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ORIGINAL ARTICLE

PC Algorithm using MATLAB-Based Time-Domain Signal Processing for UWB Wall Gap Detection

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ABSTRACT

In this work, a Peak Clustering (PC) algorithm and MATLAB based time-domain signal processing of Ultra-Wideband (UWB) wall gap detection is presented. The primary aim of this work is to develop an improved computational algorithm that can process received UWB signal data and find those peaks that are significant to allow separation distance between wall structures to be estimated. The approach under consideration in this paper is based on the study of received UWB signals to determine the distance of gaps within the wall structure. The received signals are obtained by simulation with a CST Studio Suite simulation model using a UWB antenna for transmitting and receiving. Then the received signal is imported into MATLAB for processing. The proposed algorithm is comprised of noise removal, peak detection and peak clustering to extract reflection patterns of different interfaces in the wall. The time delay between clustered reflections is calculated and applied to calculate the distance between the gap using the time-of-flight principle. The simulation results show that the proposed PC algorithm is effective and can accurately detect the wall gaps ranging from 300 mm to 500 mm. It shows how to properly perform signal processing-based gap detection suitable for security, search and rescue and structural inspection applications.

Keywords: **Peak Clustering Algorithm, Time-Domain Signal Processing, MATLAB, Peak Detection, Wall Gap Detection, Ultra-Wideband (UWB)**

Author`s Contribution

[1,2] Data analysis, interpretation, and manuscript writing, Active participation in data collection
[2,4] Conception, synthesis, planning of research. Interpretation and discussion

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INTRODUCTION

The properties of Ultra-Wide Band (UWB) technology with a large bandwidth, low power spectral density and high time domain resolution make it a suitable solution for high resolution sensing and detection over short distances [1, 2]. Contrary to conventional narrowband systems, UWB transmits ultra-short pulses which allow for highly accurate time-of-flight measurements and multipath resolution, which are important for applications such as through-wall and structural sensing [3] and [4]. Recently, UWB radar and sensing systems have attracted much attention in non-destructive evaluation, human detection in the presence of obstacles (walls, debris, etc.) and localization in indoor environments [5] [6]. The systems have heavily on time-domain signal processing methods, where the time of the reflected signals on various interfaces is used to obtain meaningful spatial information [7]. The received signals are, however, corrupted by noise and multipath reflection, resulting from the materials' attenuation, and the signals are difficult to interpret accurately and must be detected with certain reliable algorithms [8].

To improve interpretability of UWB signals, various signal processing methods, such as filtering, thresholding, and feature extraction have been widely used [9]. Of these, the peak detection and clustering techniques have gained significance as a way of determining reflection components associated with various structural boundaries [10]. A few recent studies have demonstrated that usage of the clustering approach for signal interpretation can greatly enhance target separation and distance estimation accuracy in complex environments [11]. Taking advantage of its computational and visualization power, MATLAB has been widely adopted as a popular platform for the development of signal processing algorithms for UWB systems [12]. It enables the researcher to import simulation or experimental data, to process the time domain signals and to apply complicated detection algorithms in a structured environment [13]. In this research, MATLAB is employed as the main tool to implement a PC algorithm to analyze the reflection signals of UWB.

The purpose of the PC algorithm is to detect and cluster reflection peaks according to their temporal proximity to detect the wall interfaces in multi-layer structures accurately [14]. The time difference between the clustered reflections is then measured, and the distance (gap) measured in physical space is calculated based on the time-of-flight principle. This method is more robust to noise and overlapping reflections than the standard peak counting techniques [15]. The electromagnetic propagation of UWB signals in wall structures with different gaps is simulated using CST Studio Suite [16]. A controlled environment is provided in simulated data to verify the proposed algorithm before being used in real-life applications. The combination of CST simulation and MATLAB based processing creates a full end-to-end signal analysis pipeline for UWB based structural sensing system [17]. Recent developments in UWB radar signal processing demonstrate the need for intelligent algorithms for feature extraction and target identification in complex environments [18]. Studies have shown that clustering and adaptive thresholding methods in the time domain can greatly enhance detection capability in through-wall sensing applications [19]. The developments are helping the use of algorithmic methods, like the proposed PC algorithm, for reliable gap detection. Hence, the present study is aimed at developing a time domain processing framework using a PC algorithm for accurate detection of hidden gaps in between the wall structures using MATLAB.

