Analysis, Comparison and Application Scenarios of Nighttime Infrared Image Technology

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Abstract. As a breakthrough technology that transcends human visual limitations, nighttime infrared imaging demonstrates immense potential and application value across military, civilian, and industrial sectors. This paper systematically reviews the research progress of nighttime infrared imaging technology, focusing on its current applications, core challenges, and future development trends in various fields. The article first analyzes the technical principles and characteristics of active and passive infrared imaging, comparing performance differences and application scenarios between refrigerated and non-refrigerated infrared detectors. Building on this foundation, it elaborates on innovative applications and implementation effects of infrared technology in nighttime security monitoring, autonomous driving perception, industrial inspection, and medical diagnosis. Simultaneously, the paper thoroughly examines prominent issues in current infrared imaging technology, including insufficient image resolution/contrast, sensitivity to environmental interference, high cost constraints on widespread adoption, and limitations in intelligent processing algorithms. Finally, the article outlines emerging trends in cutting-edge directions such as multispectral fusion imaging, novel low-dimensional material detectors, and deep learning-enhanced processing, providing reference for further research and application of nighttime infrared imaging technology.

Keywords: Infrared imaging, Night vision, Technical Challenges.

1 Introduction

In recent years, with the gradual liberalization of low-altitude airspace management mechanisms and the rapid development of low-altitude economy-related industries, the low-altitude sector has become a new driving force for economic growth [1]. Notably, Unmanned Aerial Vehicles (UAVs) are increasingly deployed in airport low-altitude inspection scenarios [2]. These flight platforms predominantly operate in complex, dynamic near-surface airspace environments, which impose higher performance requirements on all-weather passive sensing systems. Infrared imaging technology, as a critical means for UAVs to achieve environmental perception under nighttime or dense fog conditions, is gaining significant attention [3]. China's economy has been developing at an exceptionally rapid pace, and the global landscape continues to evolve,

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driving the swift growth of the maritime industry. Due to the range of content and activities involved in marine activities, ship detection technology has gradually emerged and gradually developed as an important support for the construction of maritime regulation, fishery and national defense security [4]. The impact of ship detection technology on maritime rescue is very important. In addition, ship detection technology also has a profound impact on public service and military applications [5]. In the field of infrared detection technology, because of its own advantages, it can be applied in long-range detection with strong anti-jamming performance. The main technical problem is that small target detection technology is still immature. Because of the weak feature parameters, the feature information of distant ships is easily disturbed by maritime clutter and noise in the complex maritime environment. The edge of the target is blurred. The risk of missed detection or mistaken target will be greatly enhanced. In addition, the infrared imaging also has low resolution, high background complexity and multi-source noise, which restricts the improvement of target detection accuracy [6]. In the field of vehicle-to-everything (V2X) networks, modern technologies are being increasingly applied with technological advancements. Ensuring nighttime driving safety remains a key focus in autonomous driving research, where the development of infrared imaging technology has significantly reduced accident rates during nighttime operations [7]. This paper aims to systematically compare the comprehensive performance of different infrared imaging technology approaches, evaluate their economic costs and performance in practical applications, thereby identifying the optimal solution that balances technical feasibility with cost-effectiveness.

2 Night infrared Image Technology Classification and Principle

During World War II, the prototype of active infrared imaging technology was first developed and widely adopted in military applications. This technology works by actively emitting near-infrared or short-wave infrared beams at targets, using reflected light for imaging. The system employs laser diodes or LED arrays as light sources, with detectors composed of silicon-based CCD/CMOS or InGaAs sensors. Shortly after, passive infrared technology emerged, which can be categorized into two types based on whether low-temperature refrigeration is required: cooled infrared systems and non-cooled infrared systems.

Refrigerated infrared systems operate based on the photoelectric effect, utilizing cadmium telluride mercury or quantum well infrared photodetectors that function at 77K temperatures (cooled by Stirling refrigerators or liquid nitrogen). The first non-cooled infrared system was developed in the United States during the 1980s [8]. It wasn't until 2020 that NASA created a new-generation non-cooled long-wave infrared imaging system, the Hyperspectral Infrared Imager [9], which operates in the 8-12 μ m long-wavelength infrared spectrum.

With the advancement of technology, emerging technical fields are gaining increasing attention. Scholars are increasingly focusing on research in areas such as multispectral/high spectral infrared technology and intelligent infrared imaging.

