54. IWK
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International Scientific Colloquium

Information Technology and Electrical Engineering - Devices and Systems, Materials and Technologies for the Future

Faculty of Electrical Engineering and Information Technology

Startseite / Index:
http://www.db-thueringen.de/servlets/DocumentServlet?id=14089

TECHNISCHE UNIVERSITÄT
ILMENAU

Impressum

Herausgeber: Der Rektor der Technischen Universität Ilmenau
Univ.-Prof. Dr. rer. nat. habil. Dr. h. c. Prof. h. c.
Peter Scharff

Redaktion: Referat Marketing
Andrea Schneider

Fakultät für Elektrotechnik und Informationstechnik
Univ.-Prof. Dr.-Ing. Frank Berger

Redaktionsschluss: 17. August 2009

Technische Realisierung (USB-Flash-Ausgabe):
Institut für Medientechnik an der TU Ilmenau
Dipl.-Ing. Christian Weigel
Dipl.-Ing. Helge Drumm

Technische Realisierung (Online-Ausgabe):
Universitätsbibliothek Ilmenau
ilmedia
Postfach 10 05 65
98684 Ilmenau

Verlag: isle
Verlag ISLE, Betriebsstätte des ISLE e.V.
Werner-von-Siemens-Str. 16
98693 Ilmenau

ISBN (USB-Flash-Ausgabe): 978-3-938843-45-1
ISBN (Druckausgabe der Kurzfassungen): 978-3-938843-44-4

Startseite / Index:
http://www.db-thueringen.de/servlets/DocumentServlet?id=14089

A NEW EFFICIENT TRACKING ALGORITHM FOR THROUGH WALL TRACKING OF MOVING TARGET BY USING UWB RADAR

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ABSTRACT

In this paper, through wall moving target tracking by M-sequence UWB radar is described. For that purpose, the imaging method consists of radar signal processing phases such as raw radar data pre-processing, background subtraction, data fusion obtained by receiving antennas of radar, detection, localization and tracking itself, is used. Our paper is focused on last phase - tracking. Here, new nonlinear low-complex two-section tracking-filter (2S-TF) is introduced for target tracking based on the target localization phase result. It will be shown, that the proposed new tracking filter presented in this paper can provide better smoothing of target trajectory at much less computational complexity than the well-know linear Kalman filters.

Index Terms - back projection, imaging method, Kalman filters, moving target tracking, radar signal processing, through wall tracking, tracking filter, UWB radar

1. INTRODUCTION

Electromagnetic waves occupying a spectral band below a few GHz show reasonable penetration through most typical building material, such as bricks, wood, dry walls, concrete and reinforced concrete. This electromagnetic wave penetration property can be exploited with the advantage of UWB radars operating in a lower GHz-range base-band (up to 5 GHz) for through wall detection and tracking of moving and breathing persons [2]. There are a number of practical applications where such radars can be very helpful, e.g. 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.

There are two basic approaches for through wall tracking of a moving target. The former approach for through wall tracking of moving target by using a M-sequence UWB radar equipped with one transmitting and two receiving antennas has been originally introduced in [1]. Here, target coordinates as the function of time are evaluated by using time of arrival (TOA) corresponding to target to be tracked and electromagnetic wave propagation velocity along the line transmitting antenna-target-receiving antenna.

The later approach is based on radar imaging techniques, when the target locations are not calculated analytically but targets are seen as radar blobs in gradually generated radar images [2]. For the radar image generation, different modifications of a back projection algorithm can be used [2]-[4]. With regards to the fundamental idea of the method - the radar image generation based on raw radar data, the method is sometimes referred to as the imaging method. According to imaging method, moving target tracking, i.e. determining target coordinates as the continuous function of time, is the complex process that includes following phases-tasks of radar signal processing: raw radar data pre-processing, background subtraction, data fusion from radar antennas, detection, localization and tracking itself. The significance of these particular phases of radar signal processing can be found in [1] and [2]. In this paper, we will focus on the last phase-tracking algorithm.

Target tracking provides a new estimation of target location based on its foregoing positions. Usually, target tracking will result in the target trajectory error decreasing including trajectory smoothing. Most of tracking systems utilize a number of basic and advanced modifications of Kalman filters as e.g. linear, nonlinear and extended Kalman filters and particle filters [5], [6]. Besides Kalman filter theory, further methods of tracking are available. They are usually based on smoothing of the target trajectory obtained by the target localization methods. Here, the linear least-square method is also widely used (e.g. [7]).

