Recent Advances and Classification of Radar Technology

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Abstract. This paper provides a comprehensive exploration of radar technologies, categorizing them by their unique technological attributes. It delves into phased array radar, known for its rapid directional control, interference resistance, multitasking capabilities, and adaptability. Then compares traditional phased array radar to digital phased array radar and discuss the future potential of phased array radar. Synthetic aperture radar is examined for its all-weather, all-day observation abilities in civilian and military applications, considering performance indicators like frequency, resolution, and repetition observation cycle. Lastly, quantum radar, utilizing quantum entanglement and superposition principles, is discussed for its potential in target detection, ranging, and enhanced system security. Although quantum radar technology is currently not mature and there are still many technical and application challenges, its unique advantages make it a technology with promising prospects. This evolving technology remains indispensable across numerous domains, from defense to agriculture.

Keywords: Phased array radar; Digital array radar; Synthetic aperture radar; Quantum radar.

1. Introduction

Radar, an acronym for "radio detection and ranging", has undergone a remarkable journey since its inception, evolving into a technology that permeates virtually every facet of modern life. This paper embarks on a comprehensive exploration of radar technologies, tracing their historical roots, pivotal milestones in development, and their enduring significance across a multitude of applications. Moreover, it delves into the diverse facets of radar technology, categorized by their unique technological attributes, offering insights into the transformative power of this technology.

The genesis of radar can be traced back to the tumultuous years of the last mid-20th century, where its development found a strategic foothold in the realm of air defense during World War II. In this period, radar technology underwent rapid evolution as scientists and engineers sought ways to harness radio waves for detection and ranging. The outcome of this intensive research was the birth of radar systems, capable of detecting incoming aircraft and guiding ships through the treacherous waters of war. These early successes laid the foundation for radar's expansive journey into civilian domains. Today, radar technology transcends its military origins, becoming an indelible part of daily lives. Its applications span a multitude of sectors, from aviation and navigation to weather monitoring, agriculture, and defense. It is the guiding hand behind aircraft navigating through storms, the watchful eye monitoring climate, and the silent sentinel ensuring national security. The ubiquity of radar reflects its indispensable role in modern society [1].

Radar technology has experienced a renaissance in recent decades, marked by a continuous quest for innovation and advancement. In this era of rapid technological progress, radar has not remained stagnant but has evolved to address emerging challenges and opportunities. Within this milieu, radar technologies can be categorized based on their distinctive technological attributes. Phased Array Radar, distinguished by its swift directional control, interference resistance, multitasking prowess, and adaptability, stands as a testament to radar's capacity for innovation. Furthermore, Digital Phased Array Radar, an offspring of digital signal processing and innovative circuit design, promises enhanced flexibility, multi-beam capabilities, adaptive interference suppression, and high-precision beamforming. These developments underscore radar's enduring relevance and its ability to meet the ever-evolving demands of the modern world.

2. Theory and Mechanism

2.1. Phased Array Radar

The first technology is phased array radar. The term "phased array" comes from the inclusion of phased array antennas in this radar system. A phased array radar is constructed from an array of radiating elements, each individually controlled in phase and amplitude through waveguides and phase shifters. This design enables the radar to achieve accurate and predictable radiation patterns and beam directions [2]. During operation, the transmitter allocates power to each antenna element through a feed network. Energy is emitted outward by numerous independent antenna elements, and spatial power synthesis occurs, resulting in the desired beam direction.

Phased array radar is renowned for its ability to swiftly control direction, perform programmable scans, and resist interference. This technological feature makes phased array radar applicable in domains like air defense, navigation, and aerial monitoring. Additionally, it possesses multitasking capabilities, allowing it to concurrently track targets and perform search tasks.

2.2. Digital Array Radar

The digital array radar concept has its roots in digital signal processing and in digital phased array sonars. In the mid-1970s, research into digital beam- forming (DBF) for radar and related adaptive and super resolution array techniques mature. During the 1990s and early 2000s, significant strides were made in the implementation and experimentation of Digital Beamforming (DBF), a momentum that continues to this day. The impetus behind this heightened engagement stems from advancements in device scaling and inventive circuit design methodologies applied to Radio-Frequency Integrated Circuits (RFICs), data converters, and digital processing circuits [3].

Digital phased array radar holds several advantages over analog phased array radar. The First one is flexibility. Digital phased array radar achieves flexible beam control by adjusting phase and amplitude weights, as well as time delays. In contrast, analog phased array radar requires physical adjustments of antenna elements and connections, resulting in limited flexibility. The second one is Multi-beam Capability. Digital phased array radar can generate multiple independent receive beams simultaneously, enabling multi-target tracking and multi-angle measurements. Analog phased array radar typically generates a fixed beam. The third one is adaptive Interference suppression. Digital phased array radar can employ adaptive beamforming techniques to suppress interference signals, enhancing target detection and tracking performance. Analog phased array radar usually cannot achieve this adaptive interference suppression. The last one is the high-recision beamforming. Digital phased array radar achieves high-precision beamforming through precise phase and amplitude control, enhancing accuracy in angle measurements. The beamforming accuracy of analog phased array radar is constrained by physical elements.

The phased array radar now is still facing the problems of computational complexity, the high cost and Interference. In the future, the phased array radar technologies will develope in domains such as photonic beamforming, micro-electromechanical phase shifters, and advanced space-time adaptive processing arrays [4]. In addition, the utilization of a hybrid phased array radar with a mixed-mode array configuration involves integrating digital phased array technology with analog antenna arrays, effectively harnessing the strengths of both approaches to enhance system performance.

