

Of course, this is ubiquitous in the intelligent manufacturing experiment, and there is PLC control in each functional area. Once the students master the practical operation of the assembly area, they can extend to other PLC signals such as the raw material area, the finishing car area, the finishing milling area, and the finished product area. At the same time, the virtual AGV car will move to the corresponding position in the scene along the magnetic stripe trajectory in the virtual scene according to the signal input of the PLC, which effectively provides a highly realistic and functionally rich practical environment for students, so that they can deeply understand all aspects of intelligent manufacturing. Master the skills of PLC debugging, signal logic control, and the collaborative operation of virtual equipment and real hardware, and have a deeper understanding and feeling of intelligent manufacturing^[14].

In the assembly area, the model of the virtual intelligent assembly area is highly restored, which is similar to the actual production and processing, which can be described as accurate reproduction. There are all kinds of accessories and fixtures involved in the processing in reality, and there are also corresponding models to choose from in the virtual world. At the same time, it also displays accurate actions such as the extension and retraction of the limited cylinder, the action of the robot jig to grab the material, and the operation of the screw machine, to help students practice operation more realistically. Like the real equipment, the intelligent manufacturing virtual system supported by the digital twin system can make corresponding changes by receiving real-time PLC signals^[15]. With a high degree of synchronization and reduction, it provides strong support for the management and optimization of the whole intelligent manufacturing process. More intuitively understand the entire production line production process, identify potential problems in advance, and make adjustments to improve production efficiency and quality.

5. Concluding remarks

The intelligent manufacturing teaching experiment and training platform supported by digital twin has the characteristics of integration of theory and reality and a combination of virtual and real. It supports modern resource platforms and teaching conditions, provides the majority of students with new practical experience, and lays a solid foundation for their future academic research and employment. The platform has a complete simulation of the digital manufacturing process, virtual debugging, and judgment and verification of PLC logic signals, which meets the needs of teachers and students for real cases of enterprises, covering from simple production line unit equipment to automated production line, so that students can learn step by step. After learning professional theory content, students can periodically train and complete project tasks through the training platform, and integrate theoretical knowledge and practice, to better use professional skills and improve their innovation ability and competitiveness. In the future, the development of relevant platforms and the innovation of teaching models are still worthy of our attention and optimization.

Disclosure statement

The authors declare no conflict of interest.

References

- [1] Tian L, Bao Z, 2024, Research Analysis and Relevant Improvement Suggestions for Accounting Training Platform Under the Background of Data Intelligence. *Accounting for Township Enterprises in China*, 2024(06): 193–195.