SIMULATION MODEL (CST STUDIO SUITE)

CST Studio Suite is a popular full-wave electromagnetic simulation platform for modelling and analyzing high-frequency antenna systems and wave propagation environments. It offers time domain and frequency domain solvers and is very useful for UWB sensing, through-wall detection applications [21, 22]. CST is employed to develop and simulate the proposed wall gap detection system based on UWB in this work. As the first step of the simulation model, UWB antenna is designed and validated in the model. A Slot-Loaded Antipodal Vivaldi Antenna (SL-AVA) is implemented in this purpose. This antenna is chosen because of its large impedance bandwidth, high gain and strong directional radiation properties, making it suitable for time domain sensing and radar detection system [23]. The antenna design of SL-AVA used for this study is from a past published and validated structure reported in [24].

Once the antenna is implemented, the simulation structure is built by positioning two parallel wall structures with a separation distance "d" between them (refer to Figure 1). The wall structures shown here are a simplified version of the structural gap detection analysis model. The separation distance between the walls varies systematically to evaluate the performance of the proposed detection algorithm under different scenarios.

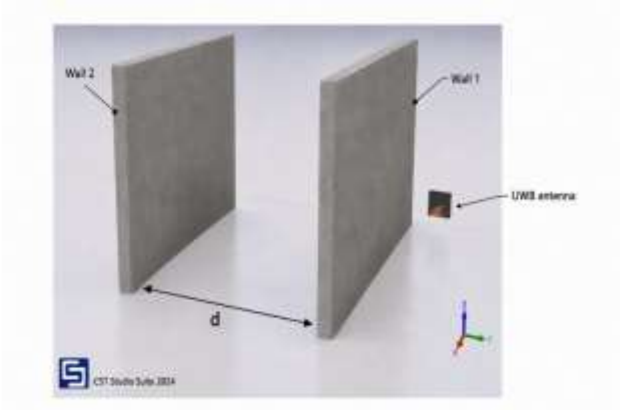

Figure 1: CST Model using UWB antenna

The UWB antenna is oriented towards the wall structure, transmitting and receiving electromagnetic waves. The operating frequency range of the antenna is determined between 2 GHz and 10 GHz, to provide enough bandwidth for high-resolution time-domain analysis and detection of multiple reflection components. This wide bandwidth allows for a more precise identification of reflections from individual reflection surfaces [25]. After the setup of the simulation has been finished, the CST solver is run to calculate the propagation of the electromagnetic waves, which includes transmission and reflection as well as scattering at the wall structures. Once the simulation is finished, the CST received signal data is extracted in the time domain and then exported to MATLAB for further processing. This data will be input to the proposed PC algorithm used to estimate the gap distance between the two walls using the time domain reflection analysis.

PC ALGORITHM

The processing unit for this work is the proposed PC (Peak Clustering) algorithm which is used to extract meaningful reflection features from UWB time-domain signals for accurate wall gap estimation. The algorithm is executed on the data of the received signal, which is exported from CST Studio Suite and imported into MATLAB where the digital processing of the signal takes place, as shown in the flowchart in figure 2. The main purpose of the PC algorithm is to detect, classify and cluster reflection peaks associated with various interfaces of the wall and to use the temporal distance between these peaks to estimate the structural gap distance. To address this issue, the proposed approach focuses on temporal clustering of the reflection components, which leads to a more robust approach to peak counting in the presence of noise and multipath interference in contrast to traditional methods [26].

