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A Comprehensive Review of Ground Penetrating Radar: Techniques, Applications and Future Directions

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Abstract: **Ground Penetrating Radar (GPR) technology has facilitated growth and research in multiple fields. It is a non-invasive method used for sub-surface exploration. GPR systems operate on the principles of Radar Systems, providing large operational flexibility. Archaeology, geophysics, civil engineering, environmental studies and military sectors see a large use of GPR systems. The review paper provides a comprehensive study about the developmental stages of modern GPR systems, GPR system types, applications of GPR systems, existing GPR methodologies and specification analysis of GPR systems. GPR system types are discussed based on signal technologies used and areas of application. For GPR system analysis, hardware design and software protocol execution is considered. Advancements in antenna design, data acquisition system, data processing systems and imaging system have been studied in this review paper. Avenues of artificial intelligence, machine learning, neural networks, deep learning, quantum physics and photonics have been discussed in relation to GPR methodologies. The research work referred for the review paper illustrates the usage of GPR systems for geophysical mapping, landmine detection, through-wall surveillance systems and structural integrity testing. The paper discusses challenges and limitations of GPR systems whenever relevant and aims at providing a clear understanding of existing GPR technologies to the reader. The review paper delves into the details of existing GPR methodologies, their functioning and operation. Future work and scope for development have been discussed at the end of the paper, emphasizing the need for enhanced data processing algorithms, integration with geophysical methods, and development of safer, user-friendly systems.**

Keywords: **Ground Penetrating Radar, Data Processing, GPR Antenna, GPR applications, GPR analysis.**

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1. INTRODUCTION

The development of modern day GPR systems have been affected by needs, methods and strategies of warfare. Since GPR systems are a specialised extension of radar systems, understanding Radar systems is a pre-requisite. The earliest sophisticated radar systems were developed as an immediate precaution against enemy bombers deployed during the second World War. The foundation of the radar system was laid by the formulation of the Maxwell-Heaviside equations (1882-1884) for electromagnetic wave propagation. German physicist, Heinrich Hertz, experimentally proved the equations in the year 1886. The concept of using radio waves for the detection of distant objects was proposed by Hertz when the relation between the speed of light and EM wave propagation was understood. He demonstrated the reflection of radio waves by metallic objects. In 1904, Christian Hülsmeyer, a German engineer patented the first practical radar system named, 'Telemobiloscope' used for the detection of ships in low visibility conditions. However, the Telemobiloscope was not widely adopted due to a low range of operation. It can hence be said in accordance with Skolnik [1] that the radar system was redeveloped and rediscovered multiple times under different conditions before the emergence of the modern-day sophisticated radar systems. In 1922 American engineers, Albert H. Taylor and Leo C.

Young demonstrated radio wave usage to detect a ship passing between two radio transmitters. The 1930s saw significant advancements in radar technology. These were primarily driven by military needs of various nations. Great Britain, Germany, USA and other nations explored radar as an early warning system. Pavel K. Oschepkov, a Russian engineer developed an early radar system capable of detecting incoming aircraft in 1934. The use of radar systems for detecting aircraft was proposed simultaneously in United Kingdom. As a result, the development of the Chain Home radar stations was initiated by UK. It was the first sophisticated, fully functional radar-based air defence system. The Second World War (1939-1945) forced the rapid development of radar systems. The strategic importance of the radar system was recognised by all major nations directly and indirectly involved in the war. The development of the cavity magnetron in 1940 allowed the production of radar with higher frequencies and power. As a result, smaller and effective radar systems emerged. Simultaneous development of radar systems across the globe was initiated by the transfer of scientific discoveries in the field of radar systems amongst friendly nations. In 1941, the United States developed the SCR-270 radar. It was a pioneer long-range early-warning radar system. Airborne radars were developed for detecting submarines and for guiding bombers to targets during the second World War. After the second world war, Radar systems found applications in civilian sectors, moving away from a strictly military usage. This led to advancements in civilian sectors of research such as meteorology, air traffic control and navigation.

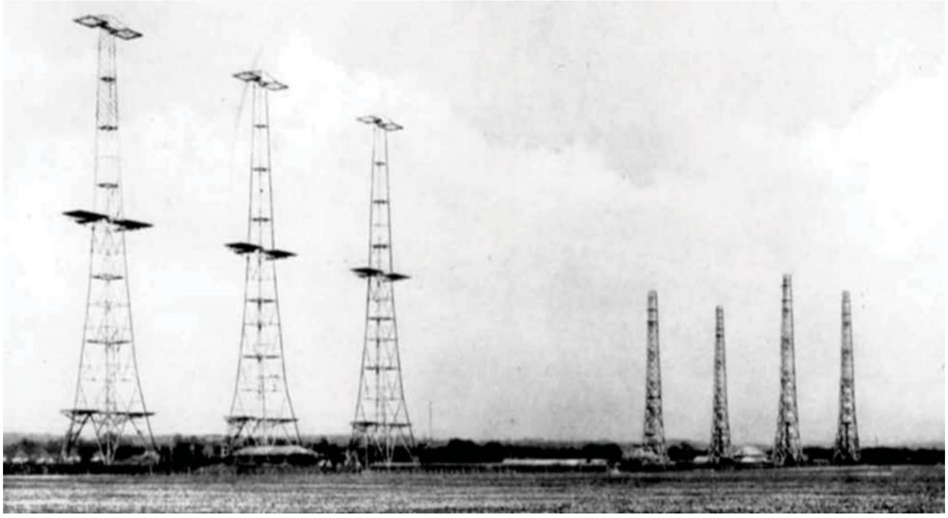

Figure 1. Chain Home Radar Stations, United Kingdom, 1939 [2]

Radar systems developed rapidly due to the introduction of digital processing technology. Advanced antenna systems such as, Phased-array antenna, largely increased the efficiency of radar systems. Multiple target detection, identification friend or foe are technologies that have exponentially increased the efficiency of sophisticated radar systems. Real-time data processing and integration of radar data with other sensor systems has evolved with evolving processing algorithms. The development of radar systems is a rapidly evolving field that has incorporated multiple sectors related to signal generation, signal processing and data handling. Radar technology has been integrated in varying applications. Ground Penetrating Radar technology was developed as a specialised radar technology used to detect buried targets [3]. The first worldwide GPR survey was carried out by W. Stern in Austria in the year 1929. The depth of a glacier was measured and the experiment is regarded as the initial application of GPR systems in a practical setting [4]. GPR systems have since advanced in terms of operational complexity, detection accuracy, data processing and data imaging. Present day GPR systems see the deployment of neural networks for target analysis as discussed by Beesaw et. Al. and Kim et. Al. in their work [5, 6]. These methods apply neural networks for feature extraction from a GPR return image. Millimetre Wave (MMW) frequency imaging is another method which provides multiple advantages including high spatial resolution, obscured object penetration ability, and body health safety [7]. Holographic technology [8], has been applied in imaging systems since the documented works of Lubecke et. al. [9,10]. The development of magnetic survey systems facilitates the rapid detection of smaller objects using magnetic surveys [11]. The Stepped Frequency Continuous Wave (SFCW) technology is widely regarded as the most promising GPR technology as demonstrated by Shen et. al. in their work [12]. It is a developing technology and various approaches of the SFCW system have been discussed since. The time complexity of data acquisition for wideband frequencies for target detection is high [13]. Therefore, SFCW-GPR technique has been widely investigated from the analytical dimension of performance and time complexity [14]. The use of ultra-wideband synthetic aperture radar (UWB SAR) for landmine and battlefield ordnance detection over large areas has gained recognition due to promising results [15]. Deep learning methods have outperformed feature extraction methods for subsurface object detection purposes [16]. However, drawbacks include the necessity of large datasets for accurate processing. Similarly, large system apparatus, introduction of clutter, false target echoes and data processing constraints are identified issues in GPR systems. Therefore, innovations in GPRs include the development of miniaturized portable systems for easier usage, quantum GPR systems for advanced computational capacity, integration of sensing technologies for clutter reduction and imaging system developments for false target reduction. As a result, GPR systems provide a comprehensive situational awareness in heterogenous environments.

