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Research on Sound Design in Mobile Games

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Abstract:

In the design of sound effects for mobile games, hardware limitations and diverse user needs remain the main challenges. Due to the processing power and memory limitations of mobile devices, sound designers need to find a balance between sound quality and resource utilization to ensure optimal performance of sound effects under limited resources. The compression, optimization, and compatibility issues of sound effect files also need to be addressed as a key focus. In addition, in response to users' demand for personalized settings, sound design needs to provide rich sound options to meet the preferences of different players, while also considering the silent mode and low volume requirements, as well as the influence of cultural and language differences on sound design. This article provides a deep understanding of the field of mobile game sound design through the analysis of the application and challenges of new technologies and provides valuable references for future sound design practices and research.

Keywords:

Mobile games
Sound design
Hardware limitations
Personalized audio settings

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1. Introduction

With the popularization of diverse mobile devices and the rapid development of mobile Internet technology, mobile games have become an indispensable part of modern people's daily entertainment. According to statistics, the number of mobile game users worldwide is constantly increasing, and the market size is expanding year by year. Compared with traditional PC and console games, mobile games have advantages such as convenience, ease of operation, and the ability to play anytime, anywhere. These features have attracted a large number of users, especially among young people, and the popularity of

mobile games has reached an unprecedented height.

In the design of mobile games, sound effects play a crucial role as one of the important elements. Sound effects can not only enhance the immersion of games but also improve players' gaming experience through changes in sound and design of sound effects. High-quality sound design can greatly enhance the visual and emotional appeal of a game, immersing players in a richer, more realistic experience. This not only elevates the overall game quality but also fosters user engagement and loyalty, ultimately increasing player retention. However, compared to intuitive elements such as graphics and

operations, there is relatively less research and application of sound effects in game development.

Developers often focus their research on graphics, controls, and plots when designing mobile games, and to some extent overlook the importance of sound effects. In fact, the design and implementation of sound effects also require a significant amount of time and resources, and their complexity and technical difficulty are no less than other game elements. Sound design not only involves sound collection and editing, but also needs to consider the performance of sound effects in different devices and environments, as well as how to achieve the best sound effects through technical means. In addition, with the improvement of mobile phone hardware performance and the continuous increase in users' requirements for game quality, sound design is facing new challenges and opportunities. Achieving high-quality sound effects under limited hardware conditions, utilizing new technologies to enhance the expressiveness of sound effects, and optimizing sound effects while ensuring smooth game operation are all issues that need to be addressed in current mobile game sound design.

Based on the above background, this study will focus on sound design in mobile games, and conduct in-depth exploration from multiple aspects such as theoretical basis, technical implementation, practical application, and optimization methods. By analyzing and summarizing existing sound design methods and techniques, the aim is to provide valuable references for game developers and bring users a better gaming experience.

2. Theoretical basis for sound design in mobile games

2.1. The role of sound effects in games

Sound effects play multiple important roles in games and make significant contributions to enhancing the gaming experience and player engagement. Sound effects also enhance the immersion of the game. Through the clever use of background music, environmental sound effects, and special effects, games can create a more realistic and vivid virtual world for players, making them feel as if they are immersed in it, enhancing the sense of immersion and experience of the game^[1]. Different sound effects can convey different emotions, for example, tense background

music can make players feel a sense of crisis and urgency, while cheerful music can make players feel happy and relaxed. By changing the sound effects and controlling the rhythm, game designers can effectively influence players' emotions, resonate with the game plot, and enhance the entertainment and appeal of the game.

Sound effects convey important information to players, such as task completion, enemy approach, item acquisition, etc. These sound effects not only help players better understand and master the game process but also provide instant feedback, making players feel a sense of achievement and satisfaction in the operation and decision-making process. Sound effects also strengthen the brand and features of the game. Many classic games have their own unique sound effects, such as the slingshot sound and pig laughter in Angry Birds, or the elimination sound effects in Candy Crush Saga. These classic sound effects not only enhance the recognition of the game but also leave a deep impression on players and become a part of the game culture.

The role of sound effects in games is multifaceted, not merely a simple combination of background music and sound effects, but also enhancing the overall quality and user experience of the game through sound design and application. Excellent sound design can enhance the game appeal, making it stand out in fierce market competition and win the favor and recognition of players.

2.2. Basic principles of sound design

Sound design must be consistent with the theme and style of the game. For example, horror games require mysterious and eerie sound effects to create a tense and terrifying atmosphere, while casual games require relaxed and enjoyable sound effects to enhance entertainment and relaxation^[2]. Sound effects should be designed according to the type and plot of the game, ensuring that they can effectively convey the core atmosphere and emotions of the game. Excellent sound design can make players feel as if they are in the game world, enhancing the immersion of the game. This requires meticulous design of various environmental sound effects, background music, and special sound effects. For example, in an adventure game, the chirping of birds in the forest, the rustling of wind and grass, and the murmuring of streams can all help players feel like they are there. Through sound,

the game can convey various information to players, such as sound effects of task completion, alert sounds of enemy approaching, and notification sounds for rewards. These sound effects can help players better understand the game process and status, thereby improving the operability and interactivity of the game^[3]. Design should pay attention to the control of rhythm and hierarchy, avoiding overly chaotic or monotonous sounds. The appearance time and frequency of different sound effects should be appropriately arranged to ensure coordination and cooperation between them. For example, in intense combat scenes, background music should be coordinated with fighting and explosion sounds, while in calm exploration scenes, background music and environmental sound effects should be relatively soft to avoid disturbing players' thinking and exploration.

In mobile games, sound design must consider hardware limitations and performance optimization issues. Due to the limited hardware performance of mobile devices, the size and quantity of sound effect files need to be controlled to avoid occupying too much storage space and computing resources. At the same time, efficient audio encoding and compression techniques should be used to ensure the quality of sound effects and smooth running of games. Providing volume adjustment options for sound effects and music allows players to adjust according to their personal preferences. Personalized sound effects settings can provide players with more choices and freedom, enhancing the playability and attractiveness of the game.

3. Technical implementation of sound design for mobile games

3.1. Common sound design software and tools

Audio editing software plays an important role in the sound design of mobile games. Audacity is a free and open-source cross-platform audio editing software that supports operating systems such as Windows, macOS, and Linux, and is widely popular among users. Its main functions include multi-track editing, recording, audio effect processing, and importing and exporting multiple audio formats. Audacity has an intuitive interface and simple operation, making it easy for even novice audio editors to quickly master. Its biggest advantage is that

it is free and open-source, making it highly suitable for individuals and small development teams with limited budgets. However, Audacity may not perform as well as professional software in certain advanced audio processing features, and its interface design is relatively simple and lacks modernity.

Adobe Audition is a professional audio editing software launched by Adobe, which is powerful and widely used in fields such as audio production, broadcasting, movies, and television. Its main functions include complex multi-track editing and mixing, high-quality recording, rich audio effects, waveform and spectrum editing, and audio restoration^[4]. Adobe Audition has professional-level audio editing and processing capabilities, seamlessly integrates with other Adobe software, has a modern user interface, and provides a good user experience. Although Adobe Audition offers comprehensive audio editing and processing tools, its subscription fees are relatively high, making it suitable for users with sufficient budgets and a pursuit of professional quality. In addition, Audition features are complex and beginners need to spend a lot of time learning and mastering them.

3.2. Common audio formats

Choosing the appropriate audio format and compression technology is crucial in the sound design of mobile games. The commonly used audio formats include WAV, MP3, and OGG, each with its own advantages and disadvantages in terms of sound quality, file size, and compatibility. WAV (Wave Audio File Format) is a lossless audio format that preserves the original quality of the audio, resulting in extremely high sound quality, but with a large file size. It is suitable for scenarios that require extremely high sound quality, but may be limited in mobile gaming due to occupying a large amount of storage space and bandwidth.

MP3 (MPEG Audio Layer-3) is a lossy audio format that reduces file size through compression algorithms while preserving sound quality as much as possible. It is one of the most common audio formats widely used for music storage and transmission. For mobile games, MP3 format strikes a good balance between sound quality and file size and is a common choice. OGG (Ogg Vorbis) is also a lossy compressed audio format, similar to MP3,

but typically provides better sound quality at the same bit rate. OGG format is open-source and free, suitable for developers who need high-quality sound effects and want to avoid copyright issues.

The audio compression algorithm directly affects the quality of sound effects and file size. Lossless compression algorithms such as FLAC (Free Lossless Audio Coding) preserve all the details of the original audio without affecting the sound quality, but the file size is still relatively large. Lossy compression algorithms such as MP3 and OGG reduce file size by discarding audio information that is difficult for the human ear to perceive. Although lossy compression can affect sound quality, modern algorithms can provide satisfactory sound effects at smaller file sizes, which is particularly important for mobile games with limited storage space and bandwidth.

3.3. Real-time adjustment and processing of sound effects

Real-time sound processing technology plays an important role in modern mobile games, enabling sound effects to be generated, adjusted, and mixed in real time based on game dynamics. These technologies not only enhance the immersion of the game, but also optimize performance and user experience. Dynamic sound generation technology allows games to generate appropriate sound effects based on the current situation and player actions. For example, in racing games, the sound of the engine changes in real time based on the player's acceleration, braking, and turning movements. Mixing technology synthesizes multiple sound effects in real time to ensure that various sound elements in the game are harmoniously integrated. For example, background music, character dialogue, and environmental sound effects can be played simultaneously, and sound overlap and distortion can be avoided through mixing processing.

The implementation of sound design in mobile games not only relies on software and algorithms, but also involves the application of physical acoustic principles. Digital signal processing (DSP) is the foundation of sound design, which includes sampling, quantization, filtering, and spectral analysis of audio signals. Discrete Fourier Transform (DFT) and Fast Fourier Transform (FFT) are the core technologies for frequency domain analysis and

sound processing.

3.4. Discrete Fourier Transform

DFT is used to convert discrete-time signals into frequency domain signals, and its formula is as follows:

$$X(k) = \sum_{n=0}^{N-1} x(n) \cdot e^{-j2\pi kn/N}$$

Among them, $X(k)$ represents the frequency domain signal, $x(n)$ represents the time domain signal, N is the number of sampling points of the signal, and k is the frequency index. FFT is an efficient implementation of DFT, which can reduce the time complexity from $O(N^2)$ to $O(N \log N)$. FFT uses divide and conquer to decompose DFT into smaller DFT calculation units, thereby improving computational efficiency.

