Multiple Target Detection and Localization in UWB Multistatic Radars

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Abstract—An ultra-wideband (UWB) multistatic radar system, typically composed of one transmitter and several receivers, is a promising solution for tracking an intruder moving within a given surveillance area, because of its extraordinary localization accuracy and very low probability of intercept. In this paper, a new pixel-based localization approach using constant false alarm rate (CFAR) detector is proposed and compared with conventional direct method of localization for UWB multistatic impulse radio radars. Also, a simple processing is proposed to be added after CFAR detector and before either of these localization approaches. This processing which is based on a simplified median filter allows us to reduce the CFAR threshold to a very low value and hence to heavily reduce the number of missed detections. The performance of the proposed approach is evaluated through numerical simulations in multiple target scenarios, accounting for the spatial configuration of the receivers, propagation effects, presence of residual clutter, and noise.

I. INTRODUCTION

Precise localization and tracking of intruders inside an area is of great interest for many surveillance applications. Indeed, an increasing attention is recently being devoted to the capability of detecting and tracking unfriendly non-collaborative objects. This is sometimes referred to as passive localization and is typical of radar systems [1], [2]. Unlike a monostatic radar, which uses the same antenna for both the transmitted and received signals, a multistatic radar uses at least three non co-located antennas for transmitting and receiving the waveforms [2]. The major advantages of a multistatic radar system over a conventional monostatic radar include better area coverage, and an intrinsic spatial diversity.

A promising solution for anti-intruder cooperative wireless networks is the ultra-wideband (UWB) technology, especially in its impulse-radio version, characterized by the transmission of short duration pulses of the order of a few nanoseconds [3], [4]. Advantages of UWB include, but are not limited to, high spatial resolution (typically a few centimeters) even in indoor environments, low power consumption, robustness to multipath, co-existence with other systems, robustness to narrowband jamming, high security and low probability of intercept [5].

In the last years, passive localization through multistatic UWB radars has been the subject of several works such as [6]–[9] and [10]. In most of the works such as [11], [12] and [13], detection and localization are done using constant false alarm rate (CFAR) thresholding and direct method (also called tri-lateration), respectively. The target time of arrival (TOA) is estimated first by CFAR detector at each receiver and then the target location is calculated by finding the intersection of three ellipses corresponding to the target TOAs with respect to three receivers. In [14], a pixel-based detection and localization technique is proposed in which the whole surveillance area is divided into pixels and a soft metric related to the correlation of the received signal and the reference pulse is calculated for each pixel at every receiver. Then, a fusion node combines the soft images provided by all receivers. The pixel with the maximum combined metric determines the target location. This approach suffers from high complexity in calculating the soft metrics for every pixel. Moreover, in this work just a single target scenario is addressed.

In this paper, we propose a pixel-based localization technique using CFAR detector for multiple target cases. In this approach, the surveillance area is divided into pixels in a similar manner as in [14]. However, instead of calculating a soft metric for each pixel, the energy of the received sample at each receiver corresponding to that pixel is calculated and then CFAR thresholding is performed. The final estimated position will be the pixel for which most of the receivers have experienced a threshold exceeding.

We compare our proposed pixel-based localization approach with conventional direct method of localization using CFAR detector. Then, we propose to add a simple processing after CFAR detector and before either of these localization approaches. This processing which is based on a simplified median filtering done on the previous and current samples around the sample under verification, allows us to reduce the CFAR threshold to a very low value and hence to heavily reduce the number of missed detections. The performances of all above techniques are evaluated numerically in case of multiple targets accounting for the spatial configuration of the receivers, propagation effects, presence of residual clutter, and noise.

This paper is organized as follows. In Section II, the UWB multistatic radar system setup is presented. Section III explains conventional detection and localization techniques. In Section IV, our proposed CFAR detection and pixel-based localization techniques are described. In Section V, the performances of all techniques are compared numerically.
Concluding remarks are provided in Section VI.

II. SYSTEM DESCRIPTION

We consider a UWB multistatic radar system composed of one transmitting (TX) node and $N_R$ receiving (RX) nodes. This system is sometimes referred to as a radar sensor network. The transmitter and multiple receivers may, for example, be deployed on the perimeter of the area as depicted in Fig. 1. A central node collects the received signals from all receiver nodes, jointly processes the information and performs the target detection and localization.

During a frame time of duration $T_F$, a sequence of $N_s$ UWB pulses at intervals $T_{IP}$ (the interpulse period) is emitted by the TX node, i.e., $T_F = T_{IP}N_s$. The system is designed in such a way that the channel response to a single pulse when a moving target is present does not change appreciably during a frame time, but is different for pulses belonging to subsequent frames. If a target is present inside the area, the received signal at each RX node corresponding to a UWB transmitted pulse consists of the direct path pulse followed by pulse replicas due to both the clutter and the target and the additive noise [14].

