Fig. 2. Scenario 1 is represented by moving person tracking through a light concrete wall with a thickness of 18 cm. The person is moving from position P(1), through positions P(2), P(3), and P(4) and back to position P(1) (Fig. 2). The distance between adjacent Rx_1 and Rx_2 was set to 76 cm. The Tx was located in the center between the Rx_1 and Rx_2. All antennas were placed 78 cm above the floor. Other distances are schematically depicted in Fig. 2.

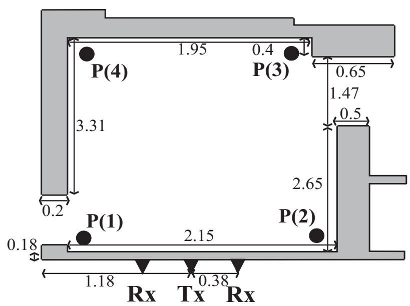

Figure 2

Scenario 1: measurement scheme

The $TOA_i(t)$ for i=1,2 corresponding to the target to be tracked have been obtained by using the above mentioned radar signal processing procedure. By using estimated $TOA_i(t)$, the target position of the moving person for every observation time instant has been determined. For that purpose, the direct calculation method was applied within the target localization phase. The target localization results are depictured in Fig. 3 by the thin curve. In order to improve the target trajectory estimation, target tracking by using linear Kalman filtering applied to the localization phase output given by the direct localization method has been used. For the join target localization and tracking, the TST proposed in this contribution has been also applied. The results of target tracking by these methods are given also in Fig. 3. Here, the target trajectory estimation by linear Kalman filtering and the TST are represented by a dotted and a thick curve, respectively. For this scenario, the weighting factor w has been set to w = 5. It can be seen from Fig. 3, that the positions of the moving person obtained by the TST are estimated more precisely than that of the positions estimated by the direct calculation method or by the direct calculation method followed with linear Kalman filtering. The largest difference between the true and estimated trajectories are visible around the positions P(3) and P(4), which is due to the wall niche (Fig. 2).

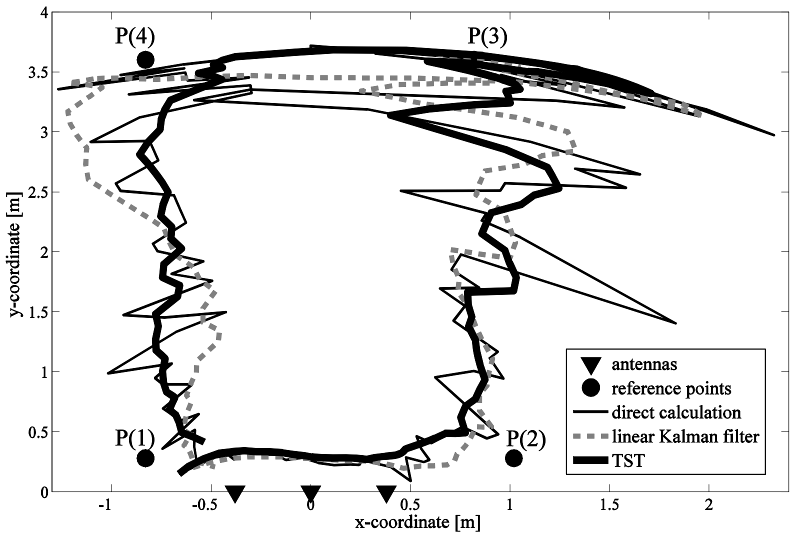

Figure 3

Scenario 1: Target trajectories estimated by the direct calculation method, linear Kalman filtering and the TST

The alternative form of the visualization of the target position estimation accuracy is shown in Fig. 4. In this figure, two tetragons sketched by the dashed lines are outlined. The part of the scanned area bordered by these tetragons, where the true trajectory of the target is located (i.e. the positions P(1) - P(4)), will be referred to as the region of the true positions of the target. The width of this region along the *x*- and *y*-coordinates is set to 40 cm, which corresponds approximately to the effective width of a human body. In Fig. 4, the target position is represented by a single point. Since the real width of the target is non-zero and the resolution of the radar used for measurement is approximately 3 cm, we can accept the estimated position of the target as the true one, if the target is located inside the region of the true positions of the target. This approach allows us to evaluate the target position estimation accuracy as the percentage of the “true” estimates of the target positions. This quantity can be evaluated as the ratio of the number of the target positions inside the region of the true positions of the target to the total number of the estimated target positions. The percentages of the “true” estimates of the target positions for the Scenario 1 for the tested localization and tracking methods are given in Table 1. The results presented in this table confirm the results provided by Fig. 3, i.e. the TST in light of the target positioning accuracy overcomes very clearly the other tested methods.