3.5. Space sound effects and 3D sound field

In virtual reality (VR) and augmented reality (AR), the implementation of spatial sound effects requires simulating the propagation of sound in three-dimensional space. This involves physical phenomena such as sound source localization, distance attenuation, and sound wave reflection. Sound source localization utilizes the Head Related Transfer Function (HRTF) to simulate the effect of sound reaching the ear from different directions. HRTF includes the transmission path of sound waves passing around the head and outer ear. HRTF is expressed in the time domain as Head Impulse Response (HRIR), also known as binaural impulse response. It is related to the head related transfer functions HL and HR. They are Fourier transform pairs, the formula is:

$$h(r, \theta, \varphi, \omega, \alpha) = \frac{1}{2\pi} \int HL(r, \theta, \varphi, \omega, \alpha) e^{i\omega t} dt$$

$$h(r, \theta, \varphi, \omega, \alpha) = \frac{1}{2\pi} \int HL(r, \theta, \varphi, \omega, \alpha) e^{i\omega t} dt$$

Among them, ϕ and θ respectively represent the azimuth and elevation angles of the sound source, and f represents the frequency.

Sound attenuates with increasing distance during propagation. According to the inverse square law, the attenuation formula of sound pressure level (SPL) with distance d is:

$$SPL(d) = SPL_0 - 20 \log_{10} \left(\frac{d}{d_0} \right)$$

Among them, SPL_0 is the sound pressure level at the reference distance d_0 .

3.6. Real-time sound processing

Echo and reverberation are the effects formed by the superposition of sound reflected on different surfaces. The reverberation time T_{60} is an important parameter that represents the time required for sound attenuation of 60dB. The formula is:

$$T_{60} = \frac{0.161 \cdot V}{A}$$

Among them, V is the volume of the room, and A is the total sound absorption area.

Real-time sound processing requires low latency to ensure the immediacy of the player experience. The size of the audio buffer and the efficiency of the processing algorithm are key factors. The delay formula for a typical low-latency audio processing system is:

$$x_k = Ax_{k-1} + Bu_{k-1} + w_{k-1}$$

This state equation is used to infer the current state based on the previous state and control variables. w_{k-1} is the noise that follows a Gaussian distribution and is the noise of the prediction process. It corresponds to the noise of each component in x_k , which is the Gaussian white noise w_{k-1-N} (0, Q) with an expected value of 0 and covariance Q. Q is the process excitation noise Q. By optimizing the latency of each stage, faster sound response can be achieved. **Figure 1** shows the real-time audio delay function.

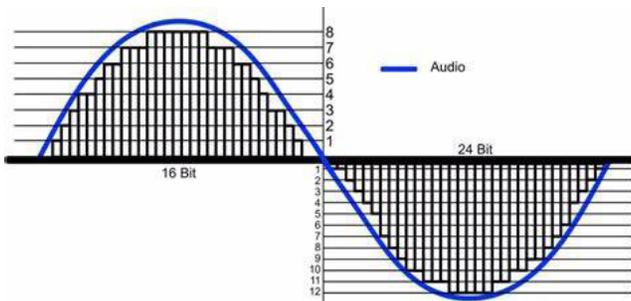


Figure 1. Real-time audio delay function

3.7. Audio compression and encoding

The compression and encoding of audio signals can significantly reduce the bandwidth of storage and transmission. Common compression algorithms such as MP3, AAC, etc. are based on perceptual encoding principles to remove audio components that are insensitive to the human ear. Gain Computer calculates the required gain based on the level (volume) of the input signal. This stage involves three parameters: Threshold (T), Ratio (R), and Knee Width (W). Once the input signal level exceeds T, it will attenuate according to R, calculated as follows:

$$y_G = \begin{cases} x_G & x_G \leq T \\ T + (x_G - T)/R & x_G > T \end{cases}$$

During the compression process, it is necessary to balance the sound quality and compression rate. Distortion D and signal-to-noise ratio (SNR) are indicators for evaluating compression quality:

$$D = \frac{\sum_{n=0}^{N-1} (x(n) - \hat{x}(n))^2}{\sum_{n=0}^{N-1} x(n)^2}$$

$$SNR = 10 \log_{10} \left(\frac{\sum_{n=0}^{N-1} x(n)^2}{\sum_{n=0}^{N-1} (x(n) - \hat{x}(n))^2} \right)$$

Among them, $x(n)$ is the original signal, and $\hat{x}(n)$ is the compressed signal.

The technical implementation of mobile game sound design involves various technologies such as digital signal processing, spatial sound effects, real-time sound effects processing, and audio compression. By applying physics formulas and algorithms reasonably, the quality and performance of sound effects can be optimized, enhancing the immersion and user experience of the game. Despite facing hardware limitations and diverse user demands, the continuous development of new technologies provides more possibilities and solutions for sound design.

In order to achieve real-time sound processing, commonly used audio middleware in game development such as FMOD and Wwise provide powerful tools and APIs. FMOD is a popular audio middleware that supports multiple platforms and audio formats, providing real-time sound generation, mixing, and adjustment functions. It allows developers to control the playback, pause, stop, and parameter adjustment of sound effects through

programming interfaces. Wwise is a professional audio middleware widely used in large-scale game development projects. It provides rich audio design tools and flexible real-time processing capabilities, enabling developers to create complex sound systems and achieve high-quality sound performance in games. Choosing the appropriate audio format and compression technology, as well as mastering real-time sound processing techniques, are crucial for improving the sound quality and user experience of mobile games. Through the reasonable selection of lossless and lossy audio formats, advanced compression algorithms, and dynamic generation, mixing, and real-time adjustment techniques, game developers can achieve high-quality sound effects under limited hardware conditions, bringing players a richer and more realistic gaming experience.

4. Workflow of mobile game sound design

In mobile game development, sound design is a complex and crucial aspect. It not only affects the immersion and user experience of the game, but also largely determines the overall quality of the game. A complete sound design workflow typically includes three main stages: requirement analysis and solution design, sound production and testing, and integration and debugging.

4.1. Requirement analysis

Communication with game designers, programmers, and other relevant personnel allows an understanding of the overall design, plot, characters, and scenes of the game. The types and quantities of sound effects required for each scene and action are clearly defined. The game script and design documents are carefully read to determine the specific scenes and actions that require sound effects, such as character movements, battles, environmental sound effects, etc. The user experience goals of game sound effects are determined, such as enhancing players' sense of immersion and conveying game emotions through sound effects.

4.2. Conceptual design

After clarifying the requirements, it is crucial to design a comprehensive sound design plan. This includes

the classification of sound effects, the style of sound effects, and the technical implementation scheme of sound effects. Sound effects are classified by function, such as background music (BGM), ambient sound (ambience), character sounds, special effects sound (SFX), etc. Specific requirements and implementation methods are determined for each type of sound effect. The overall style of sound effects is determined based on the theme and style of the game. For example, the sound effects of horror games should be eerie and tense; the sound effects of casual games should be relaxed and enjoyable. Appropriate audio formats, sampling rates, and compression methods are selected to ensure compatibility and performance of sound effects on various devices.

4.3. Audio production

Audio production is the process of transforming conceptual design into actual sound effects. This stage requires the creativity and technical ability of sound designers. The required sound is recorded or sampled according to the requirements. Recording can be done in a professional recording studio, and sampling can be done by selecting suitable sound materials from a sound library. Audio editing software such as Audacity and Adobe Audition can be used to edit recorded or sampled sounds, including editing, noise reduction, mixing, adding effects, etc. For original sound effects, sound designers need to create specific sounds. This may include synthesizing sound effects and using virtual instruments or sound synthesis software to generate specific sound effects.

5. Optimization and performance improvement of mobile game sound effects

5.1. Methods for optimizing sound design

In the sound design of mobile games, optimizing file size and loading time, memory usage, and processing performance are key to ensuring smooth game operation and improving user experience. By selecting appropriate audio compression formats (such as MP3 or OGG) and bit rates, the size of sound effect files can be effectively reduced while maintaining good sound quality. Audio editing and noise reduction processing helps remove unnecessary parts and background noise, further reducing

file size. In addition, dynamic loading and unloading of sound effects can reduce memory usage by loading and releasing unused sound effects on demand, maintaining efficient memory usage. Audio middleware such as FMOD and Wwise can provide sound pool management, caching, and priority settings, optimizing the loading and playback of sound effects. The use of efficient sound processing algorithms and hardware acceleration can improve processing performance and reduce CPU burden^[5]. When playing sound effects, limiting the number of sound effects played simultaneously and utilizing sound effect multiplexing technology can avoid performance degradation and confusion. Through these optimization methods, game developers can achieve high-quality sound performance with limited hardware resources, improving game fluency and user experience.

5.2. Coordination of sound effects with other game elements

The coordination of sound effects and visual effects is the core of enhancing game immersion. To achieve this, sound effects need to be precisely synchronized with visual events. For example, when a character jumps, the sound effect of the jump should be consistent with the character's jumping movements to enhance the player's immersion. In addition, sound effects also need to be consistent with visual feedback. For example, when a player clicks a button, the sound effects and visual response of the button should be coordinated to provide clear feedback signals. Sound effects can also be used to emphasize and enhance visual effects, such as using heavy sound effects to enhance the impact of strong visual effects such as explosions or collisions. Meanwhile, the combination of sound effects and visual effects can also convey the atmosphere and emotions of the game through emotional resonance. For example, soft background music and delicate visual effects can convey a peaceful atmosphere, while intense sound effects and fast visual effects can convey a tense and thrilling experience.

6. Future development and challenges

With the continuous advancement of technology, the field of sound design is also undergoing tremendous changes. New technologies, such as artificial intelligence,

machine learning, virtual reality, and augmented reality, are redefining the way sound design is done. These technologies not only improve the quality and expressiveness of sound effects, but also bring new challenges and opportunities.

Artificial intelligence (AI) and machine learning (ML) technologies are gradually being applied in the field of sound generation. By training deep learning models, AI can automatically generate sound effects materials. For example, Generative Adversarial Networks (GANs) can create realistic sound effects and simulate sounds in different environments. The application of this technology can reduce the time and cost of manually creating sound effects while providing more diverse and abundant sound effect materials.

By analyzing the scenes and events in the game, AI can automatically match suitable sound effects materials. For example, when there is an explosion scene in the game, AI can automatically select the most suitable explosion sound effect, thereby enhancing the expressiveness and immersion of the sound effect. In addition, ML models can analyze players' preferences and recommend personalized sound effects settings to meet the needs of different players.

Intelligent algorithms are used to dynamically adjust the volume, frequency, and effects of sound effects to adapt to real-time changes in the game. This real-time adjustment can improve the sound response speed of the game, allowing players to have a consistent sound experience in different scenes. Meanwhile, AI technology can also help optimize the loading and playback performance of sound effects, reducing latency and stuttering.

