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The survey of through-wall radar system

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Abstract. In contemporary times, optical cameras have garnered extensive usage, particularly in the realm of surveillance applications. Nevertheless, optical cameras possess certain limitations that hinder their ability to capture images efficiently in certain scenarios. For instance, they struggle to produce clear photographs in environments characterized by excessive brightness, darkness, or the use of flash. Additionally, the acquisition of high-definition portraits using optical cameras may raise ethical questions regarding potential violations of personal privacy. The detection of occluded objects by optical cameras poses a significant difficulty in the context of security applications. The topic of through-wall radar has gained significant interest due to its notable camouflage, as well as its advantageous features such as through-wall detection and resilience to optical causes. Researchers have successfully devised and developed several efficient through-wall radar systems that have shown to be helpful in several domains such as search and rescue operations, counter-terrorism efforts, medical applications, and urban warfare scenarios. This study provides an overview of prevalent through-wall radar technologies, conducts comparative evaluations, and explores the potential advancements and issues associated with this technology.

Keywords: Through Wall Imaging, Continuous Wave, Ultra-Wideband.

1. Introduction

The increasing demand for imaging in diverse circumstances is driven by the rapid advancement of radar technology. The subject of through-wall imaging has progressively garnered significant interest. This technique has the potential for use across various disciplines. In general, the act of putting optical cameras within private areas, such as toilets and bedrooms, is commonly regarded as unfriendly. The utilization of through-wall imaging enables the acquisition of data pertaining to the internal characteristics of a room without the need for direct installation of sensors. Optical cameras encounter challenges in effectively managing elements such as glare and low-light settings. In the context of natural catastrophes, such as earthquakes, floods, and tornadoes, the utilization of through-wall imaging technology proves to be effective in the detection and localization of survivors trapped beneath debris. Furthermore, this technology has the potential to provide direct visualization of the structural composition of the rubble, thereby facilitating rescue operations with enhanced efficiency and clarity. In the context of ensuring security, it is deemed precarious for law enforcement personnel to enter a premises without prior knowledge of the internal circumstances. Through-wall imaging enables law enforcement personnel to obtain advanced knowledge of critical information, including

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the precise quantity and spatial distribution of individuals within a structure. This capability serves to mitigate potential risks to the safety of law enforcement employees and enhances operational efficiency.

The main aim of this paper is to bring together the current through-wall radar systems, assess their strengths and limitations, and improve understanding of the suitability of various technologies through comparison. This will provide a basis for making well-informed decisions in specific application scenarios. The objective of this article is to provide guidance to professionals and scholars in the domain of through-wall radar technology, facilitating a comprehensive comprehension of the current state of the field. Additionally, this paper highlights prospective areas for innovation and enhancement in the future development and investigation of through-wall radar systems.

2. Process of Through-Wall Imaging

The process is illustrated in Figure 1.The process commences with the emission of wireless signals, such as radar or Wi-Fi, which are directed towards the target area. These signals possess distinct characteristics in terms of frequency, waveform, and power levels, enabling them to traverse barriers.

Upon encountering obstacles, such as walls or rubble, a portion of these signals interacts with the objects. Some signals are reflected back, while others might be scattered, refracted, or absorbed to varying degrees, depending on the material composition of the obstacles.

The signals that have interacted with the objects and obstacles subsequently return as echoes, including a substantial amount of valuable information. The reverberations of sound waves offer valuable information regarding the structure, size, and arrangement of concealed entities that are not readily observable.

The acquired echo signals undergo a sophisticated range of signal processing procedures. This entails the examination of characteristics such as the phase, amplitude, and frequency of the signal. Signal processing techniques can be employed to extract these features with the aim of image restoration.

With these extracted features in hand, the final step involves the intricate task of image reconstruction. This step essentially involves the translation of signal data into visual information, providing an image of the obscured environment. Various mathematical and computational algorithms are employed to transform signal attributes into a coherent representation of the hidden space.

The effectiveness of through-wall imaging depends on various factors, including the frequency of the emitted signals, power levels, the type of encountered obstacles, and the complexity of the environment. The main focus of this paper is to discuss the types of emitted signals.

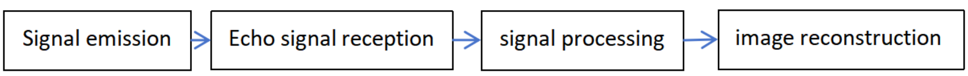

Figure 1. process of Through-Wall Imaging.