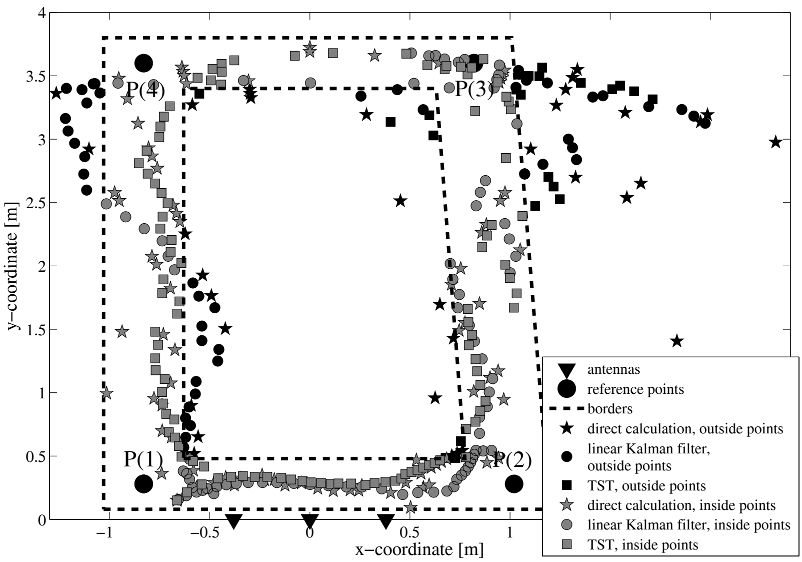

Figure 4

Scenario 1: Visualization of the target position estimation accuracy

In Table 1, the so-called average time of calculation is also brought out. This quantity represents the average time of calculation of the target positions based on TOA for the tested localization and tracking methods at their implementation in MATLAB environment. Therefore, this quantity can be taken as an approximated measure of the implemented algorithm complexity. Then, it can be identified from Table 1 that good TST performance is reached at a lower complexity than the complexity of linear Kalman filtering.

Table 1
Scenario 1: Comparison of the direct calculation method, linear Kalman fitlering and the TST

Localization methods	Percentage of the "true" estimates of the target positions	Average time of calculation [ms]
Direct calculation method	70%	0.07339
Linear Kalman filtering	63%	0.70462
TST	83%	0.29672

4.2 Scenario 2. The TST Performance Depending on the Selection of the Weighting Factor

Scenario 2 is devoted to the illustration of the dependence of the TST tracking accuracy on the selection of the above mentioned weighting factor *w*. In this case, the obtained result will outline how to choose the weighting factor *w* for the different reliability of the estimation of the TST input quantities.

The scheme of Scenario 2 is outlined in Fig. 5. This scenario is represented by a moving person tracking through a brick wall covered by tiles with a total thickness of 24 cm. The person was moving from position P(1), through positions P(2), P(3), and P(4) and back to position P(1) (Fig. 5). The distance between adjacent Rx_1 and Rx_2 was set to 260 cm. The Tx was located in the center between the Rx_1 and Rx_2. All antennas were placed 120 cm above the floor. Other distances are schematically depicted in Fig. 5.

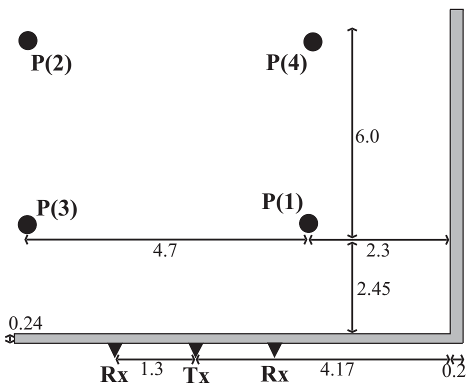

Figure 5
Scenario 2: measurement scheme

The $TOA_i(t)$ for i=1,2 corresponding to the target to be tracked have been obtained by using the radar signal processing procedure mentioned above. By using estimated $TOA_i(t)$, the target position of the moving person for every observation time instant has been determined. For that purpose, the direct calculation method and the TST method have been used. For the TST, the weighting factor *w* has been set subsequently to $w = 1, 5, 10$. Similarly to in Scenario 1, the results of the target positioning for Scenario 2 are represented by the target trajectory estimations (Fig. 6), target positions inside and outside the region of the true positions of the target (Fig. 7) and by the percentage of the “true” estimates of the target positions (Table 2). In Scenario 2, the distance between the parallel lines representing the inside and outside border of the region of the true positions of the target (Fig. 7), has been set to 50 cm.