VR and AR technologies have posed new requirements and challenges for sound design. In VR and AR environments, sound effects need to provide a more realistic and immersive experience. For example, surround sound and spatial sound effects technology can simulate the propagation of sound in three-dimensional space, enhancing players' perception of virtual environments. By using spatial sound effects technology, players can accurately perceive the source and distance of sound, thereby enhancing the immersion and interactivity of the game.

The design of dynamic environmental sound effects

is particularly important in VR and AR environments. The sound effects in the game need to be dynamically adjusted according to the player's movements and changes in perspective. For example, when a player moves in the virtual world, the background sound effects should change with the player's position to simulate a real sound environment^[6]. This requires sound designers to adopt advanced audio engines and real-time processing technologies to achieve highly dynamic and realistic sound experiences. In sound design, integrating with other sensory experiences to provide a more comprehensive immersion is an important challenge. For example, designers can use haptic feedback devices (such as vibration controllers) in conjunction with sound effects to enhance players' tactile and auditory experiences, thereby improving the interactivity and immersion of the game.

The hardware limitations of mobile games, including processing power and memory capacity, directly affect the design and performance of sound effects. Mobile devices typically have lower processing power and memory, and sound designers need to optimize the quality and performance of sound effects within limited resources. High-quality sound files and complex real-time sound processing may lead to device performance degradation or game lag, thus it is necessary to find a balance between sound quality and resource utilization.

To cope with hardware limitations, sound effect files need to be compressed and optimized. Although compression techniques can reduce the size of sound effect files, excessive compression may result in loss of sound quality. Therefore, designers need to choose the appropriate audio format and compression bit rate to ensure that the sound effects maintain good quality while adapting to the storage and processing capabilities of the phone. Different models and brands of mobile devices may have compatibility issues in audio processing. Sound designers need to ensure compatibility and consistency of sound effects across various devices, including different operating systems and hardware configurations. Through extensive device testing and optimization, the performance differences of sound effects on different devices can be reduced, improving the overall quality and user experience of the game.

With the diversification of user demands for gaming experience, sound design needs to meet the personalized

needs of different players. For example, some players may enjoy immersive sound effects, while others may prefer simple background music. Sound designers need to provide a variety of sound effect settings options, allowing players to adjust sound effects according to their preferences, including volume, sound effect type, background music, etc. Many mobile gamers may choose a silent mode or low volume settings when using their phones to avoid disturbing others. This requires sound designers to take this into consideration when designing, ensuring that even in low volume or silent mode, the game's sound effects can still provide clear feedback and a good experience. By optimizing the dynamic range and volume control of sound effects, the sound performance can be improved at different volume settings. Players from different regions and cultures may have varying preferences and expectations for sound effects. For example, in some cultures, specific sound effects may have special meanings or influences. Sound designers need to consider these cultural and linguistic differences to ensure that game sound effects can adapt to different markets and player groups. During the localization process, the style of sound effects, voice, and background music can be adjusted to meet the habits and preferences of players in different regions.

7. Conclusion

The application of novel technologies in sound design, such as artificial intelligence, machine learning, virtual reality, and augmented reality, has brought new opportunities and challenges to the creation and performance of game sound effects. AI technology can automatically generate and match sound effects for real-time adjustment, while VR and AR technology require more realistic spatial and dynamic environmental sound effects. However, the design of sound effects for mobile games still faces challenges from hardware limitations and diverse user needs. Designers need to make detailed adjustments in optimizing sound files, ensuring compatibility, and meeting personalized needs to provide a high-quality sound experience. Through continuous innovation and adaptation to technological advancements, sound design can enhance the gaming experience while overcoming these challenges, creating a more immersive and engaging gaming world.

Disclosure statement

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Enterprise Digital Planning and Architecture Based on Industrial Internet Platforms

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Abstract:

Under the current background of information society, the digital transformation of enterprises has become a necessary means to enhance the competitiveness of enterprises. This article is based on the industrial Internet platform, digital planning, and architecture of enterprise research. First, we analyze the current challenges of digital transformation and the development opportunities brought by the industrial Internet. Then, we propose a digital planning method based on the industrial Internet platform, which takes the full connectivity of humans, machines, and objects and intelligent decision-making as the core, takes data collection, processing, analysis, and application as the main line, and finally forms the top-level design of the digital transformation of enterprises. At the same time, we also build an industrial Internet platform architecture model, the four levels of the previous end perception layer, network transmission layer, platform service layer, and application innovation layer, to support enterprises in the innovative application and decision support under the industrial Internet environment. Research shows that this kind of enterprise digital planning and architecture based on industrial Internet platforms can effectively promote enterprises to achieve business model innovation and system innovation, and strengthen the flexibility and agility of enterprises to respond to market changes. The results of this research not only have important theoretical and practical significance for guiding enterprises to carry out digital planning and build industrial Internet platforms but also provide useful references for relevant policy formulation.

Keywords:

Industrial Internet platform
Enterprise digital planning
Architecture model
Innovative application
Agility

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1. Introduction

In today's information society, companies need to adapt to digital change. While this transformation is challenging, the use of industrial Internet platforms has brought new opportunities for enterprises. The paper first expounds on the challenges of digital transformation faced by enterprises and then analyzes the development opportunities brought by the industrial Internet platform for enterprises, such as deepening the application, promoting innovation, and strengthening decision-making. Then, the paper proposes an enterprise transformation method based on an industrial Internet platform and builds a model of an industrial Internet platform. Finally, the paper discusses how to successfully achieve this transition. This study aims to help enterprises in digital planning and improve their ability to respond to market changes. The results of this study are not only theoretically instructive, but also helpful for practical operation and provide a reference for relevant policy making.

2. Challenges of enterprise digital transformation and industrial Internet platform

2.1. Challenges of digital transformation in current enterprises

At present, digital transformation has become an important strategic direction for enterprises to adapt to the rapidly changing market environment^[1]. Despite the wide range of opportunities brought by digital transformation, enterprises face many challenges in the implementation process. Technological challenges are undoubtedly the most prominent part of the digital transformation process. Many enterprises lack corresponding technical reserves and specialized talent support when adopting new technologies, leading to often being in a passive position when choosing and implementing digital solutions. The compatibility of old and new systems also limits the effective realization of technology updates and integration, increasing the cost of digital transformation and technology complexity.

On the other hand, the transformation of corporate culture and organizational structure is also a major challenge in digital transformation. The decision-making

mechanism and management concepts of many traditional enterprises are deeply rooted, and inertia thinking and resistance to change often lead to the digital process^[2]. In some enterprises, digital transformation is too dependent on the commitment of the management, and there is a lack of full participation and understanding^[3]. This situation easily causes internal communication, resulting in the digital transformation measures cannot be implemented at the practical level. The organization is often not flexible enough to support the agility and quick response needed for digital transformation.

Data security and privacy issues are also important challenges in the digital transformation of enterprises. In the application process of an industrial Internet platform, a large number of enterprise data needs to be transferred and shared in different systems, which undoubtedly increases the risk of data leakage and improper use^[4]. At present, the increasingly stringent data protection laws and regulations around the world also require enterprises to strengthen the control and compliance management of data. Rapidly promoting digitalization to ensure data security and compliance is an urgent problem for enterprises to solve.

The uncertainty of the market environment and the intensification of the competition have also put forward higher requirements for digital transformation. Companies should not only transform technically and culturally but also have the ability to dynamically adjust their strategies to cope with the changing market demand and competitive situation. This requires enterprises to enhance their innovation ability, identify market opportunities in time, and respond quickly to changing needs^[5]. The contradiction between the speed of this environmental change and the speed of internal transformation makes it difficult for many enterprises to maintain a continuous competitive advantage.

The uncertainty of economic cost and return on investment is also one of the key challenges of the digital transformation of enterprises. Digital transformation requires enterprises to make a large amount of capital investment, including hardware facilities upgrading, software development, and talent training, but its return cycle is often long, and the exact return on investment is difficult to predict. This has greatly affected the investment decisions of enterprises in the process of

digital transformation, especially in small and medium-sized enterprises. The doubts of senior managers about the transformation investment may lead to insufficient support for the digital transformation, or overly conservative thinking, thus affecting the overall progress and effect of the transformation.

In the process of digital transformation, technology, culture, data security, market environment, and economic cost are interwoven and have far-reaching influences, which bring great complexity to the decision-making and implementation of enterprises. It is critical that companies develop effective digital transformation strategies based on the various challenges and their own actual conditions. This requires not only technological innovation, but also the transformation of organizational structure and culture to ensure the coherence and sustainability of digital strategies and achieve a true success of transformation.

2.2. Development opportunities brought by the industrial Internet

As the product of the deep integration of the new generation of information technology and the manufacturing industry, the industrial Internet provides important opportunities for the digital transformation of enterprises. By combining the Internet of Things, cloud computing, big data, artificial intelligence, and other technologies, it has built a brand-new, manufacturing-oriented Internet ecosystem. In this system, data becomes the core element driving enterprise innovation and development.

The primary opportunity brought by the industrial Internet is to improve production efficiency. By building a digital network covering the whole production process, enterprises can realize real-time interconnection between production equipment, production lines, workshops, and factories. The seamless connection and data sharing between devices enable enterprises to accurately monitor and regulate the production process in real time. This can not only effectively reduce the production loss caused by equipment failure, but also optimize the production scheduling and resource allocation through big data analysis, so as to significantly improve the production efficiency and reduce the operating costs.

The second important opportunity is to promote innovation in enterprise business models. Under

the ecology of the industrial Internet, traditional manufacturing enterprises can break through the past single-product sales mode, and gradually change to the “product + service” mode. Through the Internet of Things technology, enterprises can access customer use data and product performance data, thus providing personalized follow-up services, and realizing the upgrade from one-time sales to continuous services. Such a change can not only improve customer satisfaction but also increase the added value and profit margin of enterprises.

Industrial Internet also provides a new perspective and method for the supply chain management of enterprises. Through the widely used Internet of Things interconnection technology, enterprises can realize the overall control and optimal management of all links in the supply chain. This enables enterprises to flexibly adjust production plans and inventory strategies according to the changes in market demand, enhance the elasticity and response speed of the supply chain, reduce risk and cost, and improve market competitiveness.

In terms of quality management, the industrial Internet also provides unprecedented opportunities. By establishing a comprehensive quality monitoring system, enterprises can use big data analysis to conduct real-time monitoring and feedback on product quality. Predictive maintenance and optimization of the quality control strategy can significantly improve the quality of products and enhance the brand image and market reputation.

The industrial Internet has also greatly promoted cross-industry and cross-field collaborative innovation. Enterprises can break the boundaries between traditional industries, connect other enterprises, scientific research institutions, and service providers through data sharing and resource integration, and jointly develop and promote new technologies, products, and services. This collaborative innovation not only drives technological progress but also brings new market opportunities and commercial value.