One of the problems in UWB radar sensor networks is the presence of blind zones arising as an effect of finite sampling resolution which maps the target position onto quantized ellipses inside the area [15]. Blind zones are regions inside which the difference between the delays corresponding to target-reflected path and direct path is lower than system time resolution. When the target is close to one of the line-of-sights (LOS) between the TX and any of the RX antennas, it may fall inside the blind zone, in which case it may not be detected by that receive antenna. For detailed description of the possible causes of blind zones, we refer the reader to [15].

III. TRADITIONAL DETECTION AND LOCALIZATION TECHNIQUES

The aim of the detection stage is to decide if any target is present in the observed area, based on the received radar signals and to estimate the target TOAs at each receiver. Then, at the localization stage, the potential target positions are measured using estimated TOAs. Localization outputs are then passed to the data association step which is responsible for associating the measured positions to the target tracks.

A. CA-CFAR Detector

For the purpose of target detection by UWB radars, CFAR detectors have been widely used because of the robustness of this method demonstrated in experimental results (see, e.g., [16]). Besides conventional schemes, a number of modifications of the CFAR detector have been proposed, depending on the background noise and clutter models. Out of them, Cell Averaging CFAR (CA-CFAR) remains the simplest and most common version [17].

Let us assume that $r_{k,n}$ is the $n$'th sample of the received signal at one of the $N_R$ receivers, obtained by averaging the $N_s$ received signals corresponding to the $N_s$ pulses transmitted within $k$'th frame. Therefore, for each frame time (scan time) $k$, we have a vector of $N$ samples at any receiver which is passed to the CFAR detector.

Fig. 2 shows the processing done in the CA-CFAR detector for every sample $r_{k,n}$ at either of the UWB radar receivers. In CA-CFAR detector, the threshold level is calculated by estimating the level of the noise floor around the sample under test ($r_{k,n}$). This can be found by taking a block of $N_{ref}$ samples around $r_{k,n}$ and calculating the average noise power level of these reference samples. To avoid corrupting this estimate with power from the sample under test itself, $N_g$ samples immediately adjacent to $r_{k,n}$ are normally ignored and referred to as guard samples. In our case, we have assumed a guard band equal to the transmitted pulse width. A target is declared to be present in the $r_{k,n}$, if its instantaneous power is greater than the calculated local average power level which can be interpreted as a threshold. So, the output of the detector, $b_{k,n}$, is set to 1 if threshold is exceeded, otherwise it is set to 0. The threshold can be increased by a scale factor $\alpha$ depending on the scenario.

This thresholding often generates more than one TOA for each target because of the UWB pulse width. In this paper, clustering is performed to group together TOAs that are close. Then, the middle time in each cluster is considered as the detected TOA.

B. Direct Method of Localization

Direct method of localization, also called tri-lateration, is the most conventional approach for measuring target positions in UWB radar sensor networks based on the estimated TOAs [18]. Assume that the transmitter and the $j$'th receiver are located at $(x_t, y_t)$ and $(x_j, y_j)$, respectively. The TOA of the target at receiver $j$ has been estimated before by the detector as $\tau_j$. The following equation holds assuming no detection errors:

$$
\tau_j = \frac{1}{c}\sqrt{(x-x_t)^2+(y-y_t)^2} + \sqrt{(x-x_j)^2+(y-y_j)^2}
$$

(1)

\[^1\]Received pulse width can vary because of pulse distortions introduced by the channel and clutter removal filter.
where \( c \) is the velocity of the electromagnetic wave propagation and \((x, y)\) are the unknown coordinates of the target. For each triplet of receivers out of the \( N_r \) receivers, a system of three simultaneous equations in the form (1) is solved by least-squares calculation.

After doing direct calculation for all possible triplets of receivers and considering all possible combinations of TOAs detected by the selected receivers, we have a number of target locations (true or false) measured by each receiver combination. If a preset number of receiver combinations have generated solutions sufficiently close to each other, then those close solutions are kept, while the others are discarded. In this way, the number of false targets are considerably reduced. The final measured location will be obtained by average of all these close solutions over corresponding receiver combinations.

IV. PROPOSED DETECTION AND LOCALIZATION TECHNIQUES

A. Proposed CA-CFAR Detector with Median Filtering

Reducing the threshold in CFAR detectors reduces the number of missed detections but on the other hand, it increases the false alarms. Our proposed CFAR detector makes it possible to set a very low threshold which highly reduces the number of missed detections, but still provides reasonable false alarm rate.