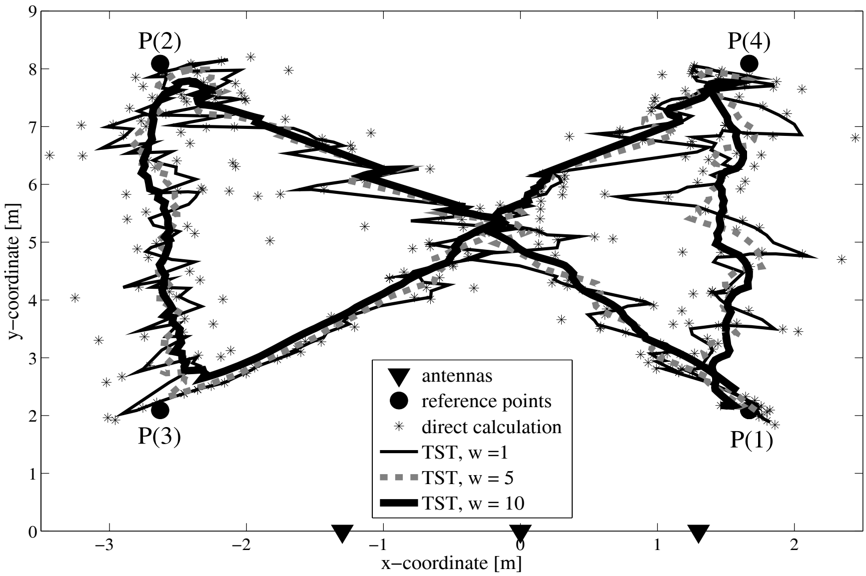

Figure 6

Scenario 2: Target trajectories estimated by using the direct calculation method and the TST for different values of the weighting factor *w*

The analyses of these results show that the TST surpasses the direct calculation methods. It can also be observed that the TST controlled by the higher weighting factor *w* can provide a more smoothed estimation of the target trajectories than if the lower values of the weighting factor are used. As can be identified from Figs. 6 and 7, the higher weighting factor *w* can be used with advantage especially in the case of the straight-line motion of the target. In constrast, if the person changes the motion direction sharply (e.g. in the positions P(1), P(2), P(3), P(4)), the TST using the higher weighting factor gives less precise results of the target positioning. These results indicate that the weighting factor *w* should be adapted according to the shape of the estimated trajectory of the target. However, a detailed solution of this task is beyond the scope of this paper and will be the object of our next research.

Table 2
Scenario 2: Comparison of the TST for the different values of the weighting factor *w*

Weighting factor *w*	Percentage of the "true" estimates of the target positions
w = 1	81%
w = 5	89%
w = 10	91%

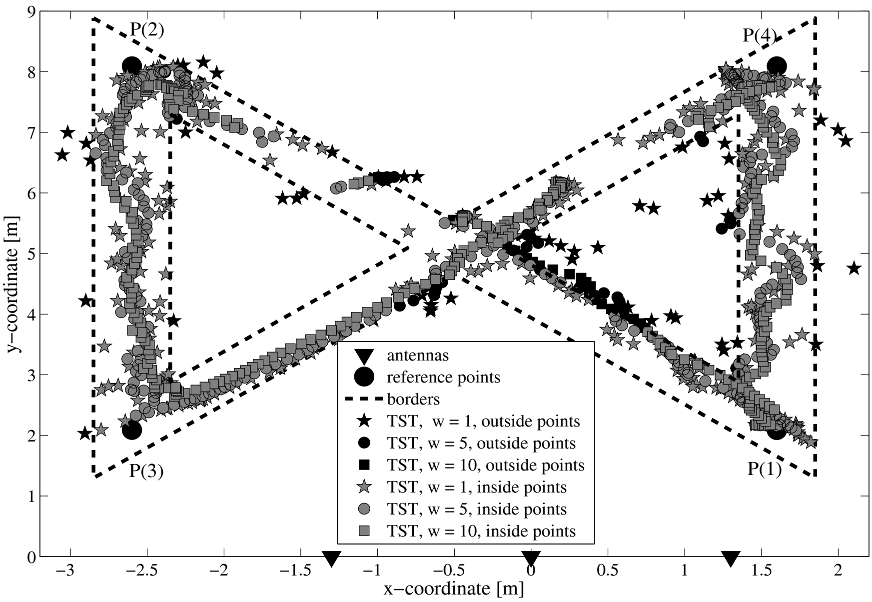

Figure 7
Scenario 2: Visualization of the target position estimation accuracy

Conclusions

In this paper, the TST has been introduced for the purpose of joining the localization and tracking of a moving target. The proposed algorithm uses for the target localization in the time instant t not only actual TOA estimates, but also the target coordinates estimated for the time instant $t-1$. The TST tracking ability has been illustrated and compared with the direct calculation method and linear Kalman filtering for through wall tracking of a moving person. The obtained results confirm that the TST provides a greater accuracy of target positioning at lower computational complexity than linear Kalman filtering. It has also been shown that the smoothness and accuracy of the target trajectory estimates by the TST depend on the selection of its weighting factor *w*. It has been outlined that an improvement in the TST performance could be reached by the adaptation of the weighting factor *w* according to the target motion style.

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