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In-Depth Analysis of UAV Image Transmission and Communication Systems: Principles, Models

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Abstract:

UAV technology, originally developed for military reconnaissance in the early 20th century, has evolved into a versatile tool in both military and civilian applications. This paper explores the progression of UAV image transmission technology, from early analog systems to modern digital transmission. Key advancements in compression algorithms, including the use of H.264 and H.265 standards, have significantly improved data transmission efficiency, image quality, and system stability. The integration of wireless communication technologies such as Wi-Fi, 4G, and 5G has broadened UAV applications across various sectors, including aerial photography, agriculture, logistics, and disaster management. Additionally, emerging technologies such as millimeter wave communications, 6G networks, and artificial intelligence-driven image processing will further enhance the performance and reliability of UAV systems. The future of UAV image transmission lies in the adoption of these innovations, allowing for improved bandwidth efficiency, real-time video transmission, and expanded applications in smart cities, telemedicine, and precision agriculture.

Keywords: drones; image transmission; signal.

1. Introduction

UAV technology originated from wartime reconnaissance in the early 20th century [1], and with the continuous progress of technology, it has gradually been applied in the strategy of target attack and electronic warfare, and has also contributed to data collection and disaster assessment in the research field [2]. Today, drones have become an important carrier in many civil and commercial areas of monitoring, agriculture, logistics and other scenarios, greatly improving the accuracy of urban monitoring, agricultural precision, and the efficiency of express emergency services in remote areas [3]. UAV military, scientific research and commercial missions are inseparable from video transmission technology, in these missions, the true and smooth image transmission directly affects the success of the mission [4].

In the development of image transmission technology of UAV system in China, obvious changes have taken place in all aspects from the earliest analog

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transmission system to the modern digital transmission system [5]. Since the initial analog transmission resists interference with the signal and the resolution is low, the image quality is poor, so the establishment is not used for detailed cases [6]. Today's digital retransmission technology, based on compressed coding transmission, encrypted transmission and anti-interference design, can not only transmit ultra-high resolution images, but also transmit high-definition video [7], so the UAV can be successfully applied in complex environments [8].

The future development direction is to use efficient stream compression algorithm to reduce bandwidth occupation; Research more stringent transmission protocol to enhance anti-interference ability and delay [9]; The combination of 5G and satellite communication technology has expanded the application of UAVs in aerial photography, rescue, logistics and other fields [10], greatly broadened the application field of UAVs, and enhanced the universality and practicality of UAVs [11].

2. Organization of the Text

The research of UAV image transmission system has long covered the evolution of digital and analog image transmission technology in different periods [12]. Due to its simple structure and low cost, the early analog image transmission technology occupies a major position in the application of film and television by drones, despite its strong portability [13]. But obviously, its disadvantage is the signal interference, poor transmission stability, low resolution and other limitations, far beyond the current UAV image quality and information transmission reliability of the high requirements [14]. With the successful promotion of digital transmission technology, these technical constraints have been basically eliminated [15]. The advantages of digital transmission technology include higher resolution, better resistance to interference, and reduced bandwidth requirements through data compression [16]. However, digital technology is not perfect, and design latency and high bandwidth are particularly difficult, especially in complex or remote environments [17]. As for the research status of digital image transmission technology, researchers generally believe that at this stage, it mainly focuses on the application of different compression technologies in UAVs [18]. H.264 and H.265 are the most popular video scaling standards [19]. H.264 is an early standard that provides efficient compression and good video quality, making it widely suitable for real-time image transmission by drones [20]. The compression capability is further enhanced to better adapt to the transmission of higher image quality in the case of limited bandwidth, which is particularly suitable for the long-range and high-resolution needs of drones [21]. And with the increasing popularity of unmanned civil aircraft applications, additional research will develop the data transmission technology of aircraft to a higher level, resulting in reduced transmission delays and increased stability [22], which will provide better technical support for real-time monitoring and target recognition tasks [23].

The research of UAV communication and data transmission technology covers the application of various wireless communication technologies, including Wi-Fi, 4G/5G, etc [24]. Wi-Fi technology is widely used in short-distance UAV image transmission due to its low cost and high transmission speed, but its limited coverage and easy to be affected by interference and signal blocking limit its use in complex environments [25]. Through 4G technology, the range of image transmission has been greatly expanded, and relatively speaking, whether the image can be transmitted with higher quality has also been better supported [26]. However, the bandwidth range of 4G is still too small to meet the needs of higher resolution images and real-time transmission of images [27].