- [2] Lu D, 2024, Design of Digital Twin Simulation and Debugging Training Platform. *Science and Technology Information*, 22(04): 50–52.
- [3] Yang B, Yu Q, Zhang D, 2023, Research on Virtual Simulation Training Teaching of Intelligent Production Line Based on Digital Twin Technology. *Science and Education Guide*, 2023(26): 46–49.
- [4] Wei F, Zhang T, Luo P, 2022, Research on Online and Offline Training Teaching of Intelligent Manufacturing Based on Digital Twin—Taking Industrial Robot Assembly and Adjustment Training Course as an Example. *Journal of Xichang University (Natural Science Edition)*, 36(04): 124–128.
- [5] Xiao C, Yang X, Miao L, et al., 2021, Design and Implementation of Intelligent Manufacturing Comprehensive Training Platform for Metallurgical Industry Under the Background of New Engineering. *Experimental Technology and Management*, 38(12): 230–234 + 238.
- [6] Ji Z, Fu X, Jiang D, 2021, Construction of Intelligent Manufacturing Comprehensive Training Platform Based on “Engineering and Management Integration”. *Experimental Technology and Management*, 38(11): 254–259.
- [7] Du P, Chen H, Jiang H, 2021, Construction of Multi-Party Collaborative Information and Electricity Cross Composite Practice Platform Under the Background of Intelligent Manufacturing. *Journal of Experimental Technology and Management*, 38(04): 30–35.
- [8] Li GQ, Huang H, 2021, Research on the Construction of Intelligent Manufacturing Training Platform for Mold under the Background of Modern Apprenticeship Training—Taking Wuhan Vocational College as an example. *Journal of Wuhan Metallurgical Management Cadre Institute*, 31(01): 64–66.
- [9] Yang M, 2020, Virtual-Real Combination Training Platform and Automation Teaching Integration to Improve the Quality of Talent Training. *Labor Security World*, 2020(06): 56.
- [10] Zhou Y, Wang G, Wang Z, et al., 2019, Thinking on the Construction of Intelligent Manufacturing Training Platform for Petroleum Equipment under the Background of New Engineering. *Contemporary Educational Practice and Teaching Research*, 2019(16): 222–223.
- [11] Chen GC, Zhang LF, Wu YJ, et al., 2018, Development of High-Quality Teaching Resources of Spinning Process Design and Quality Control Based on Cloud Training Platform. *Textile Industry and Technology*, 47(10): 46–48.
- [12] Qi X, 2018, Discussion on the Construction of Simulation Law Enforcement and Case Handling Area Training Platform for Investigation Science Major—Taking Xinjiang Police Academy as an Example. *Journal of Xinjiang Police Academy*, 38(03): 59–64.
- [13] Zhang B, Wang R, Li S, 2018, Research and Exploration on the Construction of Industry-Education Integration Training Platform for Group Intelligent Manufacturing of Mechanical and Electrical Majors. *Journal of Taizhou Vocational Technical College*, 18(01): 7–9.
- [14] Zhang L, 2015, The Information-based Teaching Design of Computer Courses in Higher Vocational Colleges—Taking “Common Problems and Countermeasures of the Installation of ERP Software Development Training Platform” as an Example. *China Education Informationization*, 2015(06): 46–48.
- [15] Wu Z, Liang C, 2014, Research on the Construction and Implementation Strategy of Dual Platform of Logistics Management Professional Training in Higher Vocational Colleges Based on Information Characteristics—Taking Guangdong Vocational College of Science and Trade as an example. *Logistics Engineering and Management*, 36(11): 209–212.

Publisher’s note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Study on the Hydraulic Performance and Efficiency of a Siphon Sediment Discharge Device with Bottom Hole Opening through Simulation Experiments

Henglong Hui, Yan Li, Zhiying Cui*

School of Hydraulic Engineering, Changchun Institute Of Technology, Changchun 130012, China

*Corresponding author: Zhiying Cui, Cuizhiying@ccit.edu.cn

Copyright: © 2025 Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY 4.0), permitting distribution and reproduction in any medium, provided the original work is cited.

Abstract: In this study, the hydraulic behavior and sand transport efficiency of the siphon automatic sand discharge device were studied by software simulation tests. By simulating the actual situation, this study analyzed how factors such as the difference in water level, sediment concentration, and pipeline layout affected the sediment discharge effect. The results show that the sediment discharge device can effectively discharge sediment under diverse operating conditions and show adaptability to different environmental conditions, which indicates that it is suitable for various types of reservoir environments.

Keywords: Siphon sand discharge; Bottom hole opening; Sand transport efficiency; Simulation experiment.

Online publication: February 12, 2025

1. Introduction

The problem of sediment deposition in reservoirs has always been a major challenge in the field of hydraulic engineering. Traditional methods of sediment removal, such as mechanical excavation and hydraulic irrigation, often require a large amount of energy support and have a large impact on the environment. Siphon sand drainage technology has attracted attention due to its advantages of energy saving and environmental protection. To improve the efficiency of sand discharge and reduce the environmental impact, this paper studies the siphon automatic sand discharge device through the model test.

2. Research status

2.1. Current situation of sediment deposition in the reservoir

Globally, the problem of sediment deposition in reservoirs has become increasingly prominent, which has a serious impact on the water storage, flood control, and water supply functions of reservoirs ^[1]. The sediment carried by

the upper reaches of rivers accumulates in the reservoirs for a long time, resulting in the effective storage capacity of the reservoirs decreasing year by year. According to a report by the United Nations Environment Programme, about half of the world's reservoirs are suffering from sediment accumulation, and the problem is getting worse [2].