Obviously when setting a very low threshold, CFAR detector generates an intolerable number of false alarms. In the binary image showing the propagation time versus scan time constructed for each receiver, the false alarms appear as salt and pepper noises, a typical situation in which median filters turn out to be useful. In conventional median filtering employed in image processing, each pixel of the image is replaced by the median value in the \( 3 \times 3 \) neighborhood pixels around [19]. Since in radar processing we have no knowledge of the upcoming pixels, they are not considered in our median filter in order to allow real-time processing.\(^2\) That is, for the pixel \( b_{k,n} \) (the binary output of CFAR detector in Fig. 2), corresponding to scan time \( k \) and propagation time \( n \), only the \( 3 \times 2 \) neighborhood pixels \( b_{k-1,n-1}, b_{k-1,n}, b_{k-1,n+1}, b_{k,n-1}, b_{k,n}, b_{k,n+1} \) are considered for median filtering. These neighborhood pixels are shown in Fig. 3. If the majority of these pixels are equal to 1, then the pixel \( b_{k,n} \) is set to 1, otherwise it is set to 0, that is:

\[
b_{k,n} = \begin{cases} 
1 & \text{if } \sum_{i=k-1}^{k} \sum_{j=n-1}^{n+1} b_{i,j} > T_{med} \\
0 & \text{otherwise}
\end{cases}
\]

(2)

where \( T_{med} \) is a threshold chosen according to system parameters such as UWB transmitted pulse width and target minimum velocity. Note that the threshold \( T_{med} = 3 \) in (2) provides acceptable performance for our UWB radar settings in Section V.

This simple image processing allows to considerably reduce the CFAR threshold without being worried about the false alarms. Fig. 4 shows an example of the binary image constructed by CFAR detector output before and after the median filtering stage at one of the receivers as obtained in the simulation scenario described in Section V. We can see how setting a low CFAR threshold generates very large number of false alarms and how the median filtering is able to remove them. Note that because the transmitted pulse in UWB impulse-radio radars occupies more than one pixel, median filter is not able to remove the target echoes, but only the false alarms.

B. Proposed Pixel-based Localization Technique

In the proposed pixel-based localization technique, the whole surveillance area is divided into pixels.\(^3\) After performing CA-CFAR detection for every sample at each receiver \( j \), the TX-pixel-RX time delay, \( \tau_j \), for a given pixel is calculated using (1), in which \((x, y)\) is replaced by the coordinates of that pixel. The corresponding sample in the received signal will be the \( [(\tau_j - \tau_{LOS})/T_s] \)th sample, where \( \tau_{LOS} \) is the LOS time delay, \( T_s \) is the sampling time and \([.\) stands for nearest integer. Then, the output of CFAR detector is seen at this sample to verify if a threshold exceeding has happened.

After doing the above processing for all pixels in the area, the final estimated positions will be the pixels for which most of the receivers have experienced CFAR threshold exceeding.

\(^2\)However, buffering and making delayed decision can be also used for better robustness.

\(^3\)Note that the definition of pixel here is different from that of used in Section IV-A for image processing.
The TX node emits first derivative Gaussian monocycles with duration parameter 1.4\(\text{ns}\) and whose power spectral density is assumed to exceed the Federal Communications Commission (FCC) mask by 10\(\text{dB}\).\(^4\) The center frequency is 4.5\(\text{GHz}\) and the transmitted signal bandwidth (at 10\(\text{dB}\) w.r.t. the maximum) is 500\(\text{MHz}\). The number of pulses in each frame is \(N_s = 114000\) and the frame duration is \(T_F = 68.4\text{\(\text{ns}\)}\). The sampling frequency is set to 1.5\(\text{GHz}\). For each RX node, the receiver noise figure and the antenna temperature are set to \(F = 6\text{\(\text{dB}\)}\) and \(T_a = 290K\), respectively. These settings result in a transmitted signal power of −32.5\(\text{dBW}\) and a received noise power −86.2\(\text{dBW}\).

We consider a number of 100 pointwise objects to be present in the surveillance area as clutters. The clutters are distributed uniformly over the whole surveillance area. We consider static clutters with \(1m^2\) radar-cross-sections, the same as the target. Each RX node implements a frame-to-frame clutter removal technique based on a first-order high-pass IIR filter with one pole equal to 0.9 operating at a sampling frequency \(1/T_F = 14.6\text{\(\text{Hz}\)}\) [15].

Three targets are assumed to be present inside the area. Each target is moving on a straight line trajectory with a constant velocity of 10\(\text{km/h}\), representing the speed of a human being walking quickly. Note that since detection and localization are performed scan by scan, independently, more complicated trajectories do not affect the performance.