The detail analyses of the target coordinates obtained within the localization phase at through wall tracking of moving target by UWB radar has shown that the target coordinate estimation error does not possess the nature of additive Gaussian or impulsive noise. As the consequence, the “traditional” tracking

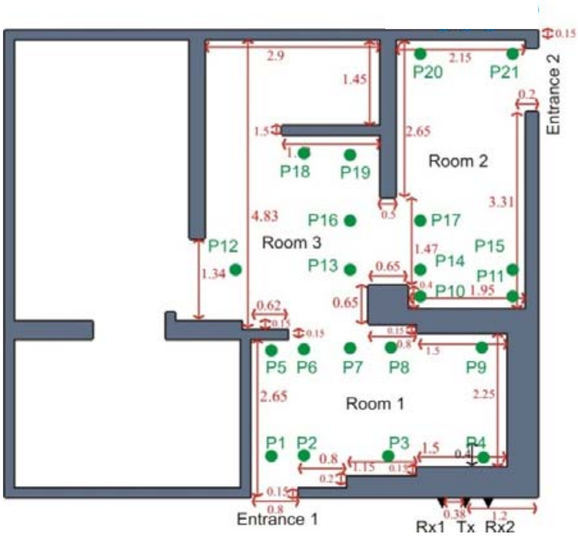

Figure 1 Measurement scenario

Figure 2 M-sequence UWB radar system

Figure 3 Measurement room interior

or smoothing algorithms (e.g. averaging, Wiener filters, linear Kalman filters, median filters, etc.) will have reduced efficiency. A possible solution to that problem could be given e.g. by the applications of extended Kalman filters or particle filters. However these alternatives are characterized by their relatively high computational complexity.

In this paper, we will introduce a new low-complexity nonlinear 2S-TF not requiring Gaussian noise assumption fulfilling. The basic idea of operation of the particular sections of the 2S-TF consists in an estimate of an interval in which the actual output of the section has to be located and in subsequent analysis intent on findings if the actual input of the section is or is not within the estimated interval. Based on the result of this analyses the 2S-TF response is generated.

In order to fulfill this intention, our contribution will have the following structure. In the next section, a real through wall scenario of single target tracking will be described. As the radar device considered for the scenario, M-sequences UWB radar equipped with one transmitting and two receiving antennas will be used [8], [9]. In the Sections 3, the particular phases of radar signal processing following imaging method with the exception of tracking phase will be described. The Section 4 is the core of our contribution. In this section, selected problems of target tracking will be discussed and the 2S-TF will be introduced. Subsequently, a performance comparison of the 2S-TF with that of linear Kalman filter will be presented in this section, too. Conclusions and final remarks concerning tracking algorithm for through wall tracking of moving target by UWB radar will be drawn in Section 5.

2. BASIC SCENARIO OF THROUGH WALL TRACKING OF MOVING TARGET

The basic scenario analyzed in this contribution is outlined in the Fig. 1-3. The scenario is represented by moving target tracking through two lite concrete walls. The thickness of the first and the second wall has been 50 cm and 40 cm, respectively. The walls have been arranged in a parallel way at the mutual distance 2,25m. A person was walking along perimeter of the Room 2 from Pos.14 through Pos. 11, Pos. 21 and Pos. 20 back to Pos. 14 (Fig. 1).

The raw radar data analyzed in this contribution were acquired by means of M-sequence UWB radar (Fig. 2) with one transmitting (*Tx*) and two receiving channels (*Rx1, Rx2*) [8], [9]. The system clock frequency for the radar device is about 4.5 GHz, which results in the operational bandwidth of about DC-2.25 GHz. The M-sequence order emitted by radar is 9, 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 environment impulse responses are always computed within the radar head FPGA to provide a reasonable data throughput and to improve the SNR by 24 dB. The additional software averaging can be provided by basic software of radar device. In our measurement, the radar system was set in such a way as to provide approximately 10 impulse responses per second. The total power transmitted by radar was about 1mW. The radar has been equipped by three double-ridged horn antennas placed along line (Fig. 1). Here, one transmitting antenna has been located in the middle between two receiving antennas.