3. Overview

3.1. Continuous Wave

Continuous Wave (CW) technology operates by transmitting a constant-frequency signal without modulation. In CW radar systems, a continuous signal is emitted at a fixed frequency, and when this signal encounters an object, a portion of it reflects back to the source. The time delay between transmission and reception allows for distance measurement, forming the basis of radar ranging. Furthermore, the utilization of the Doppler effect enables the detection of frequency variations resulting from the movement of objects, thereby offering valuable insights about their velocity and trajectory. Gennarelli et al. have successfully proved the efficacy of employing CW radar for the purpose of detecting humans located within confined areas [1]. Nevertheless, the difficulty in signal processing arises from the intrinsic simplicity of CW signals, which lack unique features. In order to address these constraints, enhanced methodologies such as Stepped Frequency Continuous Wave

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(SFCW) and Frequency-Modulated Continuous Wave (FMCW) are frequently utilized. The implementation of advanced radar techniques includes modifications in frequency or waveform attributes, hence enhancing the signal processing capabilities for precise identification and monitoring of targets in interior settings. Researchers can improve the efficacy of radar in detecting and monitoring human presence by incorporating SFCW and FMCW technologies, which can effectively mitigate the limitations associated with using pure CW signals.

3.1.1. Stepped Frequency Continuous Wave. The operational mechanism of a stepped frequency continuous wave (SFCW) radar system entails the emission of a continuous sequence of wave signals characterized by distinct and unchanging frequencies. These frequencies are systematically varied in a stepped or stair-step manner, progressing from an initial frequency to a final frequency. The utilization of SFCW radar is prevalent in through-wall detection for the purpose of detecting vital signals of the human body, including respiration and heartbeat. The utilization of SFCW radar systems in disaster rescue operations, such as earthquakes, is made possible by this capability. In the experimental study conducted by the researchers [2], the participants were given instructions to assume three different positions: supine lying, side lying, and prone lying, with the requirement of maintaining little movement. The simulation involves the use of clay bricks to represent rubble, positioned above the participants. The thickness of the rubble steadily escalates, reaching a maximum of 20cm. The trials provide evidence that the radar system demonstrates exceptional performance in the detection of human vital signs. The precise placement of the antenna in relation to the thoracic cavity of the human body does not significantly impact the detection of respiration. Maintaining a static posture for a duration of 30 seconds produces data of acceptable quality. The TWI radar system, which was created by the National University of Defense Technology as referenced in [3], employs SFCW signals and has demonstrated the capability to identify human presence behind barriers and monitor their motion.

3.1.2. Frequency-Modulated Continuous Wave. The operational mechanism of an FMCW radar entails the emission of a continuous signal that experiences a gradual alteration in frequency throughout its duration. In contrast to CW radar, frequency-modulated continuous wave (FMCW) radar involves the transmission of a signal that undergoes frequency modulation over a specific time interval referred to as a "sweep". The emission of this signal commences at an initial frequency, gradually transitioning to a final frequency, and afterwards repeating the process [4]. Based on the study conducted by Fioranelli, F. et. al., it has been shown that the radar system utilizes a combination of optimized patch antennas and traditional Vivaldi antennas for the purpose of receiving the reflected FMCW signals. This configuration allows for the identification of both stationary objects and moving humans located behind walls [5].

FMCW is widely applied in SIL radar (self-injection-locked radar) systems. IL radar refers to a specific type of radar system where "self-injection locked" indicates self-locking through injection. It's a technique that involves injecting a portion of the radar's own emitted signal into the received radar echoes. This is done to achieve a highly stable signal source, enhancing the accuracy of measurements related to the target's position, velocity, and other characteristics. In conventional radar systems, the signal source can be influenced by uncertainties like temperature changes and spurious frequencies, which might cause frequency or phase variations in the signal, impacting measurement accuracy. The process of self-injection locking involves the injection of a fraction of the sent signal into the received signal, hence facilitating synchronization between the two signals. As a result, in the event that the transmitted signal undergoes slight alterations in frequency or phase, the received signal adapts accordingly, therefore effectively minimizing the influence of uncertain circumstances. This technology is very useful in applications that need precise measurements, such as radar range and velocity measurements. The implementation of self-injection locking can result in improved stability and accuracy of radar systems, hence enhancing the reliability and precision of measurement findings. The utilization of a Synthetic Aperture Radar (SAR) system with SIL technology has been effectively shown by researchers for the purposes of imaging and tracking objects in motion through walls [6-7].

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3.2. Ultra-Wideband

Ultra-Wideband (UWB) is a radio technology that uses a very large bandwidth to transmit information over short distances. Ultra-wideband (UWB) signals have the ability to distribute their energy across a broad spectrum of frequencies, hence enabling their coexistence with other wireless systems without inducing any form of interference. Ultra-wideband (UWB) technology possesses notable attributes such as superior penetration capabilities, the ability to detect multiple targets, accurate distance measurement, and low-power transmission, among various other advantages. The aforementioned attributes have contributed to its extensive utilization in the field of through-wall imaging technology.