2. GPR METHODOLOGY

Ground Penetrating Radar (GPR) uses radar pulses for subsurface imaging in a non-invasive way. It is used in applications like archaeology, environmental studies, utility detection and subsurface imaging. GPR systems operate by emitting high-frequency electromagnetic (EM) waves into ground. The waves propagate through subsurface materials and get reflected back to the surface after encountering objects with different dielectric properties. When radar waves hit a boundary between materials with different dielectric constants, part of the total transmitted energy is reflected back to the surface while the rest continues to propagate through the material. The GPR system records the time taken by reflected waves to return to the surface. As a result, the depth and size of buried objects can be estimated. A standard GPR system comprises a control Unit for signal generation, antennas to transmit and receive the EM waves, and processing unit for data acquisition, storage and imaging as shown in figure 2. The processing unit creates a visual representation of subsurface from the recorded signal information. The frequency of the transmitted wave signal determines the depth of penetration and the resolution of the images. Low-Frequencies penetrate deeper but offer lower resolution, while High-Frequencies provide higher resolution with lesser penetration. A GPR system is set on the surface of the area to be surveyed, called the Area of Interest. The antenna is placed on or above the ground, and is moved along the surface in a grid pattern. The antenna emits EM waves into the ground at regular intervals. The control unit records the time and strength of the reflected signals for each point along the survey line. The recorded data is processed to produce a two-dimensional image representing the subsurface. The 2 axes of the radargram corresponds to time (an independent variable), and the horizontal and distance (a dependent variable) along the survey line. Point objects typically produce hyperbolic patterns in the radargram due to the geometry of wave reflection. The time taken for the radar waves to return is expressed in terms of depth of the buried object. Signal processing techniques remove noise from the acquired data. The process can be iterated across multiple survey lines to develop a 3D model of the subsurface. GPR systems consist of multiple sub-systems. These subsystems can be classified as the RF transmitter and receiver system, Antenna system, Imagining or Data Acquisition system and Data Processing System.

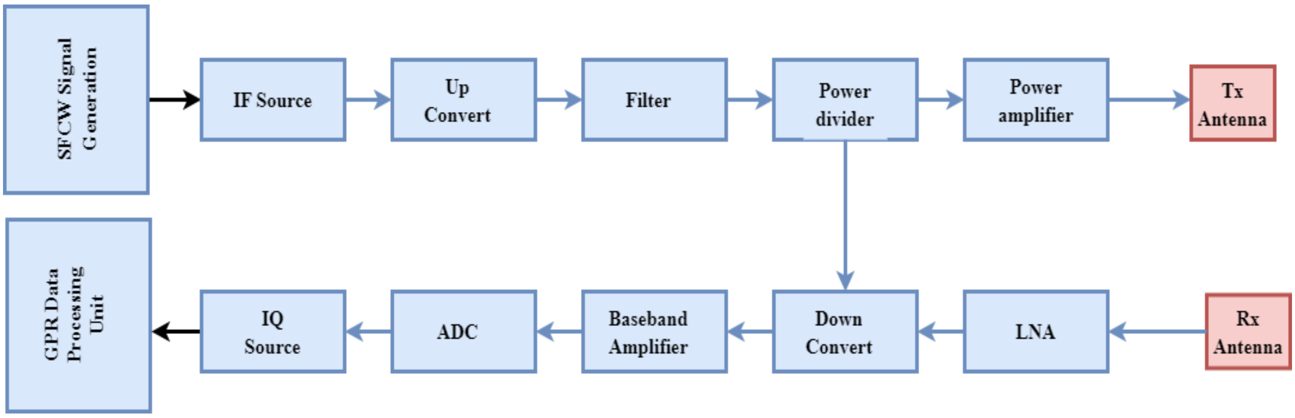

Figure 2. GPR Block Diagram Schematic

Each of the aforementioned individual systems have been realized using multiple methods. These methods differ in parameters such as system architecture complexity, signal processing time complexity, accuracy of results, power efficiency and system cost.

Since GPR systems are a sub-surface specific radar system, fundamental radar concepts and formulae remain the same.

$$(Range) = \frac{P_r.(4\pi)^3.\alpha^4}{P_t.G_{t.G_{r.}}\lambda^2} \tag{1}$$

Where equation (1) denotes the unambiguous range of the radar, and, P_r is received power, P_t is transmitted power, α is radar cross section, $G_{t.}$ Is gain of transmitting antenna, $G_{R.}$ Is gain of receiving antenna and λ is the wavelength of propagated signal.

$$R = c\frac{t}{2} \qquad (2)$$

Where equation 2 denotes time taken for signal to be received back, when c is the speed of light, and t is the transmission distance.

$$f_d = \frac{2V}{\lambda} \qquad (3)$$

Where equation (3) denotes the Doppler frequency, where v is the radial velocity of target relative to radar signal and λ is the associated radar wavelength.

3. GPR TRANSCEIVERS

The transmitter-receiver pair is an integral component of any GPR system. It is together referred to as the transceiver. The transmitter propagates the necessary wave with fixed parameters in the area of interest while the receiver facilitates the reception of target returns [17-20]. The transceiver is responsible for the generation of waveforms and the following reception process [21]. Different sub-systems and RF components exist in transceivers. These components are used to reduce noise, improve signal strength, modulate transmitted signals and convert received signal into digital formats for processing applications. Homodyne radar receivers, are radar systems that convert received signal to baseband signal without intermediate frequencies (IF). This architecture utilizes the same frequency as the transmitted signal for down conversion. Homodyne radar receivers operate by mixing a sample of the transmitted signal with the received echo signal to down convert the frequency directly to baseband. The primary advantage of this method is its simplicity and low cost. Since the local oscillator (LO) frequency is the same as the transmitted frequency, the complexity of the design is significantly reduced. Additionally, the output signal is free of any carrier frequency and is referred to as being in the baseband [22-26]. Although, the homodyne architecture has advantages, the dual synthesiser heterodyne architecture has an advantage over homodyne radar receiver in that RF harmonics are removed easily and filtered at a single intermediate frequency. The loop bandwidth of the synthesizers is greater than the radar IF bandwidth. Therefore, the transmit (TX) and receive (m) synthesisers phase noise is coherent. Signal data is converted to a coherent IQ data. This is done by fast digital demodulation technique. Fibre optic cables are used to connect radar transceiver to a portable computer for further data processing. This is done in order to limit electromagnetic induction from the PC [27-28].

4. GPR ANTENNA SYSTEM DESIGN

Antennas are used for energy coupling between a transmitted signal and medium of propagation. Antennas are used for transmission energy coupling and reception energy coupling [29]. Polarization types, directivity, structural complexity, cost of production, structural compactness and portability of system, are parameters that are considered while selecting an antenna for a GPR system. Multiple configurations regarding antenna design and types exist with individual characteristics. The flared antenna is a common antenna types seen in GPR systems [30]. It features a widening (flaring) structure from the feed point to the aperture. The flare enhances the Electromagnetic (EM) transmission and reception ability by facilitating a smooth transition between feed structure and free space. Flared antennas produce a highly directional radiation pattern, focusing the energy into a narrow beam. They are used in GPR systems to provide high directionality, broadband performance, and efficient coupling of electromagnetic energy into the ground. Applications where high resolution, deep penetration, High Directivity, Broadband Capability, Efficient Energy Coupling, Low Side Lobes and Versatility of application are required see the use of flared antennas. Flared antennas are designed to operate over a broad range of frequencies. Wide bandwidth allows transmission and reception of short pulses, which are essential for high-resolution GPR imaging. There are several types of flared antennas used in GPR systems, which include, Exponential Horn Antennas, Pyramidal . Horn Antennas, Conical Horn Antennas and Vivaldi Antennas. The flared antenna provides gradual transition from narrow feed line to wider antenna aperture. This minimizes reflection and impedance mismatch. Hence maximum energy is radiated into the ground. Flared antennas can be designed to support different types of polarization, including linear, circular, and elliptical.