Raw radar obtained by measurement according to above described scenario be interpreted as a set of impulse responses of surrounding, through which the electromagnetic waves emitted by the radar were propagated. They are aligned to each other creating a 2D picture called radargram, where the vertical axis is related to the time propagation (t) of the impulse response and the horizontal axis is related to the observation time (τ).

3. BASIC PHASES OF UWB RADAR SIGNAL PROCESSING

In the case of UWB radar signal processing by imaging method for through wall and tracking of moving persons by M-sequence UBW radar, target tracking is the complex process that includes such signal processing phases as raw radar data pre-processing, background subtraction, data fusion from receiving antennas of radar, detection, localization and tracking itself [1], [2]. In the next parts of this Section, the significance of particular phases will be outlined and a list of the most frequently methods used for these signal processing phases will be given. Because the phase of target tracking represents the core of this paper, this phase will not be discussed in this part of the paper, but it will be presented separately, in the next Section.

3.1. Raw radar data pre-processing

The intention of the raw radar data pre-processing phase is to remove or at least to decrease the influence of the radar systems by itself to raw radar data. In our contribution, we will focus on time-zero setting problem.

In the case of the M-sequence UWB radar, its transmitting antenna transmits M-sequences periodically. The exact time instant at which the transmitting antenna starts emitting the first elementary impulse of M-sequence (so-called chip) is referred to as time-zero. It depends e.g. on the cable lengths between transmitting/receiving antennas and transmitting/receiving amplifiers of radar, total group delays of radar device electronic systems, etc., but especially on the chip position at which the M-sequence generator started to generate the first M-sequence. This position is randomly changed after every power supply reconnection. To find time-zero means to rotate all the received impulse responses in such a way as that their first chips correspond to the spatial position of the transmitting antenna. There are several techniques for finding the number of chips needed for such rotating of impulse responses. The most often used method is that of utilizing signal cross-talk [10]. The significance of the time-zero setting follows from the fact that targets could not be localized correctly without the correct time-zero setting.

3.2. Background subtraction

It can be observed from radargram with correct zero-time setting, that it is impossible to identify any target in the radargrams. The reason is the fact, that the components of the impulse responses due to target are much smaller than that of the reflections from the front wall and cross-talk between transmitting and receiving antennas or from other large or metal static object. In order to be able to detect, localize and track a target, the ratio of signal scattered by the target to noise has to be increased. For that purpose, background subtraction methods can be used. They help to reject especially the stationary and correlated clutter such as antenna coupling, impedance mismatch
response and ambient static clutter, and allow the response of a moving object to be detected.

It has been shown in literature, that the methods such as basic averaging (mean, median) [11], exponential averaging [12], adaptive exponential averaging [12], adaptive estimation of Gaussian background [13], Gaussian mixture method [14], moving target detection by FIR filtering [15], moving target detection by IIR filtering [16], prediction [17], principal component analysis [18], etc. can be used for background subtraction. These methods differ in relation to assumptions concerning clutter properties as well as to their computational complexity and suitability for online signal processing.

3.3. Data fusion from receiving antennas of radar

The intention of the data fusion from receiving antennas of radar is to create a radar image $I(x, y, \tau)$ for each observation time instant τ. Here, x and y are the coordinates of the coordinate system applied for target position description.

For the radar image creating, different modifications of a back projection algorithm can be used [2]-[4]. The back projection technique consists of recording the magnitude of each impulse response samples with subtracted background on a spatial grid based on the total propagation time. After that, all the recorded magnitudes from each receiving antennas (channels) are added together on the spatial grid. At the target locations the signal magnitudes will add up coherently. The detail description of the back projection algorithm of that kind can be found e.g. [2].

3.4. Detection

Detection is the next step in the radar signal processing which comes after data fusion from receiving antennas of radar. It represents a class of methods that determine whether a target is absent or present in the examined radar signals.