2.2. The development and application of silting removal technology

In response to the widespread problem of silting in reservoirs around the world, researchers and engineers have developed a series of silting technologies. In addition to traditional methods of mechanical excavation [3–5], hydraulic flushing, and sediment discharge [5–8], emerging technologies such as ecological dredging, chemical conditioning, and microbial remediation [9–14] are now emerging. These new technologies aim to solve the sediment problem in a more environmentally friendly and economical way, although their practical application still needs to overcome the challenges of technology maturity and affect stability.

2.3. Research on siphon sediment removal technology

Siphon drainage technology is gradually becoming the focus of reservoir dredging research because of its high automation, low operating cost, and small environmental interference. Through the negative pressure caused by the water level difference, the technology realizes the siphon effect, so that the sediment can be continuously discharged. Although most of the current literature focuses on optimizing the design of siphons, improving the efficiency of sediment removal, and reducing the impact on water quality, this technology still faces challenges in practical application, such as complex system design, strict start-up conditions, and poor adaptability to working conditions.

Therefore, there is an urgent need for a more efficient and environmentally friendly silting removal technology to solve the problem of sediment deposition in reservoirs. The research and application of siphon-type automatic sediment discharge devices provide an innovative solution. Through the model test, this study aims to deeply explore the hydraulic principle of this technology and its application effect in engineering practice, in order to provide a more scientific solution strategy for reservoir sediment management.

3. Research objectives, contents and methods

3.1. Main purpose of the study

This study focuses on the key problems and challenges in the field of reservoir dredging, especially for the problems encountered in the practical application of siphon sand removal technology, aiming to propose innovative solutions and optimization strategies. The core objectives of the study include:

- (1) To improve the efficiency of sediment removal by simulating its physical characteristics and hydraulic parameters.
- (2) Design a new siphon-type sand discharge device and optimize the parameters to ensure the performance stability and reliability of the device under various working conditions.
- (3) Based on the principles of ecological engineering, the methods of sediment discharge and silting removal were studied and optimized to minimize the interference and potential negative impacts on aquatic ecosystems.

3.2. Main contents of the study

3.2.1. Theoretical study on siphon sediment discharge mechanism

- (1) Using the principle of fluid dynamics, the key influencing parameters of the siphon phenomenon are studied.
- (2) A model of siphon sediment drainage was established to simulate the effect of sediment drainage under different conditions.

3.2.2. Design and optimization of siphon sand drainage device

Design a prototype of a new siphon-type sand discharge device and test its performance through laboratory and computer software simulation.

3.2.3. Simulation experiment and parameter sensitivity analysis

- (1) Conduct a series of simulation experiments in a controlled environment to collect data on sediment movement and sediment removal efficiency.
- (2) Parameter sensitivity analysis was conducted to determine the key design parameters affecting the sediment removal effect.

3.3. Research methods

3.3.1. Theoretical analysis

Based on the basic theory of fluid dynamics and sediment kinematics, the siphon sediment drainage mechanism was deeply analyzed, and a mathematical model was established to predict the law of sediment movement and the efficiency of sediment drainage.

3.3.2. Model experiment

Under laboratory conditions, the reservoir sediment model and siphon sediment drainage system model were constructed, and the simulation experiment under large working conditions was carried out by software simulation.

3.3.3. Data analysis

Statistical methods and data analysis software were used to process experimental and prototype observation data, identify key influencing factors, and optimize the design scheme.

4. Experimental model study

4.1. Physical model design

The model is mainly composed of four parts: a water inlet device (suction pipe), an upstream water tank, a pipe composition, and a suspension device. The upstream water tank is spliced with acrylic plates. The pipe is polyvinyl chloride (PVC), the pipe diameter is 1.5 cm, and the sand discharge pipe is divided into three different ways of opening, in which the siphon pipe is opened with a water injection hole (1), the outlet pipe valve (2), and the sand suction hole (3). The water level difference between upstream and downstream is 1 m, 1.25 m, and 1.5 m. The water level difference is kept constant through the water inlet device. The influence of water level difference and sediment concentration on outlet flow velocity and the influence of opening mode on sediment discharge were mainly observed. A schematic diagram of the design is shown in **Figure 1** and **Figure 2**.