Figure 2. Archimedean Antenna

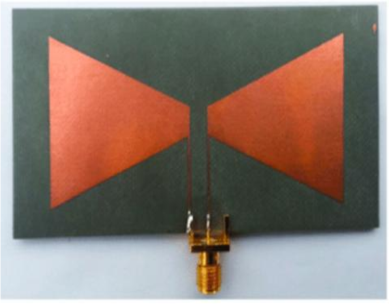

Figure 3. Bowtie Antenna

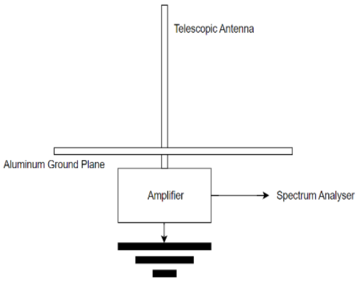

Figure 4. Monopole Antenna

Monopole antennas are used in GPR systems for applications where a compact and efficient design is required. Monopole antennas as shown diagrammatically in figure 4, are characterized by simple construction, ease of integration, and the ability to provide good performance across a range of frequencies. The ground plane serves as a mirror, doubling the antenna radiation pattern and enhancing performance. Monopole antennas produce omnidirectional radiation pattern in the horizontal plane, suitable for applications where uniform coverage is required [31]. They operate over a wide range of frequencies, hence increasing adaptability. The length of the monopole element is typically one-quarter of the wavelength of the target frequency. Compact and Lightweight design, Omnidirectional Radiation Pattern, Cost-Effective production and Wide Frequency Range are advantages provided by monopole antennas. The Archimedean antenna consists of two or more conducting arms wound in a spiral pattern that follows the Archimedean spiral equation in polar coordinates. This design facilitates a wide operating frequency range without hampering radiation pattern and impedance characteristics. Archimedean antennas produce circularly polarized radiation, which is useful in military and civilian radar systems. Applications where the orientation of the transmitting or receiving antenna is unknown or changing see the usage of Archimedean antennas. Figure 2 shows the Planar spiral antenna schematic representation.

Bowtie antennas are a type of broadband antenna, frequently used in GPR systems due to a wide operational frequency range, simple design, and the ability to produce high-resolution subsurface images. A bowtie antenna is a planar, broadband antenna characterized by two triangular or trapezoidal conductive elements that form the shape of a bowtie as shown in figure 3. The two elements are arranged and mounted symmetrically on a dielectric substrate, directly above a ground plane. They exhibit a bidirectional radiation pattern and are suitable for applications requiring good coverage in forward and backward directions. The bowtie antenna has an ultra-wideband performance due to its design structure. Ultra-Wideband Performance, Simple and Compact Design, High Resolution, Cost-Effective production and Versatility are advantages offered by bowtie antennas.

5. GPR DATA PROCESSING SYSTEM:

The GPR data processing system converts raw frequency data into spatial data. The data processing system processes transmitted frequencies and digitizes the data. Digital data is stored as received data. A windowing function is applied to convert spatial frequency into time domain. This function involves noise filtering, gain application, and migration techniques to correct the wave front. The functional ability of a GPR system to produce spatial data is affected by the characteristics of considered soil samples. Soil permittivity and water retention factor are co-dependent characteristics that affect GPR performance. Soil permittivity affects the conductivity of soil. As a result, radar signatures of sub-surface objects are altered [32]. Soil permittivity is dependent upon the water content level of soil. Since soil consists of granular particles with inhomogeneous sizes and dimensions, the water content distribution is heterogeneous in nature. Soil inhomogeneity leads to the development of clutter [33] due to a changing water retention factor. Soil samples are subject to a multitude of biological activities that increase the heterogeneous nature of soils. Presence of vegetation in soil is another influential factor that affects the moisture or water content present in soil. Similarly, subsurface vegetation leads to the development of clutter echoes in the frequency data. Clutter amplitude observed with respect to the length and variability of correlation shows the predominance of Mie Scattering [34] as compared to Rayleigh Scattering [35]. The use of a GPR system is dependent upon the aforementioned factors. All such factors of soil sample anomalies are addressed and overcome by the Data Processing Unit to accurately detect subsurface phenomena. The Data Processing System is realised in GPR systems using multiple methods.

5.1 Clutter Reduction using Likelihood Method:

In a GPR system, the received target echo has an introduced unwanted signal due to radar return of clutter objects. It consists of cross-talk between the transmitter-receiver antennas, reflection from air-ground interface and the resultant background soil scatterings. The separation of clutter signal from required target signal can be facilitated by using different separation algorithms. These include the simple mean scan subtraction [36], wavelet package decomposition [37], subspace techniques, likelihood ratio test [38], parametric system identification [39], complex average subtraction [40], background moving average estimation subtraction, whitening filter [41] and median filter. The Maximum Likelihood Estimation (MLE), is a statistical technique used for the estimation of parameters of a statistical model. The MLE function denotes the probability of observed data considering the existence of certain set parameters. It a function expressed in terms of parameters with the data being constant. A bar graph visualization of the maximum likelihood method has been demonstrated in figure 5. The observation with the highest value is used for the estimation of parameters.

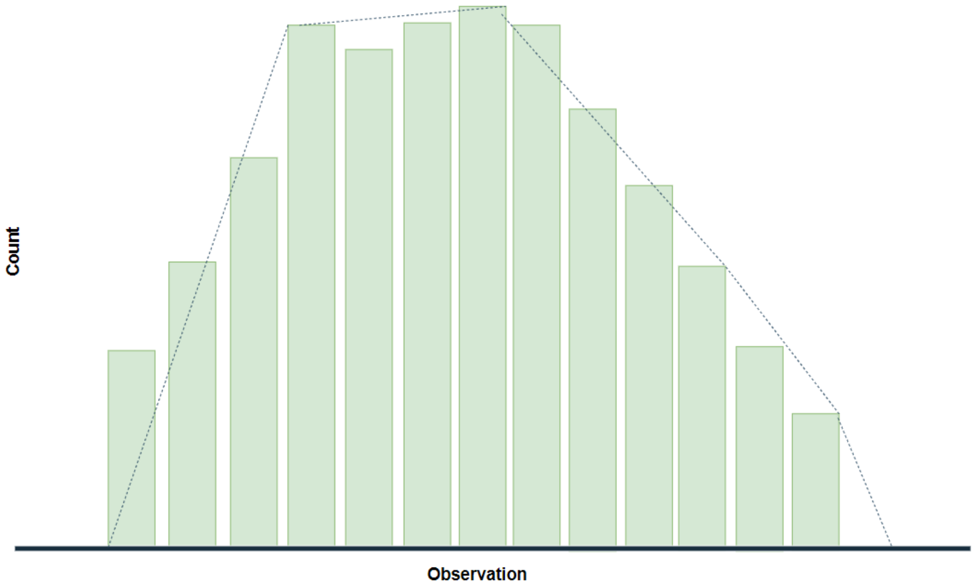

Figure 5. Maximum Likelihood Estimation Visualisation

5.2 Hopfield Neural Networks and Magnetic Gradients Technique:

Gradiometer measures the gradient of a magnetic field over a certain distance. It measures the difference between magnetic intensities at multiple points to construct a varying data. Such a system is used to locate the accurate position of a buried object, provided, metal components are present in the object structure. The gradient measurement removes undesirable effect of disturbing fields. The measurement system is unaffected by the diurnal variations in the Earth's magnetic field and compensates the influence of regional field. The data obtained by the gradiometer measurement is represented by a model that considers the shape and orientation effects of the obtained data [42]. Magnetic gradient data does not require a base station magnetometer and is therefore feasible for practical applications

A Hopfield Neural Network (HNN) is a type of recurrent artificial neural network that serves as an associative memory system with binary threshold nodes. It is used for solving optimization problems by using a minimum energy function. It can directly be implemented in field since it does not require any specific training stage. The Hopfield Network is applied to the data obtained by the gradiometer. The possible location sites present in the entire scanned area are realized as a matrix or grid. Each cell of the grid has an associated Hopfield power associated with it since the Hopfield model allocates a power value to each individual neuron. Optimization is carried out by finding the least power value. For landmine detection, the cell containing the least power value indicates the location of the landmine.