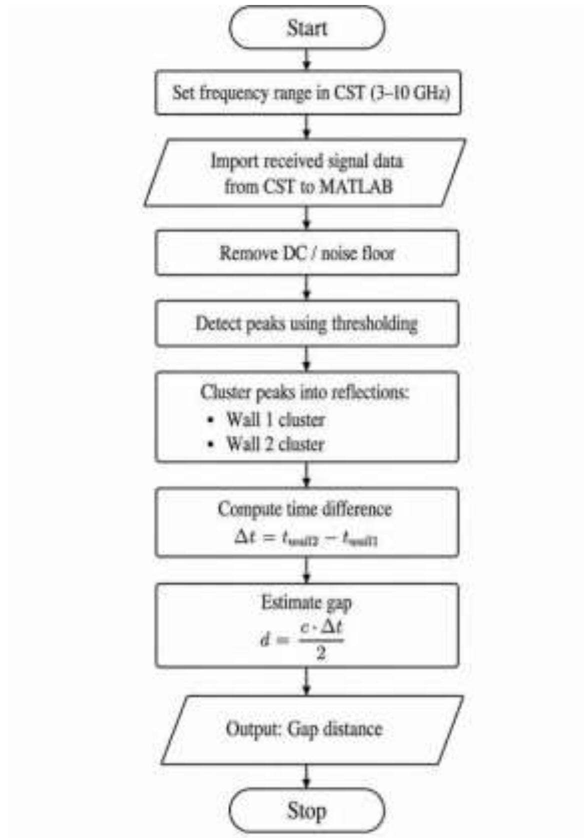

Figure 2: Flow chart of PC algorithm

Step 1: Acquisition and Preprocessing of the Signals

The first step is to get the received UWB signal into MATLAB from CST. The raw signal will have DC offset, system noise and multipath reflections. Hence, the DC components have been eliminated, and the noise floor is lowered by the pre-processing before peak detection, which results in a better accuracy in peak detection [27].

Step 2: Detect peaks using Thresholding.

The resulting signals are preprocessed and then a peak detection algorithm is used based on a threshold. The algorithm scans time-domain signal and detects the amplitude which is greater than the adaptive threshold that is set in advance. The peaks detected are likely to be reflections from the boundaries of the walls.

A peak detection mathematically is done as follows:

If $y(t) > T$, then $t \in P$

where (T) is the adaptive threshold and (P) is the detected set of peak locations.

This will help to avoid false peaks caused by noise, and only peaks that are significant due to reflection will be further processed [28].

Step 3: PC Algorithm

The PC algorithm is the main contribution of this work. Peaks are clustered together, based on their temporal closeness.

The clustering rule is:

If $|\, t_i - t_j \,| < \Delta t_{th}$, then $t_i, t_j \in C_k$

Where:

C_k= kth reflection cluster

Δt_{th}= clustering threshold Typically:

Cluster 1 → Wall 1 reflections (front & back surfaces)

Cluster 2 → Wall 2 reflections (front & back surfaces)

This clustering solution greatly aids in improving the reflection separation in complicated multipath environments [29].

Step 4: Time Difference Computation

After clustering, the maximum value for each cluster is picked. Time of arrival difference between wall clusters is calculated as:

$$\Delta t = t_{wall2} - t_{wall1}$$

It is the propagation delay of the UWB signal between the two wall structures.

Step 5: Gap Estimation

The gap distance is estimated by the time-of-flight relationship, which is:

$$d = \frac{c \cdot \Delta t}{2}$$

where:

(c) = speed of light

Prop delay (2-way) is factored in as factor 2

The final step is to convert the signal domain information to the spatial domain measurement. The proposed PC algorithm improves the accuracy of reflection separation in UWB wall sensing by creating an effective separation of time domain peaks corresponding to wall interfaces by identification and grouping process. It also improves the sensitivity to noise by making it possible to remove weak and spurious signal components from the signal by filtering with thresholds, making the reflections more reliable.