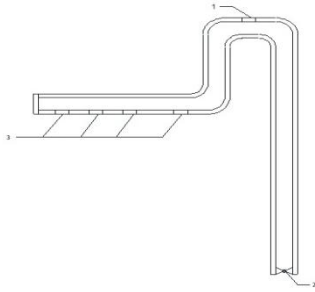


Figure 1. Side view and top view of the siphon

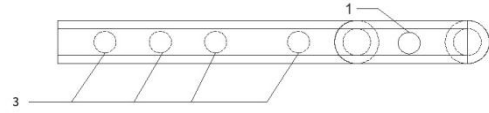


Figure 2. Top view of the siphon

4.2. Selection of simulation software and model

Ansys Fluent is a general-purpose computational fluid dynamics (CFD) software for modeling and analyzing fluid flow, heat transfer and mass exchange, and chemical reaction processes. The Euler model is the most complex multiphase flow model in FLUENT. The coupling is realized by the pressure and the phase exchange coefficient, and the Euler model has the highest calculation accuracy. Therefore, it is decided to use the Euler model as the model of numerical simulation.

4.3. Result analysis

The data from the simulation experiment and physical model experiment were plotted in Excel. The correlation between the fitting curve equation and the experimental data was more than 0.94, and the conclusion was highly correlated. It can be seen from the two curves in **Figure 3** and **Figure 4** that the simulated results are basically consistent with reality.

4.3.1. Comparison of sand discharge effect by opening mode

The form of the bottom opening can be divided into equal spacing opening and variable spacing opening. Compared with the tail opening, the bottom opening has obvious advantages in sediment discharge. Specifically, the bottom opening has a wider range of sediment discharge, which means that under the same conditions, it can cover a wider area and remove the silt in front of the dam more effectively. This design not only improves the efficiency of sediment discharge but also can better cope with sedimentation problems in different situations.

4.3.2. The impact of the head difference

Through comparative experiments, we found the influence of head difference on the sediment

discharge effect of the bottom opening system. With the increase of head difference, the outlet flow velocity gradually increased. However, with the increase of the flow velocity, the

sediment carrying capacity of the flow decreased slightly, which may be caused by the decrease of sediment suspension capacity caused by the excessive flow velocity. Nevertheless, the sediment discharge showed an increasing trend at the same time, which indicated the positive effect of head difference on sediment discharge.

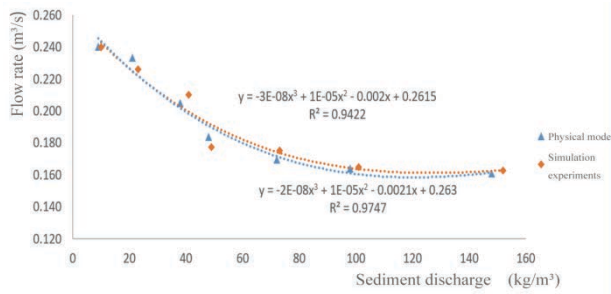


Figure 3. Plot of flow and sediment concentration

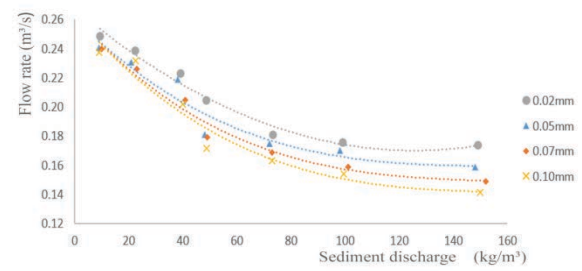


Figure 4. Plot of flow and sediment concentration

4.3.3. Effect of hole opening method on flow rate and sediment discharge

Through comparative experiments, the influence of different opening methods on the outlet flow velocity was found. As shown in **Figure 5**, compared with the tail opening, the outlet flow velocity of the bottom opening is smaller under the condition of the same head difference, which may be because the bottom opening way increases the head loss at the intake of the sand suction device. At the same time, this also means that the bottom hole has a lower flow rate for the same pipe diameter.