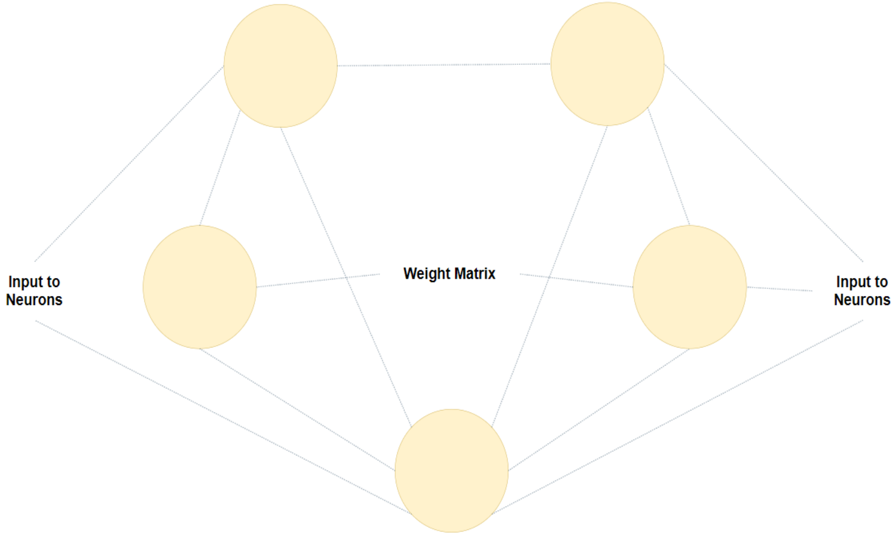

Figure 6. Hopfield Neural Network node connections

5.3 Context Models for GPR Systems:

For landmine detection with GPR systems, the application of context-dependent algorithm fusion across changing environmental and operating conditions has been proposed in [38]. Context-dependent algorithm fusion applies the strengths of multiple algorithms to a specific analytical context. Therefore, flexible, adaptive, and effective solutions are generated across a wide range of applications. The use of context-dependent algorithm fusion introduces multiple challenges related to complexity and data processing. As a result, multiple algorithms with varying levels of application and time complexities have been developed, specifically for the route-clearance platforms [43-45]. Context models are algorithms designed to utilize the context or data presentation. Context models utilize the parameters of data to define the data function. Systems built over a context model consider features such as behaviour, location, history and converge at an optimum data point. A hidden Markov model (HMM) is a spatially dependent context model. HMM shows promising results for modelling situations having partly observable systems and subsystems [46]. It is particularly useful for sequential data entities with inherent relationships. The number of contexts to be considered for a GPR system is another factor that need to be considered. Since HMM is a deep learning algorithm, the associated context determining model also employs deep learning logics. Stick-breaking prior technique is employed to automate the number of HMM contexts to consider. The first proposal for the use of a hidden Markov model trained for physics-based background feature extraction is seen in [47].

5.4 The Simulated Correlation Algorithm:

The false alarm rate of a GPR system when deployed to find landmines is high [48-49]. This is because, the signature of small AP landmines and biological factors present in soil such as tree roots and hollows are comparable. As a discrimination of required return from clutter return is an important task in GPR data processing. Therefore, the image analysis method of used in the signal processing unit should be able to reduce false alarms. The SIMCA ('SIMulated Correlation Algorithm') is an accurate landmine detection tool. Correlation between simulated GPR trace and clutter removed original GPR trace is calculated using the algorithm. As a result, subtractive unnecessary clutter returns are removed from the data [50]

5.5 Geostatic Estimation Technique.

Geostatic estimators are used for the analysis of SFCW GPR signals as proposed in [51-52]. Algorithm for GPR signals in frequency domain (SFCW radar) for background noise reduction, filtering the antenna effects, and obtaining signal features related to object position and object size. Proposed signal processing techniques to attenuate components generating interfering signals and to maximize signal-noise ratio, such as: five methods were studied for clutter reduction (mean subtraction, likelihood radio test, system identification, subspace singular value decomposition, and wavelet transform), digital high-pass filtering [53], ARMA model for clutter estimation and Kalman filter for clutter parameter estimation [54]. Subspace techniques used for improving signals acquired in a GPR system include, Singular value decomposition, Linear discriminant analysis, Principal component analysis, and Independent component analysis. These techniques have been used for signals in time domain. Required signal information can be obtained by applying Inverse Fourier Transform (IFT) to SFCW. Methods proposed for improving GPR signals in frequency domain include: Filtering soil surface and antenna effects [55]; improvement of cross range resolution [56].

6. GPR IMAGING SYSTEM

GPR imaging system is used to construct 2D or 3D subsurface images from the information acquired by the reflected target waves. Different methods are used in the realisation of a GPR imaging System. GPR system signals are used to obtain an A-scan representing amplitude vs. time for a single pulse. Pre-processing removes low-frequency bias in the signal caused by electronics or near-field effects. Time-zero correction adjusts for the time delay between pulse generation and ground entry. Gain is applied to compensate for signal attenuation with depth. Finally, filtering, migration, velocity and attribute analysis is carried out to accurately express input target data as a 2D or 3D image [57-59].

6.1 Anomaly Detection Technique:

A large percentage of GPR systems work on the B-scan images of the area of interest. B-scans are 2 dimensional images obtained by emitting and recording a radar signal. The images are plotted in the space-time domain. The radar signals are obtained by moving the transmitter and receiver antennas parallel to the area of interest. The anomaly detection technique [60], detects the presence of an anomalous object by the emergence of a hyperbolic structure. Such a structure is obtained by the radar signature of an object having a different dielectric constant with respect to the dielectric constant of the remaining area of interest. Multiple models exist for the detection of such hyperbolas [61-62] by solving fitting problems, employing modified Hough transforms and exploiting features for B-scan texture analysis respectively. Convolutional autoencoders are neural networks used for unsupervised learning of input data. It a powerful tool for the detection of anomalies in a given dataset [63-64]. The most important features of data are learnt by autoencoders by carrying out data compression and reconstruction. Through training on multiple images, autoencoders capture features that include digits, curves, lines and edges. A loss function is used to analyse and minimize the difference between original input image and reconstructed image for analysing the efficiency of the network. The application of autoencoders in the anomaly detection technique provides a robust system with good performance results. This is due to the fact that training stage scans do not include presence of any target objects. As a result, no assumptions are made with respect to the target return in terms of the dimensions of the landmine. Therefore, the possibility of missed target returns is decreased exponentially. The use of autoencoders for applying neural networks shows promising results as compared to other methods exploiting CNNs.