In addition, the algorithm allows satisfaction

grouping of wall echoes by allowing peaks identified in the area to be grouped into separate reflection areas based on their temporal proximity. Finally, it offers stable time-delay estimation between the clustered reflections, which guarantees stable and accurate estimation of gap distance even when signal distortion and multipath effect exist.

RESULTS AND DISCUSSION

The results of the simulations are shown in this section, using CST Studio Suite and processed with time domain signal analysis, performed in MATLAB. The proposed time domain signal processing framework for UWB wall gap detection is implemented on MATLAB, the main computational platform. The received UWB signal exported from CST Studio Suite is processed in MATLAB to obtain meaningful time domain features for gap estimation purposes. The imported signal data is the time domain post-interaction response of the UWB system and is the first step in MATLAB processing. This raw signal will usually be affected by noise, DC offset and multipath induced distortions. Hence, any DC component and noise signals are removed from the signal by the preprocessing step, to preserve only meaningful information of reflection. In this work, MATLAB is used as a connecting tool between simulated electromagnetic data and interpretation of the data using algorithms and is useful for obtaining structural information from raw electromagnetic data provided by the UWB. In conclusion, the MATLAB-based processing framework offers a streamlined and organized way to implement the PC algorithm, facilitating precise estimation of wall gap distances.

The performance of the proposed PC algorithm is tested for three different gap distance between the wall separating the rooms 300 mm, 400 mm and 500 mm. UWB signals received are processed in the time domain to detect the reflection peaks for the wall interfaces, and to estimate the gap distance based on the time-of-flight principle.

Figure 3 shows the received UWB signal for a separation distance of 2 walls being 300 mm apart. In this instance, the time-domain answer decisively shows two clearly characterized reflection clusters, related to the various wall interfaces. Peaks r_1and r_2 correspond to the first cluster of reflections, from Wall 1, and peaks r_3 and r_4 to the second cluster of reflections, from Wall 2. The separation of these two clusters Δt is relatively small, since the propagation distance between the walls is shorter. Although the spacing is quite small, the separation between the two reflection groups is clearly shown in the signal, indicating that the proposed PC algorithm can well separate multiple wall interfaces even at smaller gap distances.

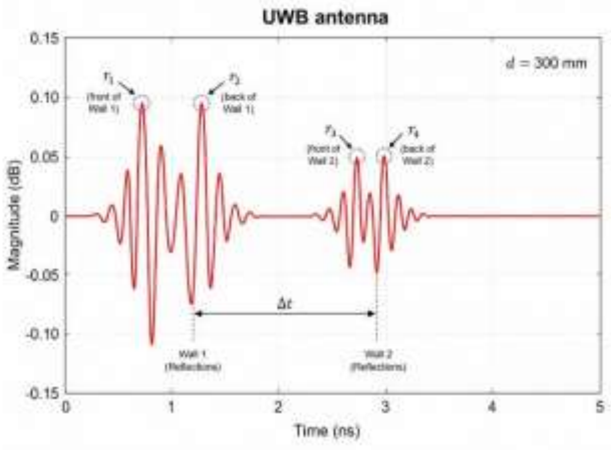

Figure 3: Shows the results for the wall gap distances of 300 mm

In Figure 4, the distance between the two walls is increased to 400 mm, and a significant time difference between the two reflection clusters is obtained. This first wall reflections are stable in time (no phase change) and in amplitude (little change), meaning that the signal interacts with the first interface in a consistent way. The second wall reflections move further along the time axis, however, because the distance traveled to the second wall through the air gap is greater. As such, the time difference Δt between the two clusters increases with respect to the 300 mm case. This behavior validates the time-of-flight principle which is used in the proposed algorithm to determine accurate gap estimation, based on the linear relationship between propagation delay and physical separation established by this behavior.