Multispectral/high spectral infrared technology achieves simultaneous detection across multiple wavelengths (e.g., 3-53-5 μ m + 8-12 μ m) through spectroscopic prisms or adjustable filters, enabling multi-band capture. In contrast, conventional infrared cameras can only capture a single wavelength, essentially acting as filters for thermal imaging. Additionally, intelligent infrared imaging employs technology integration by combining infrared images with AI to address inherent issues of infrared image blurriness (low resolution and excessive noise), achieving super-resolution reconstruction.

3 Application Scenarios and Comparative Analysis

Active infrared imaging technology demonstrates significant advantages in civilian applications, with its core strength lying in exceptional image clarity. By employing active light sources to illuminate targets, the system can generate high-contrast images under low-light conditions, typically achieving resolutions comparable to HD or even UHD standards. The system's performance primarily depends on the light source's power and detector sensitivity. Compared to thermal imaging devices, active infrared systems are significantly more cost-effective. For example, ATN Thor series night vision goggles can be sold for less than $500, which can be widely used. Of course, this technology also has its limitations and is only applicable to specific scenarios. The main problems are as follows: Firstly, the actively emitted infrared light will be detected by special equipment. There are certain risks in the military or high security environment that requires the operation mode of stealth. Secondly, the atmospheric scattering reduces the effective detection distance to less than 200 meters in rainy and foggy weather, which is much lower than the effective detection range of thermal imaging technology. Therefore, active infrared imaging is mainly used in civilian applications such as night patrol of bank vaults and warehouses, but it cannot be used in covert operation applications such as military and counter-terrorism.

Refrigerated infrared technology is mainly used in high-end detection field. Its biggest advantage is that it can achieve ultra-high detection sensitivity. The noise-equivalent temperature difference (NETD) can reach 20 millikelvin, which can achieve temperature differences of 0.02 °C. The image quality is still very good in harsh environment. Besides, due to the excellent atmospheric transmission performance of medium and long-wave infrared, the ultra-long detection range can be achieved. The detection range is more than 10 kilometers, which meets the strategic surveillance requirements. Therefore, the operating environment of refrigerated infrared detector should be in the low temperature environment to play the advantages of refrigerated infrared detector. The size of refrigerated infrared camera is relatively large, so the research direction of refrigerated infrared camera should be ultra-high operating temperature and miniaturization [10]. In addition, the refrigeration system of refrigerated infrared detector is very complex. Including Stirling refrigerators and vacuum maintenance systems, the equipment cost is extremely high. If it is military grade, the price of each unit will exceed $100,000. Moreover, the combat requirements are rapid response. The 5-10 minutes pre-cooling time before system startup may be a fatal defect. In terms of application, refrigerated infrared technology is mainly used in specific performance requirements.

Non-cooled infrared technology has become the main stream in the infrared market today because of its advantages, but there are also certain performance limitations. The most notable feature of this technology is its ability to operate without cooling devices, which brings three core benefits: First, it achieves true instant-on capability, enabling devices to be operational within one second after power-up. Second, it significantly reduces manufacturing costs, with commercial products generally priced under $10,000. Additionally, it demonstrates excellent energy efficiency, typically consuming less than 1W, making it ideal for portable applications. However, the lack of cooling components results in relatively low detection sensitivity, with noise equivalent temperature difference (NETD) typically around 50mK, and imaging resolution mostly limited to below 640×512 pixels. These factors somewhat restrict its application in high-end fields. In practical applications, non-cooled infrared technology has penetrated multiple civilian sectors. In consumer electronics, the emergence of mobile phone external thermal imagers like FLIR One Pro allows ordinary consumers to access infrared imaging capabilities at affordable prices. Furthermore, this technology is widely used in building inspection (identifying insulation defects), firefighting (fire scene rescue), and vehicle night vision, fully demonstrating its practical value as a popular infrared solution.

Multispectral infrared technology demonstrates significant application value in professional fields through its unique capability of simultaneously detecting multiple infrared bands, yet it faces certain technical challenges. This technology extracts useful information from several or dozens of different characteristic wavelengths and image data, enabling rapid and accurate sample analysis. In recent years, multispectral imaging technology has been widely applied in agricultural production. The core advantage of this technology lies in its exceptional material identification capability. By analyzing characteristic absorption spectral lines of different substances in medium-wavelength (3-5 μ m) and long-wavelength (8-12 μ m) infrared bands, it can accurately identify specific chemical components. In recent years, multispectral imaging technology has been extensively utilized in agricultural production [11]. Additionally, the collaborative operation of multiple bands endows it with outstanding anti-interference capabilities, effectively overcoming the limitations of single-band systems prone to environmental factors. However, achieving simultaneous multi-band detection requires complex spectroscopic devices and multiple detectors, leading to substantial increases in equipment size and weight. Moreover, the massive multispectral data demands highly sophisticated processing algorithms supported by professional image fusion and pattern recognition technologies.