The advent of the 5G era has formed ultra-broadband, low-latency and ultra-stable drone communication that we could not imagine before [28]. The characteristics of ultra-high bandwidth and ultra-low latency enable 5G networks to support real-time video transmission with higher resolution, and the ability to cover a wide range is the reason why drones can still maintain communication connections in long-distance or complex environments [29]. The construction cost of 5G network is relatively high, and the coverage of some areas is still high, although this limits its popularity in unmanned aerial systems [30]. Riding on the east wind of a new generation of communication protocols, such as LTE and millimeter wave communication technology, in the UAV image data transmission, in essence, provides a good opportunity [31]. LTE, which connects drones to cellular networks, has shown better coverage and reliability, especially in large-scale deployment networks, although its bandwidth is still limited by comparison [32]. Millimeter wave communication technology is expected to meet the needs of UAVs for big data transmission by providing ultra-high transmission rates and bandwidth [33]. However, millimeter wave communication may be affected by factors such as weather and obstacles, and signal penetration may not be achieved, which may cause communication interruption [34].

3. Literature References

As an important part of UAV image transmission, image compression is to enhance the transmission rhythm and reduce the bandwidth by reducing the image data. Today,

H.264(RPZ coding, also known as AVC) and H.265(RPZ coding, also known as HEVC) are the most popular video coding standards in the market. H.264/AVC: H.264/AVC (Advanced Video Coding) is an efficient video compression standard that has learned how to strike a balance between image quality and compression ratio. In other words, its frame prediction can eliminate some redundant data in the video frame sequence. Transform coding can change the data into frequency domain and further compress the data. Entropy coding reduces coding redundancy by using a probabilistic model. H.265/HEVC: H.265/HEVC (High Efficiency Video Coding) completes H.264 from the bottom of prediction and entropy coding methods that improve compression efficiency. Compared with H.264, H.265 can achieve a compression rate of about 50%, which greatly saves bandwidth requirements.

The working principle of modulation is to convert the digital data of the image into a suitable analog waveform, while the work of demodulation is to ensure that the signal is read out at the receiving end and the original image data is obtained. Modulation is to change the characteristics of the carrier signal itself, such as the amplitude, phase or frequency of the signal, to send and receive digital information. In practical applications, QAM (quadrature amplitude modulation) and psk (phase shift keying) are two mainstream modulation techniques, which show different advantages under different conditions. This modulation technique has been widely used in modern wireless communication, especially in the high speed data transmission and the need for high interference resistance.

ayleigh fading model: The Rayleigh fading model is mainly applicable to the multipath propagation scenario without direct view path (NLOS), and is often used for channel modeling in urban environment. Since the signal reaches the receiving end through multiple paths in the propagation process, the mutual interference of each path leads to rapid signal fluctuations. The Rayleigh model effectively simulates such complex propagation conditions without direct view paths.

Decay model: Rician decay is similar to Rician decay in that it takes into account the direct view path (LOS) and multipath propagation, which together affect environments with short visual distance and obstacles. The LOS path in the Rician model causes relatively small fluctuation in signal attenuation. Therefore, this model is widely used to simulate environments with obvious LOS path characteristics such as oceans, cities, and non-interference Rician.

Wireless transmission protocol is the prelude of data transmission between different layers of multiple network layers, which has a direct impact on the effectiveness and stability of data transmission. The choice of protocol determines how to handle the process of data sending, receiving, acknowledging and error recovery, thus affecting the overall transmission performance. The common wireless transmission protocols mainly include TCP/IP and UDP, which have different applicable environments and purposes.

TCP/IP protocol stack model: TCP/IP protocol stack model is a guaranteed, orderly data transmission model, so that when the data is transmitted, it can effectively ensure that the data is not lost, no duplication, and ensure the sequence of data to the destination. Through this insurance.

UDP transport model: The UDP transport model aims at speed, but the difference is that it prioritizes transmission and does not guarantee the reliability of transmission. Because UDP omits the complex handshake process and error detection mechanism, its transmission speed is faster than TCP, which is suitable for crowded environments with high real-time requirements but can accept a small amount of packet loss, such as real-time video stream transmission of drones. When they make such decisions, speed and real-time are their primary concerns, not the integrity of the information.