The solution of target detection task is based on statistical decision theory [19], [20]. Detection methods analyze the radar image $I(x,y,\tau)$ obtained within data fusion phase for propagation time instant τ and reach the decision whether a signal scattered from target $s(x,y,\tau)$ is absent (hypothesis H_0) or it is present (hypothesis H_1) in $I(x,y,\tau)$. The hypotheses can be mathematically described as follows:

$$\begin{aligned} H_0 &: I(x,y,\tau) = n_{BS}(x,y,\tau) \\ H_1 &: I(x,y,\tau) = s(x,y,\tau) + n_{BS}(x,y,\tau) \end{aligned} \tag{1}$$

where $n_{BS}(x,y,\tau)$ represents residual noise obtained by $I(x,y,\tau)$ processing by a proper background subtraction method. A detector discriminates between hypotheses H_0 and H_1 based on comparison testing (decision) statistics $X(x,y,\tau)$ and threshold $\gamma(x,y,\tau)$. Then, the output of detector $I_d(x,y,\tau)$ is a binary image given by

$$I_d(x,y,\tau) = \begin{cases} 0 & if \quad X(x,y,\tau) \le \gamma(x,y,\tau) \\ 1 & if \quad X(x,y,\tau) > \gamma(x,y,\tau) \end{cases} \tag{2}$$

The detailed structure of a detector depends on the selected strategy and optimization criteria of detection [19]-[21]. The selection of detection strategies and optimization criteria results in a testing statistic specification and threshold estimation methods.

The most important groups of detectors applied for radar signal processing are represented by sets of optimum or sub-optimum detectors. Optimum detectors can be obtained as a result of the solution of an optimization task formulated usually by means of probabilities or likelihood functions describing the detection process. Here, Bayes criterion, maximum likelihood criterion or Neymann-Pearson criterion are often used as the bases for detector design. However a structure of optimum detector could be extremely complex. Therefore, sub-optimum detectors are also applied very often [19]. For the purpose of target detection by using UWB radars, detectors with fixed threshold, (N,k) detectors, IPCP detectors [19] and constant false alarm rate detectors (CFAR) [22] have been proposed.

3.5. Localization

The aim of the localization task is to determine the target coordinates in defined coordinate systems. Target positions estimated in consecutive time instants create target trajectory.

If a target is represented by only one non-zero pixel of the detector output $I_d(x,y,\tau)$, then the target is referred to as a simple target. However in the case of the scenario analyzed in this contribution, the radar range resolution is considerably higher than the physical dimensions of the target to be detected. It results in that the detector output is not expressed by only one non-zero pixel of $I_d(x,y,\tau)$, but the detector output is given by a complex binary image. The set of non-zero samples of $I_d(x,y,\tau)$ represents multiple-reflections of electromagnetic waves from the target or false alarms. The multiple-reflections due to the target are concentrated around the true target position at the detector outputs. In this case, the target is the distributed target. In the part of $I_d(x,y,\tau)$ where the target should be detected not only non-zero but also zero samples of $I_d(x,y,\tau)$ can be observed. This effect can be explained by a complex target radar cross-section due to the fact that the radar resolution is much higher than that of the target size and taking into account different shape and properties of the target surface. The set of false alarms is due to especially weak signal processing under very strong clutter presence.

Because the detector output for a distributed target is very complex, the task of distributed target localization is more complicated than for a simple target. For that purpose, an effective algorithm has been proposed in [1] for UWB radar signal processing by using TOA estimation. The basic idea of distributed target localization introduced in [1] consists in substitution of the distributed target with a proper simple target. This basic idea can be applied in a modified form also for UWB radar signal processing by imaging method. In this case, the distributed target is substituted by simple target located in the center of gravity of the distributed target. The coordinates of the target gravity center $[x_T(\tau), y_T(\tau)]$ for observation time instant τ can be evaluated by

$$\begin{aligned} x_T(\tau) &= \frac{1}{\sum_i \sum_j I(i,j,\tau)} \sum_i \sum_j i I(i,j,\tau) \\ y_T(\tau) &= \frac{1}{\sum_i \sum_j I(i,j,\tau)} \sum_i \sum_j j I(i,j,\tau) \end{aligned} \tag{3}$$

where the summation is made through all pixels belonging to the target to be tracked. Then the target coordinates as the output of target localization phase are given $[x_T(\tau), y_T(\tau)]$.