As the key driving force for the upgrading of the modern manufacturing industry, the industrial Internet provides multiple development opportunities for enterprises in the digital transformation. By improving production efficiency, innovating business models, optimizing supply chain management, and realizing collaborative innovation, enterprises can better adapt to

market changes, enhance competitive advantages, and achieve sustainable development. In the face of these opportunities, enterprises should take active strategic measures to accelerate the deployment of industrial Internet and fully tap its potential value.

3. Enterprise digital planning based on the industrial Internet platform

3.1. Digital planning method combined with the full connectivity between man and machine

In the process of enterprise digital transformation, it is a vital link to realize the full connectivity of humans, machines, and objects. The core of the digital planning method lies in the organic combination of humans, machines, and objects through the industrial Internet platform to promote the efficient integration and coordinated operation of enterprise internal resources. The industrial Internet platform is not only a collection of technological innovations but also a bridge for enterprises to achieve full connectivity.

The full connectivity of humans, machines, and objects can break the barrier of information islands within traditional enterprises. In the traditional mode, each part of the enterprise often operates independently, and the poor flow of information leads to low communication efficiency and insufficient utilization of resources. Through the industrial Internet platform, enterprises can realize the real-time sharing and transparent management of various data, and ensure that the relevant information is timely and accurately conveyed to different decision-making levels and execution levels.

Humans, machines, and objects being fully connected can also significantly improve the intelligent decision-making ability of enterprises. When equipment and personnel can be interconnected, enterprises can collect information about equipment operation status, production schedule, and personnel operation in real time through sensors and edge computing technology. After effective integration and analysis, these data can provide insightful decision support for the enterprise executives, help enterprises quickly deal with problems in production, optimize the production process, and improve production efficiency.

In the process of realizing the full connectivity

between humans, machines, and objects, data security and privacy protection cannot be ignored. In this process, enterprises need to establish a sound data security mechanism to ensure that the data is not tampered with or leaked in the transmission process. Encryption technology and authority management systems can be used to protect important data assets and maintain the integrity and confidentiality of enterprise information.

Full human-machine and object connectivity need to adapt to the unique application scenarios and needs of enterprises, which requires fully considering the actual needs of different departments of the enterprise for digital transformation in the planning to realize personalized solutions. This personalized scheme can be realized by flexibly allocating various technology modules of the industrial Internet platform, so as to meet the specific requirements of different industries and enterprises in the process of digital transformation.

The process of enterprise digital planning based on an industrial Internet platform, combined with the method of fully connected human-machine-object can not only improve the information transmission and processing capacity of enterprises, but also support the construction of intelligent factories and the future development of intelligent manufacturing, which makes it possible for enterprises to create new competitive advantages in the era of digital economy. By integrating resources, improving efficiency, and ensuring data security, enterprises will gain the initiative in the rapidly changing market environment and achieve sustainable development.

3.2. Digital planning main line based on data acquisition, processing, analysis, and application

In enterprise digital planning, data collection, processing, analysis, and application constitute a complete main line, which is the core link of realizing the digital transformation. Data collection is the starting point of digital planning. It obtains real-time data of enterprises in production, sales, logistics, and other links through sensors, Internet of Things devices, and other ways. This step ensures that companies can obtain real, effective information from a wide range of sources, laying the foundation for subsequent processing and analysis.

Data processing plays a key role in the transformation of the collected raw data into useful information. Through data cleaning, classification, and storage steps, we can eliminate the noise in the data and improve the quality and reliability. With the support of the industrial Internet platform, enterprises can quickly carry out efficient and low-cost processing of huge data, which provides a solid foundation for data analysis.

Data analysis is the use of intelligent algorithms and analysis tools to mine valuable insights from the processed data. Analysis can be subdivided into descriptive, diagnostic, predictive, and normative analysis. These analyses can reveal potential problems in business operations, predict market trends, and provide strong support for management's decisions.

Data application is the ultimate goal of digital planning, which transforms the processed and analyzed data results into practical actions of the enterprise. By integrating the analysis results into the decision process, enterprises can optimize the production process, improve product quality, and enhance customer satisfaction. Based on real-time data feedback, enterprises can respond quickly, accelerate the pace of innovation, and maintain market competitiveness.

The main line of digital planning based on data collection, processing, analysis, and application is the central axis running through the digital transformation of enterprises, so that enterprises can move forward steadily in the wave of industrial Internet. The proper application of this main line not only improves the operational efficiency and productivity of enterprises, but also provides a solid data foundation for the realization of long-term strategic goals.

3.3. Top-level design concept of enterprise digital planning

The top-level design concept of enterprise digital planning is the basis for promoting enterprises to realize digital transformation in the complex and changeable market environment. The design concept is supported by the industrial Internet platform and aims to guide enterprises to effectively coordinate various resources in the process of digitalization through structural solutions. The core of the top-level design lies in the seamless connection of humans, machines, and objects and the

realization of intelligent decision-making. By building a comprehensive, flexible, and efficient digital platform, the business process, management process, and innovation mode of the enterprise can be optimized.

The top-level design of digital emphasizes the construction of the global architecture, which needs to determine the strategic goals from the long-term development of the enterprise and the actual needs of the present, and effectively connect with all levels and modules within the enterprise. This is to ensure that the full life cycle management of data is an important part of the digital top-level design of an enterprise. Through the collection, processing, analysis, and application of data, the efficient operation of information flow can be realized to provide strong support for enterprise decision-making. Emphasis should be placed on the standardization and modular design of the information and technology architecture to enhance the scalability and interoperability of systems and support future technology upgrades and business expansion.

The digital top-level design also needs to consider the "soft" factors such as corporate culture, organizational structure, and personnel ability. The introduction of a change management mechanism aims to promote the cultivation and implementation of digital awareness in the enterprise, so that employees can adapt to and promote the digital transformation of the enterprise. The top-level design should also focus on the market and customer needs to ensure that the products and services provided by enterprises are more competitive in the digital environment. Through integrated design, the digital transformation of enterprises can be promoted in all aspects, so that they can better adapt to market changes and improve their innovation ability and market response speed.

4. Conclusion

Based on the industrial Internet platform, this research studied the digital planning and architecture of enterprises, solved the challenges of digital transformation faced by enterprises under the current social background, and made full use of the development opportunities brought by the industrial Internet. We proposed the enterprise digital top-level design based on the industrial Internet

platform and constructed the architecture model of the industrial Internet platform, which provides support for the innovative application and decision-making of enterprises in the industrial Internet environment. The research results show that this method can effectively promote enterprises to achieve business model and system innovation, enhance the flexibility and agility of enterprises in the face of market changes, and show great practical application value. Meanwhile, there are some limitations in this study. For example, for the specific industrial Internet platform application scenarios and enterprise characteristics, carrying out a more detailed and specific enterprise digital planning and architecture

design still needs further research. In addition, quantifying and evaluating the impact of industrial Internet platforms on the effect of digital transformation of enterprises is also an important direction of future research. In general, this research puts forward new insights and strategies for enterprise digital planning under the industrial Internet platform from the perspectives of theory and practice. We expect that this study can provide certain academic support for the digital transformation of enterprises, provide useful references for relevant policy formulation, and further promote the digital process of Chinese enterprises.

Disclosure statement

The authors declare no conflict of interest.

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Data Center Virtualization and Secure Data Storage Architecture

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Abstract:

With the rapid development of data center virtualization, secure data storage has become a crucial issue. This paper aims to explore and design an efficient secure data storage architecture to address the challenges of data security in virtualized environments. The article first analyzes the impact of virtualization technology on data storage security, including data leakage, tampering, and availability issues. Then, this paper proposes a comprehensive secure data storage architecture, which includes data encryption, access control, backup and recovery strategies, and audit and monitoring mechanisms. Through case studies and security performance evaluations, this paper verifies the effectiveness and feasibility of the proposed architecture. Finally, the paper summarizes the research findings and proposes suggestions for future research directions, to provide references for data center managers and policymakers.

Keywords:

Data center virtualization
Secure data storage
Encryption technology
Access control
Backup and recovery
Audit and monitoring
Security architecture design

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1. Introduction

1.1. Research background and significance

Data center virtualization is the core of modern IT infrastructure, which optimizes the use of physical servers by creating virtual machines, thereby improving resource utilization and reducing costs. The advantages of virtualization include flexible allocation of resources, cost-effectiveness, system flexibility and scalability, and simplified maintenance and management. However, with the widespread application of virtualization technology, the security of data storage has become

particularly critical, as data in virtual environments is more susceptible to unauthorized access and data leakage threats.

1.2. Research objectives and problem statement

The main objective of this study is to identify the need for secure data storage in virtualized environments and address the shortcomings of existing security architectures. The research will focus on the following issues:

- (1) Clearly define the specific needs for secure data storage in virtualized data centers.
- (2) Evaluate the performance of existing secure data storage architectures in virtualized scenarios.
- (3) Identify and analyze the main challenges faced by data storage security in virtualized environments.
- (4) Provide strategies and solutions for data storage security in virtualized environments, to enhance data protection and reduce security risks.

2. Literature review and theoretical foundation

2.1. Overview of data center virtualization technology

Virtualization technology improves the flexibility and efficiency of resources by creating multiple virtual machines on a single physical server. Key technologies include server, storage, and network virtualization, which together promote dynamic resource allocation and management.

2.2. Basic concepts of secure data storage

The core principles of data storage security cover confidentiality, integrity, availability, and compliance. Practical methods involve data encryption, strict access control, regular backup and recovery mechanisms, and continuous monitoring and auditing.

3. Data storage security needs analysis in virtualized environments

3.1. Identification of data storage security needs

In the virtualized data center environment, the identification of data storage security needs is the cornerstone of building an effective security strategy. The core needs of data storage security include compliance, confidentiality, integrity, and availability. Compliance needs refer to adhering to data protection-related laws and regulations, such as GDPR, HIPAA, etc. Confidentiality ensures that unauthorized users cannot access sensitive data. Integrity needs to ensure

that data is not tampered with during storage and transmission. Availability ensures that data can be accessed and recovered in a timely manner under any circumstances ^[1].

3.2. The impact of virtualization on data storage security

While virtualization technology improves resource utilization and flexibility, it also brings new challenges to data storage security. Data transfer between different physical servers during virtual machine migration may face leakage risks. Snapshots and cloning operations may be maliciously exploited due to insufficient isolation, leading to data tampering or loss. In addition, dynamic resource allocation in virtualized environments may lead to inconsistent execution of security policies, increasing the risk of data leakage and unauthorized access.