In wireless communication, the wireless spectrum resources are limited due to the large amount of information, especially in the multi-UAV operation, spectrum management and interference control are particularly important. Effective spectrum management can reduce the interference in communication and improve the overall communication efficiency and stability. The interference model is used to reflect the distortion degree of the signal under various transmission conditions, so as to ensure the system has good stability in the actual working environment.

CSMA/CA model: The CSMA/CA model is suitable for Wi-Fi communication and can be used to ensure that multiple devices on different frequency bands can effectively share the same frequency band. It improves transmission efficiency by listening to the channel before packet transmission to avoid collision with other transmissions.

Spectrum sharing model: Spectrum sharing model is used to simulate the scenario where multiple devices share the same spectrum resource, and analyze how the interference between different devices affects the communication quality. The model helps design spectrum allocation strategies to minimize interference and optimize spectrum utilization. The spectrum sharing model is particularly important in multi-UAV systems because it is able to evaluate signal interference when multiple UAVs are working simultaneously and propose solutions to improve the quality of communication.

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4. Conclusion

The performance evaluation of the UAV image transmission system is usually achieved through a series of experimental designs, which are designed to simulate different flight environments, such as urban, mountain, rural and ocean, etc., and analyze the image quality, delay and anti-interference ability of the system in these environments. In the test, the unmanned aircraft will fly in these scenes, obtain images in real time, and perform subjective and objective analysis of image clarity, color authenticity and other aspects. In addition, the delay of the system also needs to be measured to determine whether the image can be displayed in real time. And the experiment is also large-scale, through the simulation of the image transmission system performance evaluation to achieve. However, the aircraft scoffs at simulation models that mimic its flight path, impact environment and transmission protocols. Usually, the validity and applicability of the model is verified by comparing it with actual experimental data. In the evaluation process, the main debate is whether the model can correctly reflect the relevant indicators, such as image quality, transmission delay and anti-interference ability.

With the emergence of dominant emerging technologies, such as millimeter wave communications, simulation models are also used to evaluate actual performance accordingly. These coherent technologies show significant potential value due to the characteristics of providing large bandwidth and low latency services, especially in the application of high-resolution video and image transmission. However, millimeter wave communication also has difficulties in practical applications such as signal easy interference and poor penetration, so model evaluation is particularly important in the feasibility and subsequent optimization of specific application occasions.

This paper briefly summarizes the main research results of UAV image transmission system, and shows the advantages of various methods to improve image transmission performance. The performance of WI-FI, 4G/5G and other communication technologies used in the experiment in image data transmission is systematically analyzed and evaluated. It is observed that these technologies have the characteristics of dynamic adjustable data transmission speed, high image definition and low interference. H.264 and H.265 video encoding technologies help to improve image compression, thereby reducing bandwidth utilization. This helps to improve transmission quality and stability. In addition, the introduction of frequency allocation and interference control technology also helps to improve the frequency efficiency of multi-UAV systems and minimize the occurrence of communication conflicts. The main advantage of Wi-Fi is its ability to cope with short distance and low latency areas, while 5G enables high bandwidth and long distance transmission.

In the future development of UAV imaging transmission technology, emphasis will be placed on the innovation of new communication methods and the most advanced image processing algorithms. Emerging technologies such as millimeter wave communications, 6G networks, and quantum communications have fundamental properties such as high bandwidth, low latency, and extremely strong anti-jamming capabilities, and their introduction will greatly accelerate this process. In addition, with the emergence of intelligent image processing and adaptive coding algorithms, artificial intelligence will undoubtedly play a prominent role in image quality optimization and compression. The demonstration of the potential of UAV image transmission technology is mainly of great significance in the construction of smart cities, telemedicine, precision agriculture and so on. In the distant future, by developing faster and more efficient transmission systems, smart cities will be able to conduct detailed monitoring and management. Telemedicine will provide more timely diagnosis and care assistance through real-time patient data, while precision agriculture will use data analysis of crop geometry and properties to predict yields and improve management techniques. The application of UAV technology in these fields will open new doors for the innovation and application of UAV technology.

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