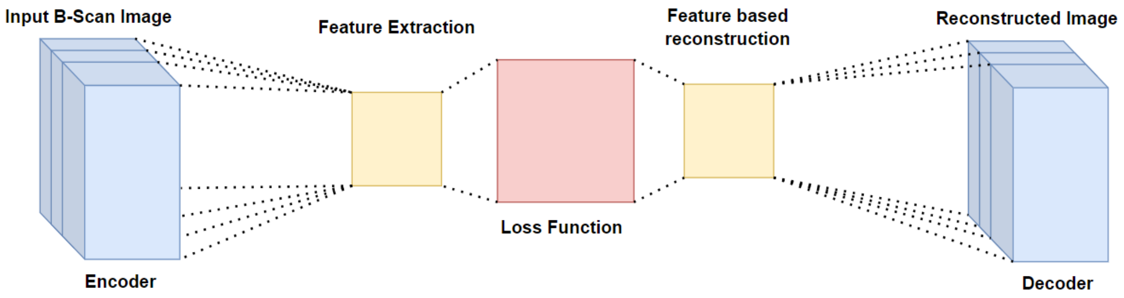

Figure 7. Autoencoder logic Schematic

6.2 Landmine Enhanced Imaging Technique.

Ultra Wideband (UWB) SAR data contains detailed target information. However, GPR systems have a tendency of generating high false alarm data. Hence, false alarms exist in pre-screening results. Therefore, prior information of landmine is used for discrimination between clutter echoes and target echoes. Conventional landmine detection methodology can be divided into imaging, pre-screening, and discrimination. SAR imaging techniques, consider targets to have an isotropic response. However, some scatterers exist with anisotropic characteristics. Certain features of target echoes exhibit dependence on the angle of viewing by the radar system. Depending upon the difference of amplitude between targets and background, Region of Interest (ROI) is extracted by SAR based radar systems [65]. For this, pre-screening is based upon the constant false alarm rate (CFAR). Extraction of aspect-invariant feature of land-mines is not dependent on the bandwidth when compared with the bandwidth dependence for extracting the double hump feature of landmines

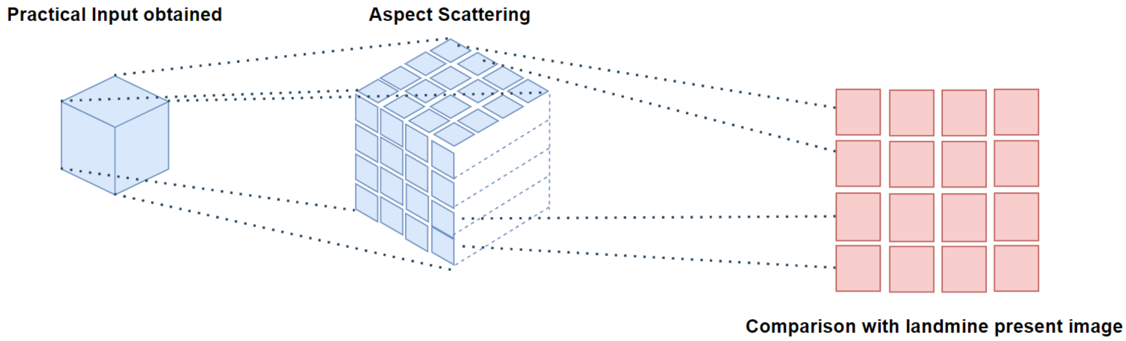

Figure 8. Aspect Scattering visualisation

The aspect-invariant feature of a landmine is used for landmine-enhanced imaging. For this, the Aspect scattering entropy (ASE) is used. It measures the aspect-invariant feature of a landmine over an observed angle. Hence, target attitudes do not affect the process. The ASE of anisotropy targets is a small value. Therefore, accuracy and tuning are significantly increased. The detection probability of land-mines increases substantially under constant CFAR when landmine enhance imaging process is used. The method is also used for detection of other targets. The only job is to modify ASE to other indicators.

6.3 SFCW based In-line Holography Technique.

Separation of background from the required image data is a major task for the processing of GPR return images. By the analysis of received SFCW power in range domain, the background and twin-image interferences is separated from the image-related term [66] As a result, the separated term can be removed with appropriate range windowing methods. Through in-line holography, a relatively small amount of data is obtained. Furthermore, easier quasi-optics is provided by an in-line holography technique. Multiple phase iteration algorithms can be applied to further reduce the suppress the background and twin-image interferences in in-line hologram [67] and [68]. However, the time complexity of these algorithms are high. Therefore, handling the SFCW signal power properly, facilitates the separation of the image-related term from unwanted interferences. The interferences can then be removed by windowing techniques. The total field of interest is received due to the interference of reference wave and target wave with each other. A multiple-frequency in-line hologram is obtained by analysing the intensity of received SFCW signal. Target image is mathematically reconstructed from the in-line hologram. Applying range domain decomposition of received SFCW power in reconstruction algorithm provides a better approach. Hence, extraction of necessary target term is facilitated.

6.4 Histograms of Dominant Orientations.

Histograms of Dominant Orientations (HDO) feature extraction technique is used for discriminating between required echo signals and clutter returns [69]. Receiver Operating Characteristic (ROC) curves are calculated for comparison purposes. HDO gives better performance than HOG for landmine detection. HDO preserves underlying image structure under conditions clutter and distortion presence [70]. Various methods for the development of data processing units include the use of Rule-based algorithm [71], Edge Histogram Descriptor [72], Histogram of Oriented Gradient [73].

7. SOFTWARE DEFINED RADIO

Radar systems can be realised using software defined Radio (SDR) platforms. A standard SDR operational flows has been demonstrated in figure 9. Low cost SDRs prohibit estimation of phase difference between the radar transmitter and receiver. The SDR approach for radar system design is adopted due to its flexibility and accessibility [74]. HackRF is a good proposal for realisation using SDRs [75-76]. It is a completely open source platform. Therefore, spectrum coverage and maximum transmitter power sufficient for most GPR applications can be obtained at a low price. Full-duplex operations require 2 HackRFs, which is the cheaper solution as compared to physical RF component GPR realisation. The Goertzel algorithm [77] is used to obtain individual DFT of each signal term. A GPR prototype realised through low-cost SDR is feasible. Appropriate calibration and configuration of system enables data gathering. Therefore, interpretation of subsurface structure imaging is facilitated. The given system design allows introductory analysis of implemented GPR without access to expensive RF devices and components. Approaches for radar system realisation apart from SDR [78].

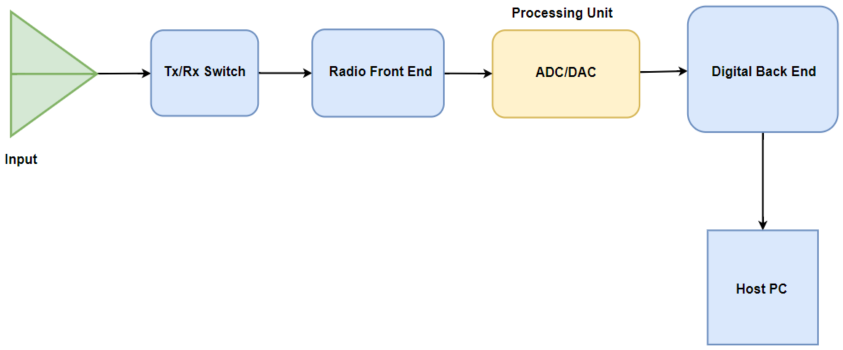

Figure 9. Software Defined Radio (SDR) operational flow

8. GPR CLASSIFICATION

Classification of Ground Penetrating Radar (GPR) systems determines system suitability for various applications. Different GPR systems are designed to address different challenges. These challenges are based upon factors like penetration depth, system resolution, portability, and operational conditions. GPR classification aligns technology with specific application needs. As a result, efficiency and accuracy of investigations is facilitated. Understanding these classifications helps in survey planning, data interpretation and result based decision making. Frequency-Based Classification; Application-Based Classification; Antenna Configuration-Based Classification and Portability-Based Classification are some of the key classification methods for GPR systems.