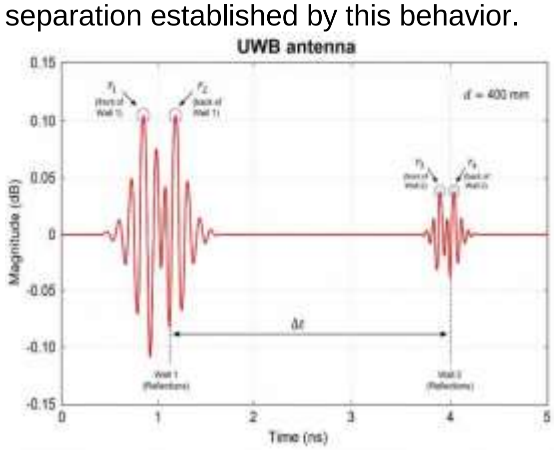

Figure 4: Shows the results for the wall gap distances of 400 mm

The time delay between the clusters of reflections becomes more apparent in Figure 5, where the space between the two walls is doubled from 500 mm to 1000 mm. The second cluster of Wall 2 reflections moves much further to the right in the time domain signal because of the longer propagation path. Also, the amplitude of the second cluster is slightly reduced, which is believed to be due to higher propagation loss and signal attenuation due to the greater separation distance. Even with this, the distinction between the two reflection clusters is still quite clear and there is a lower chance of misclassification. This case also reflects the capability and stability of the proposed PC algorithm for precise detection and discrimination of larger gaps in structural gaps for the wall sensing environment.

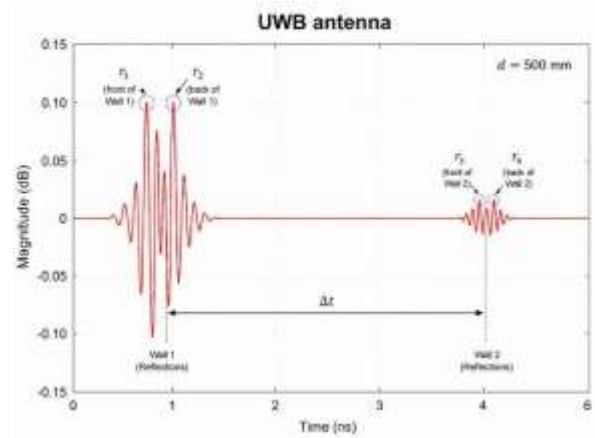

Figure 5. Shows the results for the wall gap distances of 500 mm

TABLE 1: Time-domain analysis of UWB reflection signals for different wall gap distances

Wall Gap Distance (mm)	Time Delay (Δt)	Observation	Signal Behavior
300 mm	Small	Closely spaced clusters	Strong overlap tendency
400 mm	Moderate	Clear separation	Stable detection
500 mm	Large	Well-separated clusters	Reduced amplitude due to attenuation

The proposed wall gap detection system using UWB is summarized in Table 1, which shows the relationship between gap distance, time delay, and signal behavior of the UWB-based wall gap detection system. The time delay Δt is small for a gap distance of 300 mm, which causes the formation of close reflection clusters. In this particular example, a high degree of overlap is present in the signal, (the reflections are closer in the time domain), but the PC algorithm can still accurately distinguish and separate the clusters. As the gap distance is increased to 400 mm, the time delay is moderate, and a separation between the reflection clusters is seen. This is the most stable detection case, where the peak of reflections is well defined and it is possible to classify them more accurately which gives better gap estimation performance. The bigger the gap (500 mm in this case), the longer the time delay, and the more space there is between the reflection clusters in the time domain. But with the additional distance propagation, attenuation is greater and can easily be noticed with the amplitude of the second wall reflections. This does not diminish the clustering structure, however, and both wall interfaces can be clearly identified. In general, the results show an increase in time delay as a function of the gap distance, and as the gap distance grows larger (from 300 mm to 500 mm) two distinct signals are clearly seen, but with reduced amplitude. Overall, the results show that as the gap distance increases, the time delay also increases, and that the signal behavior changes from overlapping reflections at smaller gaps (300 mm) to clearly separated but reduced amplitude signals at larger gaps (500 mm). It verifies that the proposed PC algorithm is effective in adapting in various gap sizes and still maintains a stable detection performance. The results also show the effectiveness of the PC algorithm to detect and group reflection peaks of different wall interfaces.