3.2.1. Enhanced Delay-and-Sum Ultra-Wideband. EDAS (Enhanced Delay-and-Sum) is an improvement upon the DAS (Delay-and-Sum) technique. EDAS involves coherent summation of reflected signals from different transmitting and receiving devices, along with the application of two clutter suppression techniques: focusing quality weighting [8], and pairwise multiplication [9]. These enhanced techniques in EDAS contribute to more precise directional processing of signals in specific directions, thereby offering higher performance in practical applications.

The utilization of EDAS technology for through-wall imaging is documented in reference [10]. The radar system has the capability to conduct three-dimensional imaging of a cylindrical object located behind a brick wall with a thickness of 16cm. This functionality leads to a notable improvement in contrast and a reduction in unwanted signals. Nevertheless, the process of shifting from two-dimensional (2D) imaging to three-dimensional (3D) imaging necessitates a considerable duration, rendering the attainment of real-time 3D detection impractical. The utilization of a computer with enhanced performance has the potential to reduce processing time. However, it is important to acknowledge that the processing time for 3D imaging remains a crucial factor that must be taken into account.

3.2.2. Field-Programmable Gate Array Ultra-Wideband. An FPGA, short for Field-Programmable Gate Array, is an integrated circuit that distinguishes itself by its remarkable configurability. In contrast to Application-specified Integrated Circuits (ASICs), Field-Programmable Gate Arrays (FPGAs) include the capability to be reconfigured and programmed subsequent to their manufacturing process, hence enabling the attainment of specified objectives. This attribute endows FPGAs with a higher degree of flexibility when compared to ASICs. The capacity for adaptability enables more advanced logic design optimizations, leading to improved performance. Field-Programmable Gate Arrays (FPGAs) have notable parallel processing capabilities, rendering them highly suitable for applications necessitating substantial parallelism, such as digital signal processing. Moreover, the inherent low latency characteristics of Field-Programmable Gate Arrays (FPGAs) render them suitable for real-time imaging applications, as evidenced by their utilization in radar systems.

Numerous scholarly articles have documented the effective deployment of through-wall imaging systems through the integration of field-programmable gate arrays (FPGAs) with various additional hardware components. All of them have successfully obtained effective detection and imaging results through walls.

The researchers employed a high-sampling oscilloscope with a sampling rate of 5 Giga-samples per second (Gsa/s) and a field-programmable gate array (FPGA) to effectively attain precise localization and clear identification of immobile subjects situated at various positions behind concrete barriers [11]. The radar system can distinguish objects at equal azimuth angles if they are more than 15cm apart. This radar system integrates Synthetic Aperture Radar (SAR) operations with an SP16T switch, making it suitable for real-time applications. This technology can penetrate walls due to its simple development and deployment.

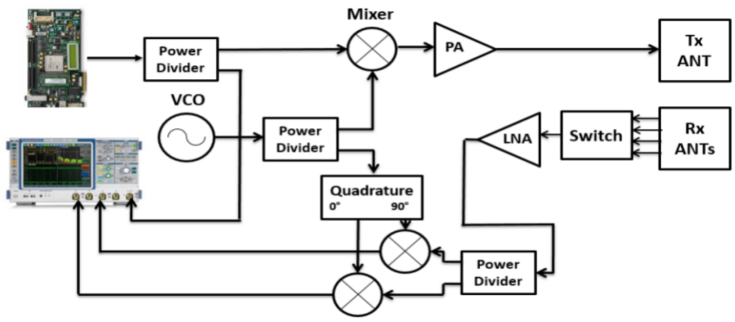

Figure 2. Radar imaging blocs [12].

The system developed by Yang, et. al. consists of several main subsystems(figure 2) [12], including microwave frontend, data acquisition module, and system control/processing module. It performs well in real-time data collection and motion tracking. According to experimental results, this system can real-time track moving targets at a speed of 1.5m/s and can also detect whether there are live individuals behind walls, provided that their breathing is stable and they remain stationary. The compact and flexible design of this system allows it to be deployed within vehicles for mobile deployment, imaging targets from different directions, and assembling 2D images into 3D images. The system is more complex than [11], with a higher design cost, but it can provide a greater imaging range and cross-range resolution. According to the research conducted by Phasukkit, P. et al., they employ Field-Programmable Gate Arrays (FPGAs) to generate Impulse Radio-Ultra Wideband (IR-UWB) pulses. These pulses are utilized for the purpose of detecting human beings located beneath layers of simulated rubble, which are constructed by stacking multiple layers of clay bricks. The participants in the experiment are provided with instructions to assume both supine and prone postures, while maintaining immobility. The findings from the experiment suggest that the system has the capability to precisely assess the respiration rate of individuals positioned under debris with varying thicknesses (9, 18, and 27 cm), in addition to determining the thickness of the rubble.