2.3. Synthetic Aperture Radar

Synthetic Aperture Radar (SAR) is a radar imaging technique that utilizes a small antenna to move at a constant speed along a long linear path and emits coherent signals. By coherently processing the echoes received at different positions, SAR can achieve high-resolution radar imaging. As an active microwave sensor, SAR has the advantage of all-weather and all-day observation of the Earth's surface, unaffected by lighting and weather conditions. It can even penetrate the Earth's surface or vegetation to acquire concealed information. These characteristics give SAR a wide range of

applications in civilian fields such as agriculture, forestry, water, geology, and natural disaster monitoring [5]. In the military domain, it offers unique advantages.

The performance indicators of Synthetic Aperture Radar (SAR) include several crucial aspects [6].

Firstly, frequency and polarization selection stand as pivotal parameters in SAR satellite design, affecting both the SAR's parameter design and various satellite system parameters. The choice of frequency is influenced by considerations of atmospheric transmission windows, the impact of frequency and polarization on information extraction, image quality, equipment complexity, and other factors.

Secondly, resolution and observation bandwidth constitute significant benchmarks. Spaceborne SAR employs pulse compression ranging techniques to achieve vertical spatial resolution perpendicular to the satellite's track direction. Utilizing the Doppler effect, it acquires the corresponding phase history at each transmitted pulse position, subsequently employing coherent ground imaging processing to achieve high azimuth spatial resolution. These metrics are crucial performance indicators in SAR satellite observation, and the intricate interplay between spatial resolution, observation bandwidth, pulse repetition frequency, data rate, and ambiguity parameters impose complex constraints on the SAR system.

Thirdly, the repetition observation cycle, referring to the time interval for re-observing the same target area, represents another vital indicator. A shorter repetition cycle allows for more timely information acquisition. Achieving a shorter repetition cycle hinges on the rational design of orbits, orbit maneuverability, and utilizing variable viewing angles to expand the visible observation swath. Orbit design is constrained by factors such as the observation scope, observation bandwidth, orbit type, power supply capability, permissible orbital drift, satellite lifespan, and launch vehicles. Expanding the visible observation swath stands as an effective measure for shortening the repetition observation cycle, although it's bound by limitations imposed by ambiguity and spatial resolution performance.

Lastly, the radiation accuracy. SAR is a novel microwave remote sensing instrument that generates data streams with distinctive geographical target features. The accurate representation of ground features, characterized by the target's backscattering coefficient (σ_0), within these data streams is another critical aspect of radar satellite design. The identification of features in SAR imagery depends not only on spatial resolution but also on the severe impact of radar return signal attenuation, inherent system deficiencies that cannot be overcome during design, and imperfections in information processing. These factors can lead to unacceptable deviations between data stream characteristics and the actual σ_0 of the targets.

2.4. Quantum Radar

The principle of quantum radar utilizes the principles and techniques of quantum mechanics to establish radar systems. Differing from conventional radar, quantum radar takes advantage of properties like quantum entanglement and single-photon detection, offering higher signal-to-noise ratio and super-resolution. Consequently, it exhibits significant advantages in tasks such as target detection, ranging, and identification. The implementation of quantum radar hinges primarily on the utilization of quantum entanglement and single-photon detection techniques involving photons [7]. By generating entangled photon pairs, one photon is directed towards the target, while the other is used for detection. Upon interacting with the target, the entangled photon pairs return, altering the state of the detecting photon. Through measuring the state of the detecting photon, information about the target, such as distance, velocity, and scattering pattern, can be acquired. The divergence between quantum radar and traditional radar lies in the former's utilization of entangled photon pairs in contrast to classical electromagnetic waves used by the latter [8]. Quantum radar leverages the properties of quantum entanglement to achieve higher signal-to-noise ratio and super-resolution, thereby enhancing radar system performance. Moreover, quantum radar can exploit the features of quantum entanglement to achieve low probability of interception target detection, enhancing system security.

Furthermore, Quantum Radar can leverage the principle of quantum superposition, allowing the radar to simultaneously transmit multiple signals of different frequencies. This capability enables the radar to gather more information within a single scan cycle, thereby enhancing range resolution and velocity measurement precision [9].

Despite the controversies, challenges, and technological hurdles, at present, quantum-enhanced far-field sensing appears to be progressing towards the development of practical, highly sensitive devices [10]. These devices operate with low-intensity signals, offer low probabilities of interception, and potentially enable super-resolved target imaging.

3. Conclusion

In this paper provides an extensive overview of radar technologies categorized based on their technological features, exploring the unique capabilities and applications of different radar types. Radar technology has evolved significantly, addressing a wide range of applications, from air defense to agriculture, and from navigation to target identification. The author has delved into three distinct radar types: Phased Array Radar, Synthetic Aperture Radar (SAR), and Quantum Radar. Phased Array Radar, with its programmable scanning, resistance to interference, multitasking capabilities, and adaptability, remains a stalwart in various domains. The emergence of Digital Phased Array Radar further enhances flexibility, multi-beam capabilities, adaptive interference suppression, and high-precision beamforming, promising even greater utility in the future. SAR, as an all-weather, all-day observation tool, has demonstrated remarkable versatility in civilian and military applications. Performance indicators such as frequency and polarization selection, resolution and observation bandwidth, repetition observation cycle, and radiation accuracy are essential considerations in designing effective SAR systems. Quantum Radar, a cutting-edge technology harnessing quantum entanglement and superposition, offers the potential for higher signal-to-noise ratios, super-resolution, low probability of interception, and enhanced system security. While it faces controversies and technological challenges, quantum radar holds promise for advanced far-field sensing and imaging applications. In conclusion, radar technology's evolving nature and diverse capabilities make it an indispensable tool in the modern world, with a promising future ahead as innovation and research continue to push its boundaries.

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