To address these challenges, a series of measures need to be taken. First, manage virtual machine migration securely, such as using encrypted channels and VPN technology to protect data during migration. Second, manage the migration of storage securely, for example, by adopting manual migration strategies for important data to reduce security risks in the automation process. In addition, monitor the dynamic migration process of virtualized storage to ensure the security of data during migration.

3.3. Security threat modeling and risk assessment

In virtualized environments, the analysis of data storage security needs must cover an in-depth understanding of potential threats and a quantitative risk assessment. The following is a detailed discussion of the threat modeling and risk assessment methods for data storage security in virtualized environments.

3.3.1. Threat modeling construction

The threat model in virtualized environments needs to comprehensively consider security issues during both static and dynamic migration processes. According to research from the CSDN library, security issues and countermeasures in virtual machine migration emphasize the risks of data leakage and service interruption during

migration. In addition, the virtualization security risk list and professional security advice provided by Huawei Cloud Community also point out security issues in virtual machine isolation failure and snapshot cloning processes.

3.3.2. Risk assessment methods

Risk assessment should use both qualitative and quantitative analysis to identify and mitigate key security threats in virtualized environments. The following methods combine storage security compliance overviews and professional advice from Alibaba Cloud and Huawei Cloud:

- (1) Asset identification and classification: Identify and classify all data assets in the virtual environment in detail, especially focusing on the protection of sensitive data.
- (2) Threat identification: Use threat modeling tools, such as threat graphs, to identify potential threats such as virtual machine escape and virtual machine isolation failure.

3.3.3. Case study and data support

According to the Alibaba Cloud Table Storage Security Compliance Overview, data storage security in virtualized environments can be ensured through multiple features, including but not limited to compliance certification, access control, data security, network security, monitoring and logging, etc. (Table 1)^[2].

The virtualization security risk list and professional security advice provided by Huawei Cloud Community provide practical guidance for assessing security risks in

virtualized environments.

4. Secure data storage architecture design

4.1. Design principles of secure data storage architecture

When designing a secure data storage architecture in a virtualized environment, the core principles focus on ensuring the security, reliability, and maintainability of the system, while considering compliance and cost-effectiveness. The following is a detailed description of the design principles:

Architecture design must comprehensively consider the confidentiality, integrity, availability, and compliance of data to ensure comprehensive coverage of all critical security areas; The selected technological solution should be able to adapt to the constantly changing virtualization environment, including compatibility and support for emerging virtualization technologies; Ensure that security measures do not have a negative impact on system performance without sacrificing security, such as optimizing encryption algorithms and access control processes; The architecture design should support future expansion, including increased storage capacity, computing resources, and network bandwidth, while maintaining the ability to respond quickly to new business demands; The architecture design should support future expansion, including increased storage capacity, computing resources, and network bandwidth, while maintaining the ability to respond quickly to new business demands; Ensure that the architecture

Table 1. Potential threats and risk assessment in virtualized environments

| Threat type | Description | Impact | Likelihood | Risk level | Mitigation measures |
|------------------------------------|--|--------|------------|---|---------------------|
| Virtual machine escape | Malware escaping from virtual machines | High | Medium | Implement strict access control and monitoring | |
| Isolation failure | Insufficient isolation between virtual machines | Medium | High | Strengthen security isolation measures between virtual machines | |
| Snapshot/cloning abuse | Insufficient data protection during snapshot and cloning processes | Low | Medium | Encrypt and control access to snapshot and cloning operations | |
| Management interface vulnerability | Vulnerabilities in the management interface | High | Low | Regularly update and patch the management interface | |

design complies with all applicable data protection regulations and industry standards, such as GDPR, HIPAA, etc., to avoid legal risks; Conduct cost-benefit analysis during the design phase to ensure that safety investments provide necessary protection while also being economically reasonable ^[1].

4.2. Data encryption and access control

When designing a secure data storage architecture for data center virtualization, data encryption, and access control are two core components that together ensure data security and compliance.

4.2.1. Data encryption

Data encryption is a key technology for protecting data from unauthorized access. In a virtualized environment, data may face leakage risks during transmission and static storage. To address these risks, strong encryption algorithms such as AES-256 are used to encrypt the data. The encryption process includes selecting the appropriate encryption key, initializing the vector, and ensuring the atomicity of the encryption operation, that is, the data will not be interrupted during the encryption process. In addition, the selection of encryption technology should consider a balance between performance and security, avoiding negative impacts on system performance.

4.2.2. Access control

Access control is a mechanism that ensures that only authorized users can access specific data. Role-based access control (RBAC) is a common approach in virtualized environments. RBAC ensures that users can only access the data necessary for their work by defining permissions for different roles. When implementing RBAC, it is necessary to consider how to define roles, allocate permissions, and dynamically adjust these permissions based on the organization's security policies ^[3].

To further enhance security, a combination of attribute-based access control (ABAC) and policy-based access control (PBAC) can be used. ABAC determines access permissions based on user attributes such as department and position, while PBAC controls access based on predefined security policies. These methods can provide finer-grained access control, thereby

reducing the risk of data leakage.

When implementing data encryption and access control, it is also necessary to consider key management to ensure the secure storage and transmission of encryption keys. In addition, access control policies should be regularly reviewed and updated to adapt to constantly changing business needs and security threats. Through these measures, secure data storage architecture can effectively protect data in virtualized environments, and prevent data leakage and unauthorized access, while also supporting compliance requirements.

4.3. Data backup and recovery strategies

In virtualized environments, data backup and recovery strategies are key components in ensuring data persistence, business continuity, and disaster recovery capabilities. An effective backup strategy should include regular backups, remote backups, cloud backups, mirror backups, and disaster recovery plans.

- (1) Regular backup: Implement regular backups through automated tools to ensure data consistency and integrity. A backup can be a full backup or an incremental backup, with the latter only backing up data that has changed since the last backup to reduce storage requirements and improve backup efficiency.
- (2) Remote backup: backing up data to remote servers or cloud storage through the network, which helps with data recovery in case of local disasters. Remote backup can reduce the impact of physical damage or theft on data.
- (3) Cloud backup: Utilizing cloud service providers such as AWS, Google Cloud, Azure, etc. for data backup, this method is suitable for secure storage and flexible recovery of large-scale data. Cloud backup provides convenience and scalability while reducing the need to maintain physical storage infrastructure.
- (4) Mirror backup: Create a mirror of the entire disk, including the operating system, applications, and data, for quick recovery to the previous state. Mirror backups are particularly useful in disaster recovery scenarios as they can be quickly deployed to new hardware.
- (5) Disaster recovery plan: Develop a detailed

disaster recovery plan, including backup strategies, data recovery processes, and partnerships with professional data recovery service providers. Regularly test the recovery program to ensure successful data recovery when needed.

- (6) Scheduled automatic backup: Set up regular automatic backups to ensure that data is always protected.
- (7) Multiple backup: Using a combination of multiple backup methods (such as local and cloud backup) to improve data security.
- (8) Regular testing of recovery procedures: Conduct regular recovery drills to ensure successful data recovery when needed.
- (9) Strengthen security: Ensure that backup data is encrypted during transmission and storage to protect sensitive information.
- (10) Backup data encryption: Encrypt the backup data to prevent it from being stolen or tampered with during transmission and storage. This helps to improve the security of data.

4.4. Audit and monitoring mechanisms

Audit and monitoring mechanisms are crucial for identifying and responding to security incidents. All accesses and operations should be recorded in logs for regular review to detect abnormal behavior. Real-time monitoring tools are used to track system status and performance, identifying potential security threats in a timely manner. Anomaly detection is achieved by setting

alert thresholds to identify changes in abnormal login attempts or data access patterns (**Table 2**).

Through these design principles and strategies, a secure data storage architecture that meets business needs and complies with security regulations can be constructed. The design elements in the table provide a comprehensive reference framework for secure data storage architecture in virtualized environments, ensuring the comprehensiveness and practicality of the design.

5. Implementation and evaluation of secure data storage architecture

5.1. Methods of architecture implementation

Implementing a secure data storage architecture involves carefully selecting technology, system integration, and deployment strategies. Technology selection should be based on a comprehensive consideration of performance, cost-effectiveness, and security. For example, adopting high-performance storage solutions while ensuring compatibility with existing systems. System integration emphasizes the collaborative work between components to ensure smooth data transfer and processing. Deployment strategies need to consider geographic distribution, load balancing, and disaster recovery capabilities.

5.2. Security performance evaluation

Security performance evaluation is a key step in measuring the effectiveness of architecture

Table 2. Elements of secure data storage architecture design in virtualized environments

| Design element | Description | Implementation suggestions | Compliance considerations |
|------------------|--|---|---------------------------|
| Scalability | Support for dynamic increase of resources | Cloud storage solutions | GDPR |
| Flexibility | Adapt to new technologies and business processes | Multi-VM monitoring tools | NIST 800-53 |
| Maintainability | Simplify maintenance processes | Automated maintenance scripts | COBIT 50001 |
| Data encryption | Encryption of data in transit and at rest | AES-256, TLS | GDPR |
| Access control | Role-based permissions | Integration of RBAC with directory services | GLBA |
| Backup strategy | Combination of full, incremental backups | Regularly test recovery processes | HIPAA |
| Audit monitoring | Record all accesses and operations | SIEM and automated tools | GLBA |

implementation. The evaluation includes encryption efficiency, access control effectiveness, and data recovery capability testing. Encryption efficiency focuses on the impact of the data encryption and decryption process on system performance. Access control effectiveness is tested by simulating access attempts by different user roles to verify the effectiveness of RBAC policies. Data recovery capability testing is done by simulating disaster scenarios to verify the reliability and efficiency of data backup and recovery processes.

5.3. Case study

Case studies provide practical application scenarios and effectiveness evaluations of architecture implementation. For example, a financial institution has effectively prevented data leakage and unauthorized access by adopting advanced data encryption technology and strict RBAC policies. By comparing the number of security incidents and system response times before and after implementation, the effectiveness of the architecture is significantly proven.

5.4. Discussion and problem-solving

Problems encountered during implementation include technical compatibility, performance bottlenecks, and operational complexity. Solutions involve adopting modular design to improve compatibility, optimizing algorithms and hardware acceleration to enhance performance, and developing user-friendly management interfaces to simplify operational processes (Table 3).

Through the above implementation methods and evaluations, the secure data storage architecture can provide strong data protection capabilities in virtualized environments. The table provides an overview, showing the key elements and considerations in the

implementation and evaluation process.