8.1 Waveform Based GPR System Classification

Modern day GPR systems implement multiple waveform modulation techniques like baseband pulse systems, noise waveforms and continuous wave systems [79]. The SFCW technique allows careful control of emitted radiation. It is compliant with modern EMC regulations. Mutual interference while using radar arrays is avoided by the use of the SFCW system. Furthermore, SFCW radar frequency control facilitates a simple calibration of system response in order to remove systematic errors present due to component distortion. EM waves emitted by radar systems are classified as short-pulse waves and continuous-waves [80]. Short pulse radars require a fast sampling rate and higher power. A CW radar system has simplicity in specification, hence it can be used without high sampling rate processing unit. After digitizing the data obtained from target echoes (RF signals), it is applied to a digital processing unit in order to accurately conclude about the range and location of the buried object.

8.1.1 Continuous Wave GPR System

Continuous Wave (CW) GPR is a type of GPR system that uses continuous electromagnetic waves for imaging purposes. CW GPR measures variations in the continuously transmitted signal as it interacts with subsurface materials. The approach offers unique advantages and has specific applications. CW GPR systems use frequency-modulated continuous wave (FMCW) techniques. Frequency of the transmitted signal is varied continuously over time, sweeping across a range of frequencies. Therefore, detection of a broader range of subsurface features is facilitated. CW GPR measures the phase difference between transmitted and received signals [81]. The phase information provides information about the distance to subsurface features and material properties. The amplitude and frequency of the reflected signal are analysed to determine characteristics of the subsurface materials. Changes in amplitude indicate different material boundaries, while frequency shifts reveal material composition information. The components of a CW GPR System consist of a transmitter to generate a continuous electromagnetic wave, a receiver to capture the reflected signals, the associated transmitter and receiver antennas and a signal processing unit for analysing the received signals and extracting relevant information. A suitable frequency range is selected based on expected subsurface conditions and depth of interest. The continuous nature of the signal allows for a detailed analysis of the subsurface features. The CW GPR system continuously sweeps through a range of frequencies during survey. This process is known as chirping, where the frequency of the transmitted signal increases or decreases linearly over time. CW GPR is useful in applications where continuous monitoring or high-resolution imaging is required. Such applications include, utility detection and mapping, structural analysis and geophysical mapping.

8.1.2 Impulse Wave GPR System

Impulse Wave GPR works on the principle of time-domain reflectometry. It sends brief, high-energy pulses of electromagnetic radiation into the ground and records the time taken for reflected signals to return from different subsurface materials. Time delay between the transmitted and received signals provides information about the depth and nature of the subsurface features. The system generates short pulses of electromagnetic energy in the transmitter block. These pulses have a wide bandwidth and the pulses interact with a variety of subsurface materials. The reflected waves are detected by the GPR’s receiver. The time taken for reflection and the amplitude of reflected waves is recorded and used for image construction by the data processing unit. The amplitude of reflected wave indicates nature of the subsurface material, while the time delay denotes the depth information of the subsurface object. The components of an impulse GPR System consist of a transmitter to generate short and high frequency electromagnetic waves, a receiver to capture the reflected signals, the associated transmitter and receiver antennas and a signal processing unit for analysing the received signals and extracting relevant information [82-84]. The data acquired by the receiver unit is processed to create a radargram of the subsurface. Impulse Wave GPR is a common GPR system and is used in applications like, Geological Surveys, Soil Stratigraphy, Bedrock Mapping and Void Detection. The impulse GPR system provides a high resolution as compared to CW GPRs. Resolution refers to the ability of a radar system to detect closely spaced individual objects. Impulse GPR systems are used on various surfaces, like soil, concrete, rock, and ice. Therefore, it is adaptable to many environments. The fast pulse rate allows quick scanning of large areas. Real-time data for on-site analysis and decision-making is acquired at a faster rate as compared to CW radar systems.

8.1.3 Stepped Frequency Continuous Wave (SFCW) GPR System

SFCW radar theory is well documented and included in [78]. The SFCW radar obtains the distance of a target from the radar system by measuring coherent target reflections over a number of stepped frequencies (N) within the given bandwidth B. The raw frequency data is sent through Discrete Fourier Transform (DFT) to yield individual target scattering. The operational methodology of an SFCW Radar system is sub-divided into 3 stages [85-87]. The detection of a buried target within the area of interest is the 1st stage. Followed by discriminating an object radar signature from clutter signature. This 2nd stage is the recognition stage. Localization of the target in order to accurately determine its location is the final stage of the GPR process. The gross radar system consists of the Human Machine Interface (HMI), the radar transmitter-receiver pair and the transmitter-receiver antennas. SFCW GPR systems are used for landmine detection, archaeological investigations, search for underground pipes and other such applications. Therefore, GPR systems provide a resolution comparable with landmine dimensions and needed penetration for each application. GPR systems are advantageous due to the ability to detect plastic mines, minimum requirement of direct ground contact and integration of target recognition techniques. SFCW technique for portable through-wall radar has also been implemented on varying levels in the military in counter insurgency scenarios and search and rescue operations. The SFCW radar is advantageous as compared to other GPR systems due to wider dynamic range, higher mean power, lower noise figure and, the possibility of shaping the power spectral density. For shaping the power spectral density, the level of the side lobes is changed by “windowing function”. The SFCW technique is adopted in GPR systems due to its low hardware requirements. Cross range Resolution and Down Range Resolution improvement is facilitated in SFCW methods [88]. The components of an SFCW GPR System consist of a transmitter to generate continuous wave of linearly varying frequencies, a receiver to capture the reflected signals, the associated transmitter and receiver antennas and a signal processing unit for analysing the received signals and extracting relevant information.

8.2 Application based GPR system Classification

GPR systems can be classified based on the type of applications of the system and the principle of operation of the radar system. Such a classification facilitates the appropriate usage of a GPR system depending upon the requirement of operation. GPRs have been used for multiple problem statements, and the techniques associated with each differs.

8.2.1 GPR for Landmine Detection

Buried unexploded land-mines pose a significant threat to human lives and property Africa, the 2nd largest continent of the world with respect to population and area is estimated to have 18 to 30 million such land-mines. As a result, it is one of the most heavily mined continents in the world as estimated by the United States Army' Foreign Science and Technology Centre (FSTC) [89]. Since civilian lives are gravely endangered, non-neutralised land-mines prevent the development of the region even after the dissolution of war-like scenarios. Globally, some 60 countries still have unidentified and live land-mines present in their geographical area. The number of these land-mines is approximated to be 120 million. It is estimated that globally, 25000 people are maimed or killed every year, due to land-mines [90]. Land-mines prove to be a long-term threat unlike other conventional weapons, since, they can function for a large period of time after installation. Therefore, landmine detection is an important humanitarian issue of global scales [91]. As per the International Campaign to Ban Landmines (ICBL), an approximate of 50 countries have developed different kinds of Anti-Personnel (AP) land-mines [92]. The detection of land-mines proves to be a big challenge for humanitarian de-mining operations globally. It is especially difficult to detect low-metal or non-metallic land-mines by using conventional methods. Land-mines are explosive devices that can be offensively used during conflicts to destroy or damage infrastructure, and their devastation can last for decades if they were not removed from the affected areas [93]. Landmine detection is vital for military and humanitarian reasons. Thousands of people are killed or maimed by landmines annually. The landmine design has changed from being completely metallic in nature to containing little to no number of metallic components [94]. Land-mines are explosive devices designed to be buried in order to incapacitate or destroy enemy personnel or vehicles. Land-mines are generally triggered by pressure. They can be categorised into 2 primary types; Anti-Personnel Mines (APMs) and Anti-Tank Mines (ATMs). An AP land-mine is designed to severely maim or kill enemy personnel units, while an ATM is designed to disable or destroy enemy vehicle manoeuvres.