Signal processing is implemented in MATLAB to efficiently remove noise and extract meaningful reflection peaks, and a clustering method is used to classify accurately even for close spaced reflections. The algorithm can also achieve good separation at a shorter gap of 300 mm, where the overlap is greater. Even for larger gaps (500 mm), the clustering approach remained stable and continued to produce accurate gap estimation, while the attenuation is increased and peak amplitude is decreased. In summary, the proposed CST simulation and MATLAB-based PC algorithm framework proves to be a powerful and effective solution for UWB-based structural gap detection.

CONCLUSION

This paper has been able to successfully develop a PC algorithm with MATLAB based time domain signal processing for UWB wall gap detection. The method that is proposed efficiently processes the received signals at UWB by filtering, peak detection and clustering for extracting meaningful features from the wall structures in the form of reflections. The time domain analysis allows for the correct identification of reflection clusters associated with different interfaces of the walls. The time difference between these clusters can be used to estimate the gap distance by the time-of-flight method. The study has concluded that the proposed algorithm for wall gap detection is effective in detecting hidden gaps in the range of 300 mm to 500 mm and that the method of wall gap detection based on the signal processing of the PC algorithm using MATLAB is reliable and has a low calculation complexity. Adaptive threshold and more sophisticated filters can be added to improve performance in noisy environments in the future.

REFERENCE

[1] M. Cheraghinia *et al*., "A comprehensive overview on UWB radar: Applications, standards, signal processing techniques, datasets, radio chips, trends and future research directions," *IEEE Communications Surveys & Tutorials*, vol. 27, no. 4, pp. 2283–2324, Aug. 2025, doi: 10.1109/COMST.2024.3488173.

[2] M. Z. Win and R. A. Scholtz, "Impulse radio: How it works," *IEEE Communications Letters*, vol. 2, no. 2, pp. 36–38, Feb. 1998.

[3] G. Pochanin *et al.*, "Modern trends in development and application of the UWB radar systems," in *Proc. Int. Conf. Ultrawideband and Ultrashort Impulse Signals (UWBUSIS)*, Sept. 2016, doi: 10.1109/UWBUSIS.2016.7724141.

[4] D. Kumar *et al*., "A novel baseline-free imaging algorithm for noncontact damage localization using UWB antennas: Validation for metallic and concrete structures," *IEEE Transactions on Instrumentation and Measurement*, vol. 75, 2026, doi: 10.1109/TIM.2026.3693453.

[5] C. Li *et al*., "A real-time UWB-based device-free localization and tracking system," *Electronics*, vol. 14, no. 17, Art. no. 3362, 2025, doi: 10.3390/electronics14173362.

[6] M. Cimdins *et al*., "Exploiting ultra-wideband channel impulse responses for device-free localization," *Sensors*, vol. 22, no. 16, 2022, doi: 10.3390/s22166255.

[7] J. Y. Kim *et al*., "Peak detection algorithm for vital sign detection using Doppler radar sensors," *Sensors*, vol. 19, no. 7, Art. no. 1575, 2019, doi: 10.3390/s19071575.

[8] A. F. Molisch, *Wireless Communications*, 2nd ed. Hoboken, NJ,

USA: Wiley, 2011.

[9] T. Adali and S. Haykin, *Adaptive Signal Processing: Next Generation Solutions*. Hoboken, NJ, USA: Wiley, 2010.

[10] J. G. Proakis and D. G. Manolakis, *Digital Signal Processing: Principles, Algorithms, and Applications*, 4th ed. Upper Saddle River, NJ, USA: Pearson, 2007.

[11] R. O. Schmidt, "Multiple emitter location and signal parameter estimation," *IEEE Transactions on Antennas and Propagation*, vol. 34, no. 3, pp. 276–280, Mar. 1986.

[12] MathWorks Inc., *MATLAB Documentation*, Natick, MA, USA, 2024.