The flow rate can be obtained by multiplying the outlet flow rate by the pipe diameter, and the data analysis of the flow rate and sediment discharge can be obtained in **Figure 6**. It can be analyzed from the figure that under the condition of the same head difference, although the flow rate of the bottom opening is smaller, the overall sediment discharge is better than that of the tail opening. This may be due to the bottom of the opening of the sand suction range being more uniform, making the suction device contact with a wider sediment area, resulting in a small flow, but a large amount of sediment discharge.

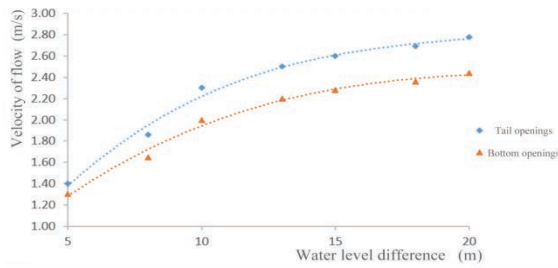


Figure 5. Relationship between water level difference and flow velocity of different ways of opening

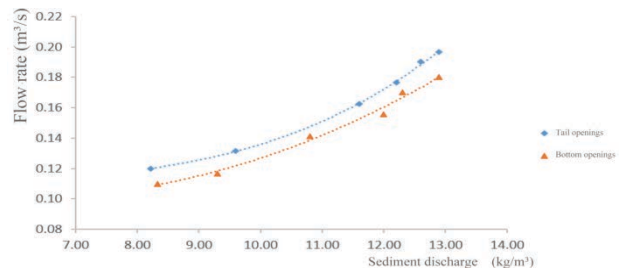


Figure 6. Relationship between discharge and flow for different types of openings

5. Conclusion

- (1) The test results show that the overall sand discharge efficiency of the siphon-type sand discharge device is significantly improved when the water level difference is increased, but the growth rate of the outlet flow velocity will gradually slow down.
- (2) The test results show that, under the same hydraulic conditions, the higher the sediment content in the water, the larger the sediment particle size, and the slower the outlet flow velocity of the pipeline.
- (3) The test results show that the bottom hole usually has a larger sediment discharge than the tail hole. This is because the bottom hole can absorb sediment deposited on the bottom more effectively. In contrast, the tail hole may be affected by weak water flow, and the sediment discharge efficiency is relatively low.

Therefore, under the same conditions, the bottom opening tends to be able to remove sediment from the water body more quickly and improve the efficiency of sediment discharge.

- (4) The test results show that in the siphon-type sediment discharge device, the suction part of the sand has little influence on the sediment disturbance. This finding may mean that the siphon sediment drainage device can effectively separate the sediment from the water body without excessive disturbance of the flow and sediment distribution. This indicates that the siphon automatic sediment discharge device has good adaptability and efficient sediment discharge capacity compared with other traditional sediment discharge methods, and is significantly superior to the traditional sediment discharge method in terms of energy saving, labor intensity reduction, and water pollution reduction.

Funding

Supported by the National Undergraduate Innovation Training Program (Project No. 202211437036).

Disclosure statement

The authors declare no conflict of interest.