Each of the landmine types has certain unique design characteristics that include trigger mechanisms, blast covers, explosive payload and deployment methods. AP mines are generally less explosive than Anti-tank or anti-vehicle mines [97]. AP mines are further classified based on their exploding tendency. Blast mines, bounding mines, fragmentation mines and directional mines are the major subtypes of anti-personnel land-mines. Blast mines are pressure triggered land-mines than undergo a single coherent explosion thus incapacitating personnel in a designated area of impact. Fragmentation mines are pressure triggered land-mines that fragment into numerous shrapnel pieces upon triggering. These mines have a larger area of impact since the light weight fragments travel across a wider area.

Figure 10. Brazilian T-AB-1 AP mine [95]

Figure 11. South African No 8, AT Mine [96]

Bounding mines are specialized fragmentation land-mines that shoot up into the air after getting triggered. After attaining a specific height, bounding mines explode into multiple fragments. Directional land-mines have a directive are of impact. The explosive force of a directive landmine is only focused in its specified direction. A shaped charge is used to maximize the impact ability of a directive landmine. Anti-tank land-mines are more powerful than AP mines and require a greater force to get triggered. ATMs are categorised further as pressure activated mines, magnetic influence mines and off-route mines. Pressure activated mines are activated when a significantly high pressure is applied. Such an amount of pressure is only possible to be applied by a vehicle. Magnetic influence mines are triggered by the magnetic signature of a vehicle.

Off road mines are placed alongside a route. These mines are triggered by trip wires or are remotely activated. Apart from anti-personnel mines and anti-tank or anti-vehicle mines, there exists another class of land-mines. These are specialized land-mines. These land-mines include plastic mines. Plastic mines consist of a very low metallic content. As a result, the magnetic signature of these mines cannot be discriminated from organic clutter (like rocks) by using conventional metal detecting de-mining systems. Scatterable mines are land-mines that are deployed by scattering them over a large field by means of aircraft. These mines are easier to deploy and can be directly dumped in their active state. Scatterable mines can include self-destruct mechanisms or timers [98-99]. Most recent variants of every standard of landmines can be found in [100]. Ground Penetrating Radar system demonstrates promising results for detecting buried land-mines. Commercially available detection systems implement baseband pulses [101]. GPR is widely used to detect subsurface objects such as buried land-mines. A large chunk of globally used land-mines is taken up by the plastic land-mine family. These land-mines have a negligible amount of metals present inside the structure. As a result, use of Ground Penetrating Radar Systems proves to be a better alternative as compared to conventional methods of metal detection [102-103]. The system is sensitive to electromagnetic changes in the characteristics of the medium. These include, electric permittivity, conductivity, and the magnetic permeability [104]. Furthermore, GPR has the ability to survey an area in front of it unlike sensors that survey an area directly beneath them [105] The first and most critical step in any landmine clearance strategy is the detection of buried mines, and the efficiency and reliability of landmine detectors depend on several factors such as safety, cost, speed, accuracy, and complexity [106]. Several techniques are introduced for landmine detection like nuclear quadruple resonance [107], thermal neutron activation [108], thermal imaging [109], optoelectronic sensors [110], and chemical sensors [111]. Other techniques suitable for GPR application are given in [112].

8.2.2 GPR for through wall detection

Through wall imaging techniques are required by safety personnel during various scenarios. Such systems are required in searching operations, rescue operations and military operations. Through-the-wall radars are a subclass of short-range radars [113]. Detection of moving people is required in multiple practical scenarios that include, enhanced monitoring systems [114], security systems [115], Aiding people with disabilities [116, 117]. Demand for reliable in-door monitoring systems for the elderly is increasing globally [118, 119]. Injuries sustained from fall incidents at home are considered to be the most dangerous cause of fatal accidents, and it represents the third cause of chronic disability [120]. Significant reduction of mortality risk is possible by instant detection of fall event. The instant detection method increases the chance of a person's return to independent living. Remote detection of fall offers the fundamental advantage that no action by the victim individual is required. Alternative approach based on the use of radar techniques was proposed [121].

8.2.3 GPR for Geophysical Mapping

GPR systems are used in archaeological surveys to non-invasively detect and map subsurface features such as buried structures, artefacts, and soil layers. The archaeological survey area is the Area of Interest and it determines the boundaries surface indications and previous investigations. Terrain assessment is conducted to ascertain feasibility of GPR use. GPR systems are used on even and uneven ground. Vegetation, surface debris, and soil inhomogeneities are considered during the survey. For archaeological surveys, moderate to high-frequency antennas (200 MHz to 900 MHz) are commonly used. Higher Frequencies are used for detecting small objects or shallow features with high resolution. Lower Frequencies are used for deeper penetration to detect larger features; such as walls or foundations. Depending on the site, a ground-coupled or air-coupled antenna is used. Ground-coupled antennas are common in archaeology due to better resolution and signal penetration. Grid establishment is used to describe the survey area to ensure systematic coverage. The GPR antenna is moved systematically along each grid line. The height and speed of the antenna movements is kept at constant. Radargrams are used to represent vertical slice of the subsurface along survey lines. Specific patterns in radargrams are identified by archaeologists. These patterns indicate the presence of archaeological features. Hyperbolas, linear reflections and layering are patterns that denotes the presence of different features. Noise and irrelevant signals are filtered out, and gain adjustments are applied to enhance the visibility of weak reflections. Time taken for radar waves to return to the surface is converted to depth using velocity of the waves in the specific subsurface material. By processing multiple survey lines, a 3D model of the subsurface is created. It provides a comprehensive view of the archaeological site, allowing visualization of buried structures in three dimensions. The migration process corrects the curvature of the wave fronts, providing a clear and accurate representation of the subsurface features. The identified features are analysed in the context of the site history and previous archaeological findings. The hence processed data is used to create georeferenced maps of the subsurface features. These maps are essential for planning future developments. GPR systems survey large archaeological sites quickly, identifying areas of interest for further excavation. Since GPR system imaging is Non-Invasive complete risk-free observation of archaeological sites is facilitated. GPR systems are used in geophysical mapping to investigate subsurface conditions without the need for drilling or excavation. Applications of GPR systems in geophysical mapping include classification of land cover variables [122], estimation of continuum variable [123], forest parameter mapping [124], and the estimation of soil heterogeneity for landmine detection [125]. GPR operates on the principle of sending high-frequency electromagnetic waves into the ground and analysing the reflected signals. These reflections occur when the waves encounter materials with different dielectric constants, such as soil, rock, water, or air. For a GPR system used for geophysical mapping, a transmitter generates and transmits electromagnetic waves into ground, a receiver captures the reflected signals and the control unit processes the signals. For geophysical mapping, georeferencing is used for generating the area of interest grid. Therefore, data collected is accurately mapped with the survey area.

8.2.4 GPR for Structural Integrity Testing

GPR systems are used for testing the structural integrity of buildings, bridges, roads, dams and other civil engineering structures. It is non-destructive in nature and provides detailed information about the internal composition and condition of materials. The GPR system transmits electromagnetic waves into the structure. As these waves propagate through the material, they are partially reflected at boundaries between different materials or at defects, such as cracks, voids, or delaminations. The reflected waves are captured by the GPR system receiver, and time taken and amplitude of wave reflections is recorded. The amplitude of the reflected signal provides information about the type and size of the subsurface defect. GPR systems locate and map reinforcing bars (re-bar) within concrete structures. This helps in assessing the re-bar placement, spacing, and potential corrosion [126-129]. GPR systems identify voids, honeycombing, and other imperfections in concrete, which compromise structural integrity if left unchecked. Therefore, GPRs for structural integrity testing facilitate a pre-emptive maintenance of structures of importance.