[13] Dassault Systèmes, *CST Studio Suite User Manual*, 2024.

[14] W. Wang *et al*., "Anomaly detection in big data from UWB radars," *Security and Communication Networks*, 2013.

[15] A. Mazzamurro *et al*., "Time domain reflectometry for improved surface acoustic wave magnetic field sensor sensitivity," in *Proc. IEEE SENSORS*, 2019, doi: 10.1109/SENSORS43011.2019.8956893.

[16] D. M. Pozar, *Microwave Engineering*, 4th ed. Hoboken, NJ, USA: Wiley, 2012.

[17] A. F. Majeed *et al*., "UWB localization system with signal preprocessing," *IEEE Sensors Journal*, 2025.

[18] K. Zhang *et al*., "UWTrack: Clustering-assisted multiperson passive indoor tracking via IR-UWB," *IEEE Transactions on Instrumentation and Measurement*, vol. 73, 2024, doi: 10.1109/TIM.2024.3485432.

[19] W. Wang *et al*., "Background and clutter removal techniques for ultra short range radar," in *Proc. 17th European Radar Conference (EuRAD)*, 2020, doi: 10.1109/EuRAD48048.2021.00031.

[20] J. Zhang *et al*., "TWPT: Through-wall position detection and tracking system using IR-UWB radar utilizing Kalman filter-based clutter reduction and CLEAN algorithm," *Electronics*, vol. 13, no. 19, Art. no. 3792, 2024, doi: 10.3390/electronics13193792.

[21] S. Ahmed *et al*., "Signal processing algorithm for detection of two concealed targets," *Lahore Garrison University Research Journal of Computer Science and Information Technology*, vol. 9, no. 2, 2025, doi: 10.54692/lgurjcsit.2025.092720.

[22] A. Taflove and S. C. Hagness, *Computational Electrodynamics: The Finite-Difference Time-Domain Method*, 3rd ed. Norwood, MA, USA: Artech House, 2023.

[23] S. Ahmed, A. Joret, N. Katiran, M. I. Abbasi, and F. S. Khan, "An improved design of UWB slotted antipodal Vivaldi antenna for through-wall imaging (TWI) systems," *Periodica Polytechnica Electrical Engineering and Computer Science*, vol. 69, no. 2, pp. 207–214, 2025.

[24] S. Ahmed, A. Joret, N. Katiran, M. I. Abbasi, and N. F. Aminuddin, "UWB slot-loaded antipodal Vivaldi antenna for through-the-wall radar imaging (TWRI) applications," *Serbian Journal of Electrical Engineering*, vol. 22, no. 2, pp. 267–279, Jun. 2025, doi: 10.2298/SJEE2502265A.

[25] M. A. Khan *et al*., "Ultra-wideband pentagonal fractal antenna with stable radiation characteristics for microwave imaging applications," *Electronics*, vol. 11, no. 13, Art. no. 2061, 2022, doi: 10.3390/electronics11132061.

[26] D. Kocur *et al*., "A novel signal processing scheme for static person localization using M-sequence UWB radars," *IEEE Sensors Journal*, vol. 21, no. 18, pp. 20489–20499, Sept. 2021, doi: 10.1109/JSEN.2021.3093658.

[27] F.-C. Chen and W. C. Chew, "Time-domain ultra-wideband microwave imaging radar system," *Journal of Electromagnetic Waves and Applications*, vol. 17, no. 2, pp. 313–331, 2003, doi: 10.1163/156939303322235842.

[28] X. Wei *et al*., "Adaptive detection algorithm with dynamic dual-threshold for low probability of intercept radar signals and its FPGA implementation," *IEEE Access*, vol. 14, 2026, doi: 10.1109/ACCESS.2026.3660312.

[29] T. Arsan *et al*., "A clustering-based approach for improving the accuracy of UWB sensor-based indoor positioning system," *Wireless Communications and Mobile Computing*, 2019, doi: 10.1155/2019/6372073.