References

- [1] Wang Z, Yue W, Wang S, et al., 2019, Review the Development Trend of Ecological Restoration in International Watersheds and Its Reference Significance. *Geographical Science Research*, 8(2): 221–233.
- [2] Guo L, Pan D, Hu X, et al., 2009, Lagrangian Numerical Simulation for Solid-Liquid Two-Phase Flow in a Curved Duct. *Int. J. of Engineering Systems Modelling and Simulation*, 1(2/3): 137–143.
- [3] Fan X, Tan D, Li L, et al., 2021, Modeling and Solution Method of Gas-Liquid-Solid Three-Phase Flow Mixing. *Acta Physica Sinica*, 70: 124501.
- [4] Lee KY, Kim WS, 2017, Study of Siphon Breaker Experiment and Simulation for a Research Reactor. *Journal of Visualized Experiments: JoVE*, 2017(127): 55972.
- [5] Sapkota A, Takei M, Yamane T, et al., 2011, Impedance Spectroscopic Measurement of Particle Concentration in Solid-Liquid Two-Phase Flow. *Journal of the Japanese Society for Experimental Mechanics*, 11(Special_Issue): s162–s167.
- [6] Agbanlog RC, Chen G, 2014, Mini Hydro-Electric Power Plant with Re-Circulated Water Power Source. *IIE Annual Conference, Proceedings*, 2014: 2145–2154.
- [7] Park YC, Yoon CH, Lee DK, 2004, Experimental Studies on Hydraulic Lifting of Solid-liquid Two-phase Flow. *Ocean and Polar Research*, 26(4): 647–653.
- [8] Lu YX, Li GX, Liu MJ, et al., 2015, Numerical Simulation of Flow Fluid in Elbow Pipe Based on FLUENT and the Establishment of the Pressure Model. *Applied Mechanics and Materials*, 3744(713–715): 39–42.
- [9] Brahim M, Keddar M, Mariam I, et al., 2023, A CFD Examination of Free Convective Flow of a Non-Newtonian Viscoplastic Fluid Using ANSYS Fluent. *Arabian Journal of Chemistry*, 16(12): 105309.
- [10] Davarpanah A, Zarei M, Valizadeh K, et al., 2019, CFD Design and Simulation of Ethylene Dichloride (EDC) Thermal Cracking Reactor. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 41(13): 1573–1587.

- [11] Gallerano F, Cannata G, 2011, Compatibility of Reservoir Sediment Flushing and River Protection. *Journal of Hydraulic Engineering*, 137(10): 1111–1125.
- [12] Yoshihiko S, Shuji I, Study on a Channel Formation Process in Double-Row Bars with Riparian Vegetation. *Journal of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Engineering)*, 69(4): I_1153–I_1158.
- [13] Kulik VV, Parkin NA, Navasardyan SE, 2016, Numerical Modeling Procedure for Micromachined Cryogenic Cooler Elements Using ANSYS Fluent Software and Viscous Flow in a Small-Diameter Channel with Heat Transfer as an Example. *Chemical and Petroleum Engineering*, 52(7–8): 531–538.
- [14] Zuo J, Yang H, Wei B, et al., 2020, Numerical Simulation of Gas-Liquid Two-Phase Flow in Gas Lift System. *Acta Physica Sinica*, 69: 064705.

Publisher's note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Research on the Interactive Design of Smart Home Interface for the Elderly Based on QFD and HCI

Kun Wang¹, Xuan Liu¹, Kexiang Li¹, Zhuang Xiong¹, Bingzhe Li^{2*}

¹Faculty of Design, Quanzhou Normal University, Quanzhou 362000, China

²Huzhou University, Huzhou 313000, China

*Corresponding author: Bingzhe Li, 02305@zjhu.edu.cn

Copyright: © 2025 Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY 4.0), permitting distribution and reproduction in any medium, provided the original work is cited.

Abstract: In an aging society, the interface design of smart home products is crucial to the quality of life of the elderly. This paper combines Quality Function Deployment (QFD) and Human-Computer Interaction (HCI) theories, taking smart washing machines as an example, to explore new paths for the interface design of smart home products for the elderly. An interdisciplinary approach is adopted to construct a design process centered on elderly users, introduce the Kano model to classify requirements, realize the mapping and sorting of requirements to design parameters, and adopt the PUGH model for comprehensive evaluation. This study provides practical and theoretical support for the interface design of smart home products for the elderly.

Keywords: Smart home and aging; Integration of QFD and HCI; Interface interaction; Design optimization

Online publication: February 13, 2025

1. Introduction

As the global aging trend intensifies, smart home technology provides opportunities to improve the quality of life of the elderly. However, the elderly often feel confused when using smart home products such as smart washing machines because the product interface design does not fully consider their particularities. Currently, products on the market pursue diverse functions and modern interfaces, but ignore the needs of the elderly user group. To improve this situation, domestic and foreign scholars have conducted in-depth explorations on the aging-friendly design of smart home products in recent years. Zhang *et al.* proposed to enhance the perception and operation ability of elderly users of smart products by introducing color sequence memory and optimizing icon design^[1,2].