At each RX antenna, the received signal is constructed as the superposition of the direct path, clutter echoes, and ground reflection in addition to the target echo and the noise. The channel gains have been simulated according to \(\sqrt{G_t G_r \lambda_0^2/(4\pi^2 l^2)}\) for the LOS and \(\sqrt{G_t G_r \lambda_0^2 \sigma_o/(4\pi^2 l^2 l_r^2)}\) for any object including the target [11], where \(G_t\) and \(G_r\) are the TX and RX antenna gains, respectively, which are both equal to 0\(\text{dB}\) for our omnidirectional antennas and \(\lambda_0\) is the wave length. Moreover, \(l\) is the TX–RX distance, while \(l_t\) and \(l_r\) are the distances of the object from TX and from that RX, respectively. Finally, \(\sigma_o\) is the radar-cross-section of the object.

This scenario is shown in Fig. 5. The triangle represents the transmitter and the squares are RX antenna positions. The gray ellipses are the blind zones corresponding to each pair of TX-RX antennas. The assumed trajectory of the three targets are shown in the figure for a duration of 600 scan times. Their starting positions are shown with circles.

In the CA-CFAR detector, \(N_g = 20\) guard samples (equal to the transmitted pulse width) and \(N_{ref} = 50\) reference samples are considered. The clustering distance is defined as 3\(m\).

Fig. 6 plots missed detection probability versus false alarm probability for proposed approaches compared to the conventional techniques. The axes are both in logarithmic scale. The plots have been developed by changing the value of CFAR detector scale factor \(\alpha\).

\(^4\)This exceeding has been chosen to cover the large area assumed. The possibility to exceed the FCC mask even by 20\(\text{dB}\) is under consideration in the EU for emergency applications.

V. Simulation Results

In our numerical simulations, we consider a square surveillance area of 100 \(\times\) 100 meters is watched by a UWB radar sensor network composed of one transmitter and six receivers located on the square sides. The origin of our assumed coordinate system is the lower left corner of the square. Therefore, the TX node is located at position (0, 50), while the other 6 RX nodes are at positions (33, 0), (66, 0), (100, 33), (100, 66), (33, 100) and (66, 100), respectively.
In order to calculate these probabilities, we consider a circular gate of radius $5\,m$ around the target true position and we assign the nearest estimated point to the target, if it falls in the gate. False alarms are defined as all the remaining non-assigned estimated points. A target is missed if no estimated point can be assigned to it. Then, the missed detection probability is calculated as the ratio of the number of missed targets to the total number of targets averaged over all scan times and all simulation runs with a given CFAR threshold, whereas the false alarm probability is defined as the average of the number of false alarms over all scan times and all simulation runs with that CFAR threshold. A total number of 50 simulation runs, each with a different noise and clutter realization has been considered for generating the plots.

The comparison shows that the pixel-based localization outperforms conventional direct method of localization in a general view. The performance of both localization techniques improves when employing median filter in CFAR detector. This improvement is more evident for direct localization compared to the pixel-based one. Altogether, the combination of pixel-based localization with median filter seems to provide the best tradeoff for false alarm probabilities higher than $10^{-1}$, whereas for lower values direct localization with median filter is the preferable. Note that the performances shown in Fig. 6 (as well as in the subsequent Fig. 7) are obtained without applying any tracking algorithm as the focus of this work is on detection. It has been observed that, if target tracking is employed, the performances in Fig. 6 and Fig. 7 improve substantially, as expected, the relative performance between different schemes behaving in a similar way.

Fig. 7 shows the CDF (Cumulative Distribution Function) localization error plots for all the above approaches. The CFAR detector scale factor for each technique has been chosen so that the best tradeoff between the missed detection probability and false alarm probability is achieved. Since the typical ranges of these probabilities are values lower than $10^{-1}$ (the grey region in Fig. 6), the best tradeoff is achieved almost at the points specified with bigger markers in Fig. 6. These points correspond to the CFAR detector scale factor, $\alpha$ equal to 10.6 for direct localization, 6.3 for pixel-based localization, 3 for direct localization with median filter and 3.5 for pixel-based localization with median filter. To generate each CDF error curve, we concatenate the estimation error vectors of all three targets over all simulation runs and then we calculate the CDF for the resulting vector.

Again, it can be seen from Fig. 7 that the pixel-based localization outperforms conventional direct method of localization. The localization error of both techniques improves by employing median filtering. In particular, the pixel-based localization with median filter seems to provide the lowest positioning error among all.

According to the above results, the proposed pixel-based localization technique with median filter can be quite appropriate for surveillance applications of UWB multistatic radars in which the blind zones can hide the target for a period of time long enough to lose the track.

VI. CONCLUSION

In this paper, a new CFAR detector based on a simplified median filter and a new pixel-based localization technique have been proposed for UWB multistatic impulse-radio radars. The performance of the proposed approaches has been evaluated numerically for multiple targets accounting for the spatial configuration of the receivers, propagation effects, the presence of residual clutter, and noise.

REFERENCES

Fig. 7. Comparison of localization errors.