9. EMERGING TECHNOLOGIES IN GPR

A photonic solution for GPR systems consists of the incorporation of optical technologies to enhance radio frequency components. Components like lasers and photo detectors are used to improve GPR performance. Laser pulses are used to probe the ground, as a result, the resolution and accuracy of the system is improved. Optical signal processing methods enhance data analysis [130, 131]. As mentioned by De et. al. in their work [132-134], photonic components are smaller and lighter enabling more compact and portable GPR systems while reducing power consumption. The work also explores aspects of photonics for the streamlined integration of fast processing, compact, portable GPR systems [135-138]. Quantum technology in GPR systems represents a cutting-edge area of research. Quantum technology refers to the use of quantum mechanical principles — such as superposition, entanglement, and quantum tunnelling — to develop new technologies. These principles enable quantum systems to process information for increased speed and accuracy of computation in communication, sensing, and imaging. Quantum sensors are applied to GPR systems to achieve high levels of sensitivity and accuracy by exploiting quantum properties. Quantum magnetometers are used detect subtle variations in magnetic fields [139 -142]. Therefore, they improve the detection of weak signals reflected from deep or small subsurface features.

10. GPR SYSTEM ANALYSIS PARAMETERS

SNR (Signal-to-Noise Ratio) of a System is a measure of the signal strength of given system relative to the strength of noise present in the system. It is expressed in decibels (dB) and is calculated as the ratio of the power of the signal to the power of the noise. High SNR indicates clear, discernible signal in a system. Low SNR indicates a signal is masked by noise. High SNR is necessary for data acquisition, processing, and interpretation in GPR systems. System Architecture Complexity refers to the sophistication of system design [143-144]. System components, interconnections, and overall structure are considered. Architecture complexity includes hardware, software, and communication protocols involved in the system operation. The number of components, level of integration, communication channels, data processing requirements, and the necessity for redundancy or fault tolerance contribute to complexity of the system. A complex system architecture increases design time, potential for errors, higher development and maintenance costs. Time Complexity of Data Acquisition refers to the time required to collect data from the environment or system sensors. It relates to an increase in time required with an increase in size or resolution of the acquired data. Sensor speed, data transfer rate, and processing capabilities of the system influence time complexity [145] Minimizing time complexity is critical to ensure timely responses and accurate data analysis of GPR systems. Cost of System Development is the total financial investment required to design, develop, test, and deploy a GPR system. It includes costs associated with hardware, software, personnel, testing, and ongoing maintenance. Accuracy refers to the degree to which a measurement, computation, or output from a system corresponds to the true or accepted value. It is a critical metric in GPR systems that require precise outputs for discriminating and locating buried objects. Sensor Quality, Data Processing Algorithms, Data Imaging methods, Environmental Conditions are factors that affect the accuracy of a GPR system. Power Efficiency is the amount of useful work done by a GPR system relative to the power consumed. It is expressed as a percentage. Individual Component Efficiency, System Design, Operational Conditions are factors of a GPR system that affect its power efficiency. High power efficiency is essential in practical field operable GPR systems. Bandwidth requirement refers to the amount of data that can be transmitted or processed by a system in a given amount of time, measured in bits per second (bps). GPR bandwidth dictates the data transfer rate. Data imaging and processing unit of a GPR system is affected by the bandwidth of operation. The size of the data being transmitted, medium of Transmission Medium, System Capabilities are factors affecting the bandwidth of a GPR system. For real-time usage of GPR systems, adequate bandwidth of operation is necessary.

11. GPR SYSTEM ANALYSIS

From the data represented in previous sections 5, 6, 7 and 8; a comprehensive analysis table is formulated. The simultaneous analysis of GPR systems on the basis of parameters discussed in section 10 provides a robust understanding of the applications of different waveforms and antenna configuration. Requirement specific solution proposal is formulated on the basis of such comparative analysis.

Table 1. Comparative analysis of GPR waveforms

Waveform *(parameter)*	Continuous Wave	FMCW	Pulse	SFCW
Bandwidth	Narrow	Wide	Broad	Moderate
Domain	Frequency	Frequency	Time	Frequency
Generation Complexity	Low	High	Moderate	High
Penetration Depth	Low to Moderate	Moderate to high	Moderate to high	Moderate to high
Range	Moderate	High	High	High
Resolution	Low	High	High	High

Table 2. Comparative analysis of GPR antenna configurations

Antenna *(parameter)*	Archimedean	Bowtie	Dipole	Horn	Monopole	Vivaldi Radiator
Aperture	Large	Moderate	Small	Large	Small	Large
Design Complexity	High	Low	Low	Moderate	Low	High
Frequency	Wide-Ultra Wide	Wide	Narrow-Moderate	Narrow-Moderate	Narrow-Moderate	Ultra-Wide
Penetration Depth	Moderate	Moderate	Moderate	High	Moderate	Moderate-high
Polarization	Circular	Linear	Linear	Linear	Linear	Linear
Radiation Pattern	Circular	Broad	Bidirectional	Bidirectional	Omnidirectional	Directional
SNR	Moderate	Moderate	Moderate	High	Low-Moderate	High

12. CONCLUSION

GPR systems have facilitated detailed subsurface imaging capabilities. Therefore, GPR has contributed significantly to advancements in the fields of geophysics, archaeology, environmental monitoring, commercial testing and military research and development. The paper has thoroughly examined fundamental principles, methodologies and technological advancements that have shaped GPR system development. GPR systems offer invaluable insights into subsurface imaging by deploying fast and accurate data processing systems, making them a versatile tool for a broad range of applications. The survey discussed various GPR realization methods, addressing system architecture, system design, waveform usage, and antenna design. Advantages of GPR such as high resolution, non-invasive operational function and high system adaptability have also been discussed.

GPR limitations such as signal attenuation, data processing limitations and constraints have also been highlighted whenever relevant. Overall, continuous advancements in signal processing algorithms, hardware miniaturization, and integration of new techniques like photonics and quantum computing are propelling existing GPR system technology towards higher efficiency and accuracy. This paper has provided a comprehensive overview of existing GPR technology. It offers valuable insights into current GPR trends as well as future ventures in civilian, military and commercial use.

13. FUTURE SCOPE FOR WORK

Integration of machine learning, deep learning and convolutional neural networks, enhances GPR target detection accuracy. Similarly, false targets are eliminated. Therefore, induction of cognitive radar technology as proposed in [146] by Rajpoot et. al., GPR target detection is enhanced. Further, integration of advanced machine learning algorithms for feature detection and discrimination increases GPR efficiency substantially [147]. Such approaches have been discussed by Kumawat, Chakraborty, Hasan et. al. in their work on Principle Component Analysis (PCA) and Support Vector Machine (SVM) integrated with GPR systems [148-153]. Further work shall focus on autonomous systems capable of detection, classification and discrimination of target returns. GPR algorithms realised through software, are re-programmable and durable. As a result, further work in the sector of software defined GPR systems shows promising avenues. Performance of the Stick Breaking Hidden Markov Model (SBHMM) GPR system is sensitive to initialization. Therefore, multiple high-confidence false alarms are generated. This is due to the limited amount of pure background data available for training the model. Therefore, future work for training the SBHMM on GPR data should include a smaller number of target-less regions. The practicability of application of the SBHMM should be studied in order to study the contexts of GPR data collected off-road instead of from test lanes. In such a data model, multiple contextual changes are expected [153-157]. The use of hovercraft for accessing rough terrains has seen implementation on various scales by military agencies globally [158]. A remotely controlled hovercraft prototype for landmine detection provides a safe detection vehicle for de-miners (sappers). It is safer than conventional hand-held metal detectors or detection systems since it can be driven remotely. Therefore, the development of such safe de-mining systems that facilitate automation is an area of further development with respect to landmine detection systems and GPRs. Fully Polari-metric system will provide better results [159-163]. The approach of landmine enhanced imaging cannot discriminate clutters of similar size and amplitude. Therefore, combination of a frequency dependent feature for enhancing the results is possible [164-167].

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