6. Conclusion and future research directions

6.1. Research summary

This study proposes an innovative secure data storage architecture specifically designed for data protection needs in virtualized data centers. Through careful technology selection, system integration, and deployment strategies, the architecture has achieved enhanced protection for data confidentiality, integrity, and availability. The main achievements of the research include effective defense against security threats such as virtual machine escape and data leakage, and the actual effectiveness of the architecture is verified through case analysis.

6.2. Research limitations and future work

Although this study has made certain progress in theory and practice, some limitations point the way for future work. First, the study mainly focuses on virtualized environments, and the applicability to other environments such as private clouds and hybrid clouds needs further exploration. Second, although the performance impact of the security architecture has been evaluated through simulation testing, more data is needed to support the long-term performance in real environments. Future work will extend to include emerging technologies such as the application of artificial intelligence in security monitoring.

6.3. Industry recommendations

For data center managers and policymakers, this study recommends considering security as an important aspect

Table 3. Overview of secure data storage architecture implementation and evaluation

| Implementation Element | Description | Technology selection | Performance evaluation | Case study | Problem and solution |
|------------------------|---|------------------------------------|---|---|---|
| Technology selection | Based on performance, cost, and security considerations | High-performance storage solutions | Encryption efficiency, access control effectiveness | Financial institution case | Compatibility issues, performance bottlenecks |
| System integration | Collaborative work between components | Compatibility and synergy | Recovery capability testing | Modular design, optimization algorithms | Deployment Strategy |

of data center virtualization from the design stage. Regularly conduct security performance evaluations to ensure that security measures can adapt to technological developments and changes in business needs. At the same time, it is recommended to invest in personnel training and new technology research to cope with the constantly changing security threats and challenges. In addition, it is recommended to cooperate with the academic

community and third-party security organizations to share security intelligence and best practices, jointly improving the security level of the entire industry.

Through these conclusions and recommendations, this study provides a comprehensive perspective on secure data storage in virtualized environments and offers guidance for future research and practice.

Disclosure statement

The author declares no conflict of interest.

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Application Analysis of Data Analysis in Power Material Procurement Management

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Abstract:

With the rapid development of China's economy, the power industry, as an important national infrastructure and energy security, is accelerating its development speed. As an important component of the power industry, the procurement of power materials directly affects the stable operation and economic benefits of the power system. Especially in the power industry, procurement management plays a crucial role, and its efficiency and accuracy directly affect the construction and operation of power engineering. With the continuous development and application of big data technology, more and more power companies are beginning to apply big data technology to the bidding and procurement management of power materials, to improve efficiency, reduce costs, and ensure the accuracy of procurement.

Keywords:

Data analysis
Power industry
Purchasing management

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1. Introduction

Data technology can help power companies transition from traditional bidding procurement to intelligent bidding procurement. By analyzing and mining massive amounts of data, more accurate demand forecasting, supply chain optimization, cost control, and risk management can be achieved. The intelligent decision-making system based on big data can improve work efficiency, reduce human errors, and provide a more scientific and reliable decision-making basis for power material bidding and procurement management.

2. Application scenarios of big data in power material procurement

2.1. Material demand forecast

The procurement of power materials has the characteristics of periodicity, volatility, and uncertainty, and traditional procurement forecasting methods often have significant errors. Big data technology can collect multi-source data such as historical procurement data, market supply and demand data, and meteorological data, and use data mining and machine learning algorithms to accurately predict procurement demand, providing a basis

for power companies to formulate reasonable procurement plans. By analyzing historical data and combining current market conditions, enterprise production plans, and other factors, a demand forecasting model can be constructed to improve the accuracy of material demand prediction and reduce inventory backlog and shortage risks. At the same time, effective measures can be taken for digital control of big data in power marketing, including improving the big data digital control system, innovating big data digital control methods, and strengthening big data digital control ^[1].

2.2. Supplier evaluation and selection

The procurement of power materials involves numerous suppliers, and how to choose high-quality suppliers is the focus of attention for power enterprises. Big data technology can collect data on suppliers' qualifications, reputation, product quality, prices, delivery times, and so on. Through data analysis and visualization, it provides strong support for power companies to evaluate and select suppliers. By utilizing big data technology, a comprehensive analysis of supplier qualifications, reputation, product quality, delivery cycles, and other data is conducted to provide an objective and comprehensive supplier evaluation basis for the procurement department and optimize the supplier selection process. In addition, the application of digital technology has become an important means to improve the efficiency of power marketing and optimize the quality of service ^[2].

2.3. Price negotiation and procurement cost control

The price of electricity materials is influenced by various factors such as market supply and demand, raw material prices, policies, etc., and fluctuates greatly. Big data technology can collect real-time market data, raw material price data, etc., and use methods such as time series analysis and regression analysis to predict the prices of electricity materials, helping enterprises formulate reasonable procurement strategies. By analyzing big data, enterprises can grasp the fluctuation patterns of market material prices, provide reasonable procurement price strategies for enterprises, and reduce procurement costs.

2.4. Warehouse management and optimization

The storage management of power materials is an

important link in the power supply chain. Big data technology can collect real-time warehouse data, such as inventory quantity, inventory turnover rate, warehouse temperature and humidity, etc. Through data analysis, it can help enterprises discover problems in warehouse management, propose optimization solutions, and reduce inventory costs.

2.5. Logistics delivery optimization

The logistics distribution of power materials involves many links, and how to improve distribution efficiency and reduce distribution costs is the focus of attention for power enterprises. Big data technology can collect logistics data in real time, such as transportation distance, transportation time, transportation cost, and so on. Through data analysis and optimization algorithms, it can provide distribution route optimization solutions for enterprises and improve distribution efficiency.

2.6. Procurement contract management

Utilizing big data technology to monitor contract performance in real-time, ensuring timely completion of contracts and avoiding the risk of breach.

3. The important role of big data in the management of power material procurement

3.1. Intelligent procurement decision-making

Combining internal enterprise needs and external market information, utilizing big data analysis technology to provide intelligent procurement recommendations for enterprises and achieve precise procurement decisions. By mining and analyzing historical data, future market changes can be predicted, providing forward-looking guidance for power material procurement decisions. Big data technology can collect, analyze, and process massive amounts of data in real time, providing strong support for the procurement of power materials. Through big data analysis, enterprises can quickly understand market supply and demand conditions, price fluctuations, supplier reputation, and other information, thereby optimizing procurement strategies and improving procurement efficiency.

3.2. Optimization of procurement process

Through big data technology, real-time monitoring and data analysis of key links in the procurement process are carried out to identify bottlenecks and problems in the process, providing a basis for optimizing the procurement process. Data analysis helps identify problems and deficiencies in the procurement process, providing a basis for optimizing procurement strategies, achieving cost control, and optimizing resource allocation. Big data technology can help enterprises achieve refined management and reduce procurement costs. By mining and analyzing historical procurement data, enterprises can identify unreasonable links in the procurement process, such as long procurement cycles and inventory backlog, and optimize the procurement process to reduce procurement costs.

3.3. Inventory management optimization

Using big data technology to conduct real-time analysis of enterprise inventory materials, adjust inventory structure reasonably, improve inventory utilization, and reduce inventory costs. Through data analysis, real-time information on the market situation, supplier status, inventory status, and other aspects of power materials can be obtained, providing strong support for procurement decisions and improving procurement efficiency.

3.4. Risk warning and control

Through big data analysis, potential risks in the procurement process are identified, and risk prevention measures are formulated in advance to ensure the smooth progress of the procurement process. In this data-driven new era, in addition to power procurement, power marketing management is an important component of the power industry, and data analysis is also of great significance for its development^[1]. Data analysis helps to understand the credit status, quality level, delivery cycle, and other information of suppliers, thereby improving the level of supply chain management^[3].

3.5. Improve supplier management level

Big data technology can achieve a comprehensive evaluation of suppliers and improve supplier management levels. By analyzing data on suppliers' qualifications, reputation, product quality, delivery time, and other

aspects, enterprises can screen out high-quality suppliers and establish stable supply chain relationships.

3.6. Ensure the safety of power supply

Big data technology can monitor the inventory, quality, and usage of power materials in real time, ensuring the safety of the power supply. By real-time tracking of materials, enterprises can promptly detect and solve problems such as insufficient inventory and substandard quality, ensuring the normal operation of power facilities. In the big data environment, the power industry is facing unprecedented challenges and opportunities. Diversified data processing needs are of great significance for the power industry to achieve innovation and efficiency improvement in the big data environment^[4].

4. Innovative application of big data in power material procurement management

4.1. Establish a big data analysis platform

Real-time collection, analysis, and processing of various data during the procurement process. Analyze market supply and demand conditions, price fluctuations, and other information to provide data support for formulating procurement strategies. Evaluate the qualifications, reputation, product quality, and other aspects of suppliers to provide a basis for selecting high-quality suppliers, monitor material inventory in real-time, and provide data support for adjusting inventory reasonably.

4.2. Optimize the procurement process

Based on the results of big data analysis, optimize the procurement process and improve procurement efficiency. Through big data analysis, identify bottleneck links in the procurement process, take targeted measures to shorten the procurement cycle, adjust the procurement plan reasonably based on the results of big data analysis, reduce inventory backlog, evaluate suppliers, select high-quality suppliers, and improve procurement quality.

4.3. Implement refined management

By utilizing big data technology, implementing refined management, reducing procurement costs, and conducting real-time monitoring of market price fluctuations through

big data analysis, reasonable procurement price strategies can be formulated for enterprises. Based on the results of big data analysis, procurement strategies can be adjusted to reduce procurement costs. Through big data analysis, inventory can be reasonably adjusted to reduce inventory costs.

4.4. Innovation in supply chain finance

The application of big data technology in the procurement of power materials can provide support for innovation in supply chain finance. By analyzing data on suppliers, logistics, and other aspects, enterprises can evaluate the credit status of suppliers and provide data support for the supply chain finance business ^[5].

5. Exploration and Practice of big data in power material procurement

5.1. Establish a big data platform

Power companies should establish a unified big data platform to integrate internal and external data resources, including procurement data, market data, supplier data, etc., to provide data support for power material procurement. The combination of big data technology and power information management enables the collection, storage, processing, and analysis of massive power data, greatly improving the operational efficiency of the power industry and effectively reducing management costs, providing strong support for the informatization and intelligent development of the power industry ^[6].

5.2. Strengthen data mining and analysis capabilities

Electric power companies should cultivate professional data mining and analysis teams, use advanced data mining algorithms and data analysis tools to deeply mine procurement data, and provide strong support for decision-making.

5.3. Promote the digital transformation of procurement

Electric power companies should promote the digital transformation of procurement, combining big data technology with procurement business processes to achieve accurate prediction of procurement needs,

intelligent evaluation and selection of suppliers, price analysis and prediction, and other functions. Big data plays an increasingly important role in the digital operation of the power grid ^[7].