Intelligent infrared imaging technology, through deep integration of artificial intelligence algorithms, is revolutionizing the application value of infrared imaging while facing technical implementation challenges. Its most prominent advantage lies in achieving intelligent analysis capabilities that traditional infrared technology struggles to match: Real-time object detection algorithms based on deep learning can accurately identify pedestrians, vehicles, and other targets within 30fps video streams with detection latency controlled under 50ms. Meanwhile, advanced algorithms like generative adversarial networks (GANs) can enhance original infrared image resolution by 2-4 times, enabling a 128 × 96 low-resolution detector to produce output approaching 384×288 HD-quality images. However, implementing these advanced features requires extensive annotated infrared datasets for model training (typically requiring over 100,000 labeled samples), significantly increasing system complexity and energy consumption. In innovative applications, this technology is achieving breakthrough progress across multiple fields. As shown in Table 1.

Table 1. Advantages, Disadvantages and Application Scenarios of Various Infrared Images

Name of infrared technology	Core advantage	Shortcoming	Common application scenarios
Active infrared technology	Clear image, low cost	Easy to detect, short detection range	Civilian surveillance, bank vaults
Refrigeration infrared technology	High sensitivity, adaptability and extreme environments	Expensive, long startup inspection	Strategic-level surveillance
Non-refrigerated infrared technology	Instant start, low energy consumption	Low sensitivity, low resolution	Electronic field, building detection
Multispectral infrared technology	Strong material identification ability	The equipment is large in size and weight	agricultural production
Intelligent infrared imaging technology	An AI algorithm for intelligent analysis	The system is complex and energy intensive	Industrial testing, medical care

4 Challenges and Future Trends

While nighttime infrared technology has been widely adopted in civilian and military applications, several limitations persist. For instance, commercial uncooled infrared detectors are constrained by manufacturing processes for micro-heat flux meters, with mainstream resolutions remaining stagnant at 640×512 (FLIR A35). Models like the Teledyne HDC-X series (1280 × 1024 resolution) cost over $15,000, hindering widespread civilian adoption. Additionally, vanadium oxide and amorphous silicon currently dominate as the two primary materials for uncooled long-wave infrared detectors. In China, vanadium oxide-based uncooled detectors account for 70% of market usage, making them the preferred choice for refrigerated long-wave infrared systems developed by many researchers [12]. Notably, vanadium oxide-based uncooled detectors outperform amorphous silicon counterparts in multiple performance metrics

[13]. Furthermore, silicon-based superlenses could replace traditional lenses to reduce camera size, for example, the iPhone 17 Pro Max adopts a hybrid solution of metalens and refractive lens, reducing the thickness of the rear camera module from 7.2mm to 4.8mm [14], with potential improvements through phase optimization and advanced materials. Therefore, the future of nighttime infrared technology depends on interdisciplinary breakthroughs in material science, artificial intelligence, and optical engineering.

5 Conclusions

This paper provides a systematic review of nighttime infrared imaging technology, aiming to offer researchers and engineers in related fields a clear technical roadmap and selection guide. The article closely follows the core framework of "technical principles-performance evaluation-application scenarios-future trends," conducting in-depth research on five major technological directions: active infrared, cooled passive infrared, uncooled passive infrared, multispectral infrared, and intelligent infrared imaging. The significance and value of this study are reflected in three aspects: First, systematicness. The article not only traces the historical origins and physical principles of various technologies but also constructs a multi-dimensional evaluation system through horizontal comparisons (such as cost, NETD, resolution, and applicable scenarios), breaking the technical isolation often seen in previous studies. Second, evaluative and instructive value. Going beyond mere technical introductions, this paper focuses on critical evaluations, clearly identifying the advantages, bottlenecks, and optimal application boundaries of each technology. Third, foresight. Based on current analysis, the article further explores cutting-edge directions such as quantum dot detectors, metasurface lenses, and edge AI, pointing out potential breakthroughs for future research. Guided by real-world problem-solving, this paper integrates profound technical principles with specific application cases and authoritative literature data, achieving a close integration of theory and practice. It aims to provide strong support for driving innovation and development in infrared imaging technology.

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