3.6. Tracking

As it has been mentioned in the introduction, target tracking provides a new estimation of target location

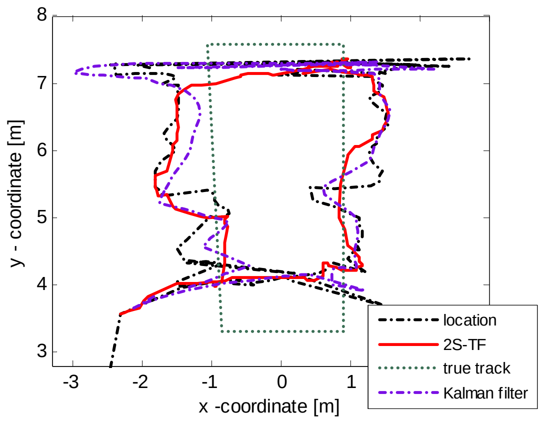

Figure 4 Target localization and tracking

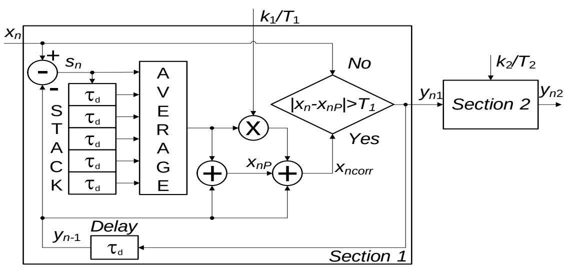

Figure 5 Nonlinear two-section tracking filter for x -coordinate tracking

based on its foregoing positions. Because the phase of target tracking represents the core of this paper, target tracking will not be discussed further in this part of the paper, but it will be subject to discuss of the next Section.

4. TARGET TRACKING

As it has been mentioned in the introduction of our contribution, target tracking provides a new estimation of target location based on its foregoing positions. There are a number of tracking algorithms. Generally, the very successful methods of moving target tracking are those based on linear Kalman filter theory [5], [6]. However, they are not very effective in the case of through wall tracking of moving target. The reasons of that fact will be outlined in this Section. Then, the proposal for improvement of target tracking represented the 2S-TF application will be introduced.

4.1. Tracking analyses for through wall tracking of moving target

The true trajectory and the trajectory estimated by localization method for target moving according to basic scenario outlined in the Section 2 are given in the Fig. 4. In order to obtain the target trajectory estimation as the localization phase output, the procedure described in the Section 3 has been applied. For the zero-time setting, background subtraction, radar image generation and distributed target detection, the cross-talk method [10], exponential averaging method [12], back projection method [2] and (N,k) detector [19] modified for image processing have been applied, respectively. The distributed target has been substituted by simple target by using of the center of the gravity of the distributed target according to Section 3.

In can be observed, from the Fig. 4 that the estimation of target position based on localization phase is very noisy, deformed and shifted along the y -axis. The detailed analyses of the reason of the described behaviour of the target trajectory estimation has shown that these effects are due to quality of the raw radar data (imperfect radar system performance at the hard conditions), quality of the signal processing methods applied for raw radar data processing and so-called wall effect [23].

The improvement of target trajectory estimation by the wall effect compensation is beyond of this paper. The solution of that task has been described in [23]. The application of the method proposed for that purpose in [23] wild result in improvement of the target trajectory shape estimation (trajectory deformation reduction) and decreasing of the trajectory shifting along the y -axis.

As it has been outlined in the Section 3, the further improvement of target trajectory estimation can be reached by using suitable tracking algorithm resulting in target trajectory smoothing. With regard to that fact, the linear Kalman filter has been applied for target tracking based on target localization. The target trajectory estimation by using Kalman filtering can be also seen in Fig. 4. Unfortunately, it can be seen from this figure, that the contribution of the Kalman filtering to target trajectory estimation improvement is not very significant.

The detail analyses of the target coordinates obtained within the localization phase at through wall tracking of moving target by UWB radar has shown that the target coordinate estimation error does not possess the nature of additive Gaussian or impulsive noise. As the consequence, the “traditional” tracking or smoothing algorithms (e.g. averaging, Wiener filters, linear Kalman filters, median filters, etc.) will have reduced efficiency. A possible solution to that problem could be given by e.g. by the applications of extended Kalman filters or particle filters. However these alternatives are characterized by their high computational complexity. Then, a possible solution of that problem is offered by the application of a new low-complex nonlinear 2S-TF not requiring Gaussian noise assumption.