3.2.3. M-Sequence UWB. The M-sequence is a distinctive type of pseudo-random binary sequence that possesses applications in noise modulation. The generation process is facilitated by a linear feedback shift register (LFSR) with numerous storage units, with each unit encoding a binary digit of either 1 or 0. The generation of the sequence is achieved through a process of shifting and applying XOR operations on the storage units, following predetermined rules. This process yields a pseudo-random sequence with an extensive period, capable of reaching the maximum length of the shift register. Consequently, the sequence can be utilized repeatedly without encountering any repetitions [13]. The N-stage shifter is responsible for producing M-sequences by utilizing the system clock. M-sequences are employed for the modulation of electromagnetic waves generated by the radar transmitter. The transmission of modulated electromagnetic waves is directed towards the designated target, and subsequent to their reflection from said target, they are received by the designated receiving antenna. Subsequently, the signals that have been received are subjected to processing using various components, including analog-to-digital converters, in order to derive signals that are suitable for subsequent analysis and interpretation. The M-sequence ultra-wideband (UWB) radar system is illustrated in Figure 3 [14].

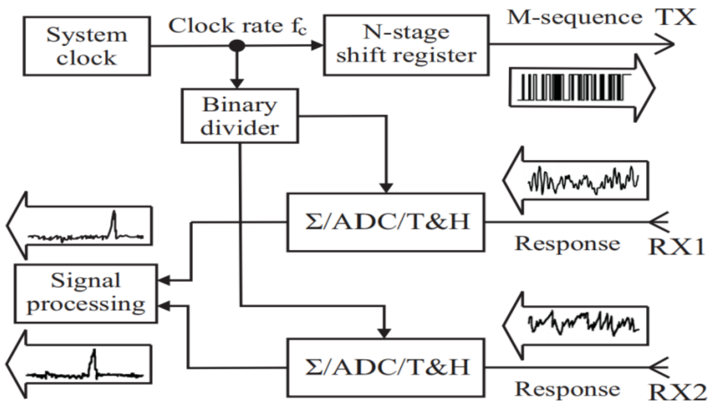

Figure 3. Block schematic of M-sequence UWB radar system [14].

The measurement of signal attenuation in the M-Sequence UWB radar system when traversing particular walls has been conducted in the context of signal preprocessing. The velocity at which the signal propagates within the walls has also been estimated by a computational formula. Since the output of the M-Sequence UWB radar system bears resemblance to that of traditional pulse radar, it is possible to utilize common preprocessing and imaging methods. Sequence is a periodic sequence that can utilize subsampling techniques to receive signals and avoid bias errors. It has a low peak-to-average power ratio, allowing for under sampling to maximize signal energy even at low peak voltages and maximize signal-to-noise ratio. M-Sequence radar systems meet strict bandwidth and low jitter requirements of integrated circuit technology with small binary voltage amplitudes. High measuring speed provides real-time measurements. Despite having lower resolution than UWB pulse radar, the M-Sequence radar system uses simple hardware and can image objects behind walls at the right places given wall thickness and dielectric constant are known [15].

4. Conclusion

The preceding content provided an overview of the operational concepts of through-wall radar, followed by an examination of various prevalent through-wall radar systems. The paper included a comprehensive examination of the design methodologies employed by the authors and critically evaluated the merits and drawbacks of these systems. The military, counter-terrorism, and law enforcement use through-wall radar. The US military used through-wall radar during the Afghanistan War. In 2015, 50 US law enforcement agencies were equipped with Range-R through-wall radar and a valid search order. Through-wall radar has great potential for search and rescue, medical treatment, and structural identification. Its low commercial adoption is due to two main factors. The experimental phase of most research has focused on detection tests using simple assumptions like single-layer brick walls and well-defined targets. The complexities of reality often limit the applicability of laboratory findings. Previous studies have studied wall penetration detection with unclear parameters [16]. In cases of uneven wall structures and other problems, more research is needed to identify objects behind walls. Additionally, commercial through-wall radar systems with great resolution are expensive. Conversely, low-cost devices fail several application criteria. Potential future trends in development encompass the integration of pre-existing through-wall radar systems to optimize compatibility across diverse settings through the utilization of a singular device. Additionally, the adoption of more prevalent and uncomplicated components is anticipated in order to attain through-wall radar performance. an AI language model, I am capable of rewriting your text to make it more academic in Previous studies have demonstrated the practical implementation of through-wall object holography utilizing Wi-Fi signals [17, 18]. The expanding reach of Wi-Fi signals suggests that the broad adoption of through-wall radar for commercial purposes may be imminent.

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