5.4. Strengthen cooperation and communication

Electric power companies should strengthen cooperation and communication with other enterprises and research institutions in the field of big data, and jointly explore the application scenarios and practical paths of big data in power material procurement. In addition, intelligent training service quality evaluation in the power industry can be used as a starting point to analyze and mine data, providing strong data support. Based on data mining algorithms, data can be analyzed and mined to provide personalized services ^[8].

6. The future development of big data in power material procurement management

6.1. Intelligent procurement decision-making

With the continuous advancement of big data analysis technology, the decision-making of power material procurement will become more intelligent. In the future, power companies may adopt more advanced machine learning algorithms and artificial intelligence technologies to achieve automated and intelligent procurement processes. These systems will be able to automatically complete tasks such as procurement planning, supplier selection, and contract signing based on real-time data and preset rules, greatly improving efficiency and accuracy.

6.2. Collaborative optimization of supply chain

Big data technology will promote the collaborative optimization of the power material procurement supply chain. By integrating data from upstream and downstream of the supply chain, power companies can better coordinate supply and demand relationships, optimize inventory management, and reduce inventory backlog and stockout risks. Meanwhile, through data sharing and analysis, collaboration between various links in the supply chain can be strengthened, improving overall response speed and market adaptability.

6.3. Predictive maintenance and risk management

Electric power companies will utilize big data technology for more accurate predictive maintenance, by monitoring equipment status and operational data in real-time, predicting potential faults and maintenance needs, thereby reducing unexpected downtime and extending equipment lifespan. Meanwhile, big data analysis can also help enterprises identify and evaluate potential risks in the supply chain, such as supply disruptions, price fluctuations, etc., to develop corresponding risk response strategies.

6.4. Green procurement and sustainable development

Big data technology will also assist in the transformation of power material procurement towards green procurement and sustainable development. By collecting and analyzing data on the environmental performance, energy consumption, carbon emissions, and other aspects of materials, enterprises can pay more attention to the environmental friendliness of the procurement process, select suppliers and products that meet environmental standards, and promote the achievement of sustainable development goals.

7. Strategic recommendations for implementing big data applications

7.1. Establish a big data platform

Electric power companies should establish a unified big data platform, integrate internal and external data resources, and provide data support for procurement management. At the same time, it is necessary to ensure the scalability and compatibility of the data platform to adapt to future technological developments and business needs. By constructing a data analysis technology framework, it can be applied to multiple levels such as data collection, management, storage, and analysis applications^[9].

7.2. Strengthen data governance

Data governance is the foundation of big data applications. Enterprises should develop comprehensive data governance strategies, including data quality control,

data security, data privacy protection, etc., to ensure the authenticity, accuracy, and security of data.

7.3. Cultivate a data culture

Enterprises should cultivate employees' data awareness and culture, and encourage them to use data analysis and decision-making. Through training and education, improve employees' data processing and analysis skills, and create a favorable internal environment for big data applications.

7.4. Building a partnership

Electric power companies should establish partnerships with big data technology suppliers, research institutions, etc. to jointly develop and apply big data technology. Through cooperation, enterprises can acquire new technologies faster and improve their big data application capabilities.

7.5. Continuous innovation and improvement

The application of big data technology in the management of power material procurement is a continuous process of innovation and improvement. Enterprises should maintain an open mindset, constantly try new technologies and methods, continuously optimize procurement management processes, and enhance their core competitiveness^[10].

8. Conclusion

The application of big data technology in the management of power material procurement can help improve procurement efficiency, reduce procurement costs, optimize inventory management, and create greater economic benefits for enterprises. Electric power enterprises should fully utilize big data technology to promote innovation and upgrading of procurement management and achieve efficient, standardized, and intelligent operation of procurement business. At the same time, enterprises will strengthen talent cultivation and technological research and development, continuously improve their ability to analyze and apply big data and provide strong support for the management of power material procurement. The application of data analysis in the management of power material procurement is of

great significance. By analyzing data on procurement needs, supplier evaluations, procurement costs, and procurement risks, procurement efficiency can be improved, procurement strategies can be optimized, procurement costs can be reduced, and supply chain management levels can be enhanced. Against the

backdrop of increasingly fierce market competition and resource constraints in the power industry, fully leveraging the advantages of data analysis to provide strong support for power material procurement management is of great significance for ensuring power supply and promoting high-quality development of the power industry.

Disclosure statement

The author declares no conflict of interest.

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Optimization Research of Lightweight YOLOv8 Model in Building Crack Detection

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Abstract:

In order to improve the detection accuracy and efficiency of building cracks based on the YOLOv8 model, this paper proposes an improved YOLOv8 model. The improved model incorporates the SlimNeck structure, the CSPELAN4 designed based on the GELAN architecture, and the InnerGIoU loss function respectively. Then, an experimental comparative study of this model in building crack detection is carried out. The experimental results show that the precision P increases by 2.1%, the recall rate R increases by 4.2%, $mAP@0.5$ increases by 2.3%, and $mAP@0.5:0.95$ increases by 6.0%. At the same time, $Params$ and $GFLOPs$ are reduced by 21.6% and 23.5%, respectively.

Keywords:

Crack detection
YOLOv8
Lightweight model
SlimNeck
GELAN
InnerGIoU loss function

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1. Introduction

Building cracks, a key sign of building structural health, can expose problems like material aging, foundation settlement, and structural deformation^[1,2]. They are often elongated, irregular, and low-contrast small areas in images, demanding high visual feature extraction from detection models^[3].

With deep learning progress, YOLO (You Only Look Once) models are mainstream for real-time

detection as they can finish target detection in one forward pass. Scholars have optimized early YOLO models for building crack detection. Li *et al.* enhanced YOLOv3 with depthwise separable convolutions, improving the detection of fine and complex cracks^[4]. He *et al.* combined YOLOv4 with deformable convolutions for better accuracy and stability^[5]. Huang *et al.* proposed a C_CB module to boost the network's feature expression and retain more crack-edge info during downsampling^[6].

Existing research indicates YOLOv8 has improved building crack detection accuracy and cut computational complexity [7]. However, it still has issues like low accuracy in complex environments, inability to detect fine cracks precisely, and inefficient deployment in resource-limited settings. Thus, further optimizing YOLOv8 to meet lightweight and accuracy demands in building crack detection is essential [8].

This paper proposes an improved YOLOv8 model to offer an effective idea for its lightweight design and enhance its computational efficiency and detection accuracy in building crack detection. Experimental comparisons verify the model's effectiveness and advancement in this area.

2. YOLOv8 model and its improvement

2.1. Improved YOLOv8 model structure

The YOLOv8 model has the structural feature of a single forward pass and mainly consists of four parts: Input, Backbone, Neck, and Head. The input image size is

640×640 [9].

Figure 1 shows the principle structure of the improved YOLOv8 model. The GSConv layer in SimNeck replaces Conv in layers 16 and 19 of the original YOLOv8. The VoVGSCSP layer replaces layers 18 and 21. To boost detection of fine building cracks in complex backgrounds, the CSPELAN4 layer from GELAN architecture replaces the C2f layer in layers 0–15. To enhance regression accuracy and generalization for complex crack detection, the InnerGIoU loss function replaces the CIoU loss function of the original model.

2.2. Design of SlimNeck structure

The SlimNeck structure in this paper's design is based on the GSConv operation module, the GS-bottleneck layer, and VoVGSCSP layer. In GSConv, depthwise separable convolution (DWConv) cuts computation while keeping key feature info. **Figure 2** shows the structural principles of the VoVGSCSP layer and GS-bottleneck. This layer combines the GS-bottleneck layer with multiple Conv layers for feature map information fusion, boosting

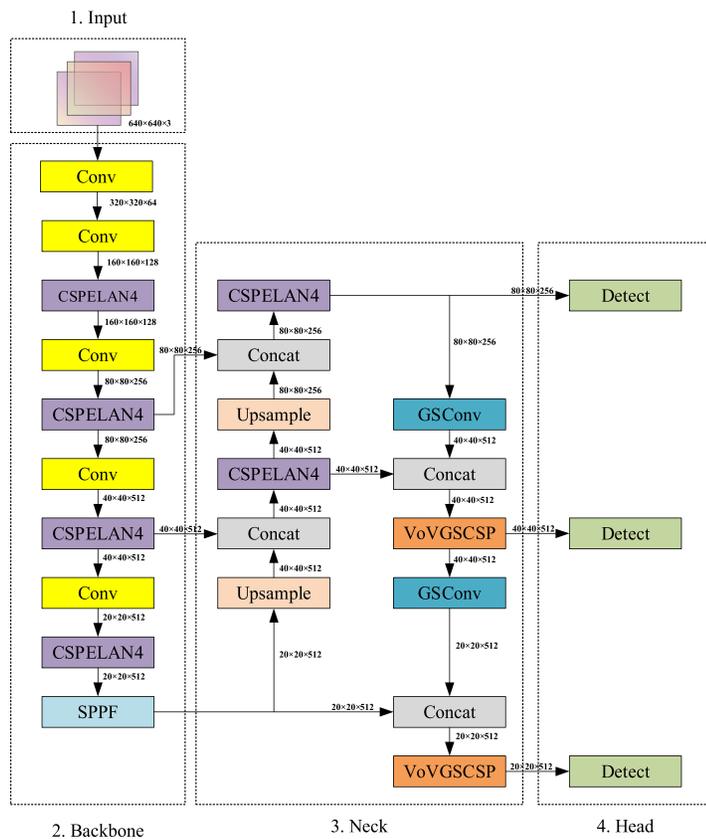


Figure 1. Improved YOLOv8 model structure

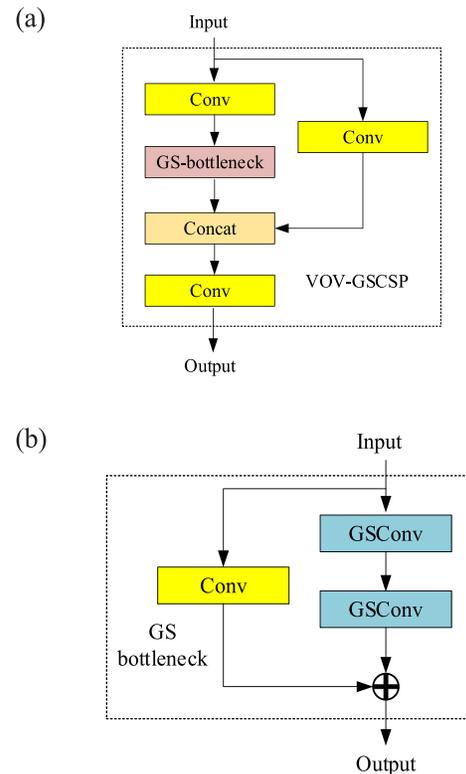


Figure 2. (a) VoVGSCSP layer; (b) GS-bottleneck layer

feature reuse efficiency.