4.2. Nonlinear two-section tracking-filter

The 2S-TF consists of two identical sections (Fig. 5), where each section is controlled by its own set of parameters (k_i , T_i for $i=1,2$). The input of the 2S-TF is represented by the target coordinate taken at the corresponding time instant ($x_n = x_T(\tau_n)$) obtained by the localization phase. Then, two identical 2S-TFs are used for target tracking (the first for x- and the second for the y-coordinate tracking).

The basic idea of operation of the particular sections of the 2S-TF can be explained as follows. As it was mentioned above, the target coordinate estimation obtained by localization is characterized by high variance of non-Gaussian noise. Taking into account this fact, the corresponding section of the 2S-TF estimates firstly the interval in which the actual output of the section has to be located. For that purpose, only a few past samples of the section output are used. If the actual input of the section is within the estimated interval, the section output is set to the section input. If this condition is not satisfied, the section output is obtained by using the past section output. Then, the performance of the first section of the 2S-TF tracking the x-coordinate can be described by using the following set of expressions:

$$s_n = x_n - y_{n1-1} \tag{4}$$

$$\overline{s}_n = average = \frac{1}{l}\sum_{i=0}^{l-1} s_{n-i} \tag{5}$$

$$x_{nP} = y_{n-1} + \overline{s}_n \tag{6}$$

$$x_{ncorr} = y_{n-1} + \frac{k_1}{T_1}\overline{s}_n \tag{7}$$

$$y_{n1} = \begin{cases} x_n & if \quad |x_n - x_{nP}| \le T_1 \\ x_{ncorr} & f \quad |x_n - x_{nP}| > T_1 \end{cases} \tag{8}$$

The same expressions, but with different input data and controlling parameters, are used for description of the performance of the second section of 2S-TF and for tracking of y-coordinate.

The 2S-TF performance is illustrated in the Fig. 4 for the scenario outlined at the Section 2 where the methods given in the part 4.1 of this paper have been applied within particular phases of raw radar data processing. It can be observed from the Fig. 4 very clearly, that the proposed the 2S-TF has provided much better estimation of the true trajectory of target than that of linear Kalman filter. The target trajectory is still deformed and shifted but it is much smoother and more similar to true trajectory in comparison with that obtained by linear Kalman filtering. The target trajectory deformation and shifting could not be suppress by tracking algorithm, but as we mentioned before, the wall effect compensation method can be applied for that purpose. It is very important, that the better performance of the 2S-TF has been reached at its much less computational complexity in comparison with that of linear Kalman filter.

5. CONCLUSIONS

In this paper, we have dealt with UWB radar signal processing for through wall tracking of moving target by imaging method. Firstly, the sequence of the particular phases of imaging method have been given and their significance has been outlined. The special attention has been devoted to the final phase - target tracking. Based on the analyses of signals obtained by the M-sequence UWB radar for through wall tracking of moving person under the real scenario, it has been shown that the well-known linear Kalman filter application has performed with reduced efficiency. This effect can be explained by non-Gaussian nature of noise presented at target coordinate estimate obtained at target localization.

May be, target tracking under this scenario could be improved by using well-known advanced tracking filters such as extended and unscented Kalman filters or by using particle filters. However, the computational complexity of these advanced trackers is much higher than that of linear Kalman filter. With regard to that fact, the novel simple nonlinear tracking filter has been introduced in this paper for the purpose of target tracking for through wall tracking of moving target. The basic idea of the 2S-TF operation consists in estimates an interval in which the actual output of the section has to be located and in subsequent analysis intent on determining if the actual input of the section is or is not within the estimated interval. Based on the result of these analyses, the 2S-TF output is produced.

The performance of the 2S-TF has been tested for the real scenario of through wall tracking of moving person. The obtained results confirms that the new 2S-TF proposed in this paper is able overcome the performance of the linear Kalman filter at the through wall tracking of moving target. The better performance of the 2S-TF has been reached at its much less computational complexity in comparison with that of linear Kalman filter. With regard to that fact, we believe that the 2S-TF is the promising tool for through wall tracking of moving target by using UWB radar.

6. ACKNOWLEDGMENT

This work was supported by the Slovak Research and Development Agency under the contract No. LPP-0287-06, by European Commission under the contract COOPCT-2006-032744 and by Cultural and Educational Grant Agency of Slovak Republic under the contract No. 3/7523/09.

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