2.3. Design of GELAN architecture

Figure 3 shows the schematic diagrams of the CSPNet architecture, the ELAN architecture, and the GELAN architecture, respectively. By comparing Figure 3, it can be seen that the GELAN architecture can be regarded as a combination of CSPNet and ELAN, having both the segmentation and recombination function of CSPNet and the hierarchical stacking function of ELAN^[10].

2.4. Design of InnerGIoU loss function

The calculation formula of the InnerGIoU loss function is as follows:

$$GIoU = 1 - IoU - \frac{|C - B^p \cap B^{gt}|}{|C|} \quad (1)$$

$$InnerGIoU = GIoU + IoU - InnerIoU \quad (2)$$

In the formula, C is the smallest enclosing area covering B^p and B^{gt} . The InnerGIoU loss function uses a scaling factor ratio in $[0.5, 1.5]$. When ratio > 1 , the predicted bounding box is smaller than the ground truth one, aiding high-IoU sample convergence; when ratio < 1 , it is larger, better for low-IoU sample convergence^[12].

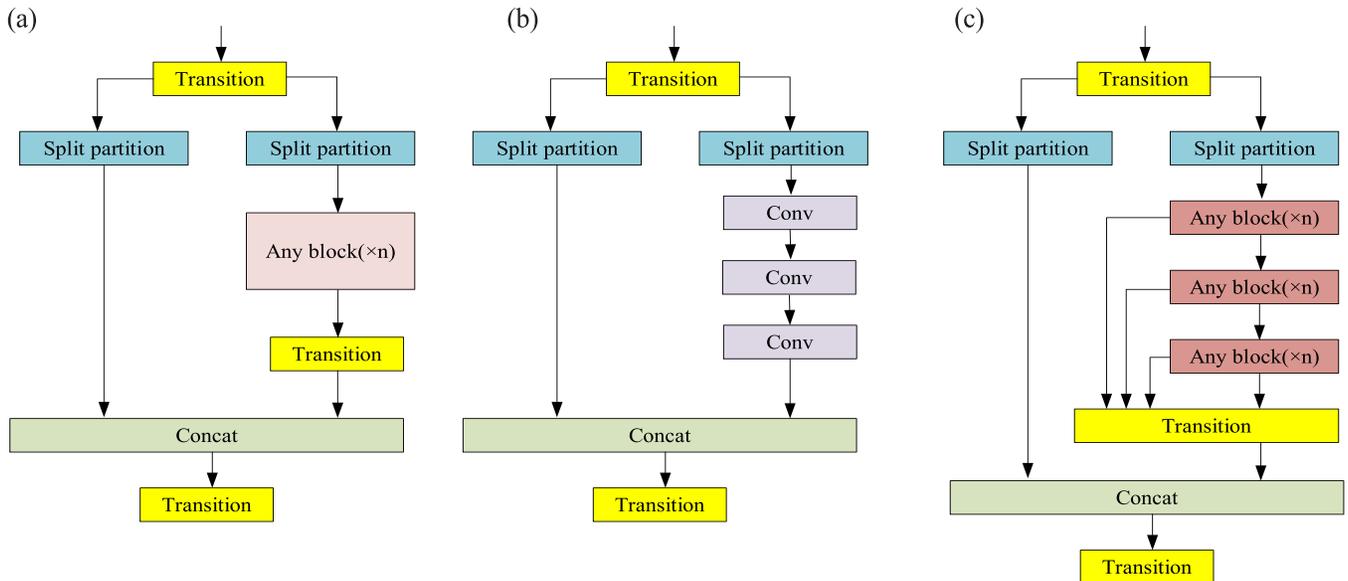


Figure 3. (a) CSPNet architecture; (b) ELAN architecture; (c) GELAN architecture

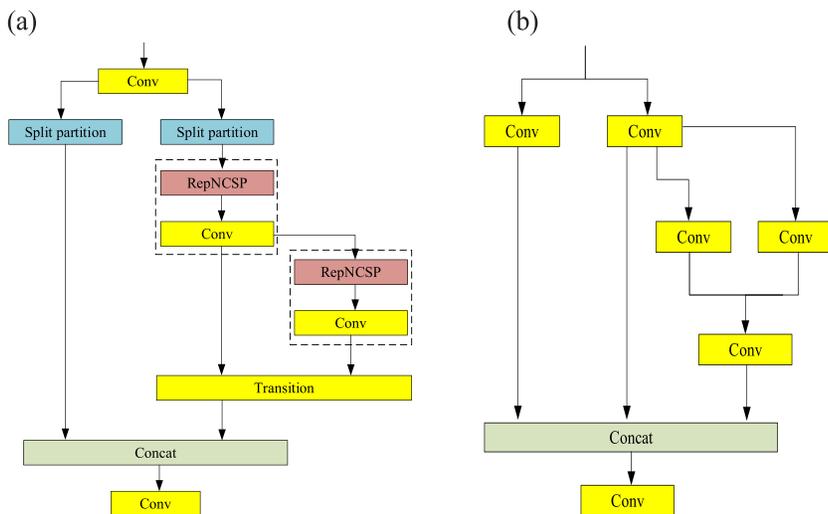


Figure 4(a) shows the structural principle diagram of the CSPELAN4 layer designed based on the GELAN architecture in this paper^[11]. The CSPELAN4 layer uses two RepNCSP layers and a Conv layer for stacking to extract deeper and more abstract features. The structural principle of the RepNCSP layer is shown in Figure 4(b).

3. Experimental environment and analysis of experimental results

3.1. Dataset

To verify the improved YOLOv8n model's effectiveness and correctness, an experimental dataset of 3,888 finely-annotated building crack images was used, covering horizontal and vertical cracks. The dataset annotation was done on the Roboflow platform and went through data augmentation like rotation, scaling, and brightness adjustment.

3.2. Experimental result evaluation indicators

The evaluation indicators of this experiment mainly include crack detection precision P , recall rate R , average precision $mAP@0.5$, average precision $mAP@0.5:0.95$, $Params$, $GFLOPs$, and FPS . The specific formulas are as follows:

$$P = \frac{TP}{TP + FP} \quad (3)$$

$$R = \frac{TP}{TP + FN} \quad (4)$$

$$AP = \int_0^1 P(R) dR \quad (5)$$

$$mAP = \frac{\sum_{c=1}^C AP_c}{C} \quad (6)$$

P is precision, the ratio of correctly predicted crack samples in all predicted ones. R is recall rate, the ratio of correctly predicted crack samples in all actual crack ones. TP are correctly predicted crack samples, FP are wrongly predicted crack samples, FN are wrongly predicted non-crack samples, C is the number of crack categories, AP is the average precision of a certain crack category, and

mAP is that of all crack categories.

3.3. Ablation experiment

To show the advantages of the improved model in building crack detection, YOLOv8n, the smallest original YOLOv8 model fitting this paper's lightweight research, was chosen. Ablation experiments were done on the model and loss function improvement schemes. The SlimNeck structure, CSPELAN4 layer from GELAN, and InnerGIoU loss function were introduced one by one for ablation. The results are presented in **Table 1**.

Comparing performance and resource data in **Table 1**, compared to the original YOLOv8n, precision P rose by 2.1%, recall rate R by 4.2%, $mAP@0.5$ by 2.3%, and $mAP@0.5:0.95$ by 6.0%, improving overall performance. It has better generalization than a single module. Plus, $Params$ and $GFLOPs$ decreased by 21.6% and 23.5%, respectively, with an FPS of 172.2.

3.4. Comparison experiment of mainstream models

To further verify the performance of the improved model in this paper compared with other models, comparative experimental evaluations were carried out using current mainstream models such as Faster-RCNN, YOLOv5n, and YOLOv6n. The relevant experimental results are shown in **Table 2**.

By comparing the performance indicators and data in **Table 2**, the improved YOLOv8n model not only has good lightweight characteristics and maintains a fast detection speed but can also obtain high detection accuracy.

Table 1. Performance and resource evaluation of ablation experiment models

| Model | P | R | $mAP@0.5$ | $mAP@0.5:0.95$ | $Params(M)$ | $GFLOPs$ | $FPS(s)$ |
|------------------|-------|-------|-----------|----------------|-------------|----------|----------|
| YOLOv8n | 0.793 | 0.766 | 0.799 | 0.567 | 3.01 | 8.1 | 367.6 |
| +Slim-Neck | 0.855 | 0.729 | 0.822 | 0.594 | 2.80 | 7.3 | 238.6 |
| +GELAN | 0.840 | 0.758 | 0.814 | 0.581 | 2.64 | 7.2 | 221.3 |
| +InnerGIoU | 0.825 | 0.743 | 0.808 | 0.588 | 3.01 | 8.1 | 364.6 |
| Improved YOLOv8n | 0.810 | 0.798 | 0.817 | 0.601 | 2.36 | 6.2 | 172.2 |

Table 2. Performance and resource evaluation of mainstream models in comparative experiments

| Model | <i>P</i> | <i>R</i> | <i>mAP@0.5</i> | <i>mAP@0.5:0.95</i> | <i>Params(M)</i> | <i>GFLOPs</i> | <i>FPS(s)</i> |
|------------------|----------|----------|----------------|---------------------|------------------|---------------|---------------|
| Faster-RCNN | 0.677 | 0.876 | 0.918 | 0.613 | 136.7 | 369.8 | 29.4 |
| YOLOv5n | 0.792 | 0.748 | 0.801 | 0.493 | 1.76 | 4.1 | 372.8 |
| YOLOv6n | 0.828 | 0.713 | 0.817 | 0.571 | 4.73 | 11.4 | 273.5 |
| YOLOv8n | 0.793 | 0.766 | 0.799 | 0.567 | 3.01 | 8.1 | 367.6 |
| Improved YOLOv8n | 0.810 | 0.798 | 0.828 | 0.601 | 2.36 | 6.2 | 172.2 |

4. Conclusion

This study proposed an improved YOLOv8 model for high-accuracy and efficient building crack detection. It uses SlimNeck structure, CSPPELAN4 layer, and InnerGIoU loss function for lightweight improvement. Results showed that the optimized model outperforms the original in *mAP@0.5:0.95*, computational complexity,

and parameter number. Detection accuracy rises by 2.3% and recall by 4.2%, while model parameters and computational complexity drop by 21.6% and 23.5%, respectively. These boost the model's performance in fine-crack and complex-background detection. The model suits resource-constrained scenarios and offers references for further optimization.

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