These methods aim to make it easier for elderly users to understand and use smart home products by improving interface design. Wang *et al.* focused on lowering the operational threshold between elderly users and smart products through non-contact interaction methods such as voice recognition and gesture control^[3]. These non-contact interaction methods can reduce the physical burden of elderly users during use and improve the

convenience and safety of operations. However, these studies mostly remain at the theoretical level, and the needs of elderly users vary greatly. The design needs to consider multiple factors comprehensively, which is complex and challenging.

Therefore, this study focuses on the difficulties faced by elderly users in using smart washing machines, integrates QFD and HCI theories, and proposes targeted interface interaction design solutions, aiming to optimize the design of smart washing machines, improve the convenience and happiness of elderly users, and provide practical guidance and theoretical support for aging-friendly design.

2. Literature review on the design of smart home products for the elderly

The current situation of the design of smart home products for the elderly shows a trend from automation to more humanization, but the adaptability to the special needs of elderly users is still insufficient. Although the early smart home washing machines have achieved automation in the washing function, their operation interface is complex and puts high demands on the user's interface operation ability, which often brings confusion and anxiety to elderly users with visual impairment and memory loss. Therefore, designing simpler, more intuitive, and convenient products has become the key to the design of smart home products for the elderly.

To this end, to improve the user experience of smart home products, especially for the elderly user group, the QFD method has been widely used in the design of smart home products. Studies have shown that the QFD method can effectively optimize the user experience of smart home products and achieve a sustainable user experience optimization strategy ^[4]. The Fuzzy-QFD model combined with grey correlation analysis further analyzes the relationship between the needs of the elderly and technical characteristics, providing strong support for the design of the elderly care service platform ^[5]. At the same time, the Kano model identifies the levels of needs of elderly users, including basic needs, expected needs, and exciting needs, thereby guiding product design and improving the overall performance and user experience of the product. Cheng *et al.* used the Kano model to classify the functional requirements of the main home automation equipment, providing empirical support for the functional planning and design optimization of smart home products ^[6]. Liu *et al.* took connectivity as the core element to build a smart home system for the elderly in the future and demonstrated the application effect of the Kano model in improving product user experience and happiness ^[7].

HCI theory also plays an important role in the design of smart home products for the elderly. Huang *et al.* introduced advanced technologies such as voice recognition and gesture recognition to create a more natural and intuitive interactive experience ^[8]. At the same time, with the help of data analysis and user feedback mechanisms, the design team can continuously optimize the interface layout and operation process to make it more in line with the usage habits and needs of elderly users. Zhou and Hu, along with Reig have studied how to reduce the difficulty and cognitive load of elderly users when using smart home products by optimizing the position and size of the touch screen and simplifying the operation gestures ^[9,10].

In addition, with the increasing application of miniaturized, basic sensors and voice control technologies in smart homes, these technologies also provide elderly users with a more convenient and safe home environment. The research of Tapia *et al.* demonstrated the great potential of sensors in improving the convenience and safety of the lives of the elderly ^[11]. Portet *et al.* studied and developed a system based on voice recognition, which promoted communication between the elderly and family members through remote voice control and enhanced the intelligent experience of the home environment ^[12].

In terms of environmental intelligence and multimodal interaction, Epelde *et al.* combined customized graphical interfaces, intuitive navigation menus, and multimodal interaction methods to build a natural and barrier-free interactive environment for the elderly ^[13]. This interactive method not only improves the user experience of elderly users but also provides them with more abundant interactive options.

In summary, QFD, Kano model, HCI theory, and smart home design direction play an important role in the design of the interactive interface of smart washing machines, and will continuously improve the user experience of the elderly.

3. Research methods

Firstly, the Kano model is used to analyze the demand information of the elderly group and determine the importance of user needs. Secondly, based on QFD, user needs are converted into design needs, the “user needs-design needs” quality house is established, and the correlation matrix is obtained. In this process, the theoretical principles of human-computer interaction (HCI) are closely followed to ensure that the interface design fully considers the physiological limitations (such as vision and hearing deterioration) and psychological characteristics (such as changes in learning ability and emotional needs) of the elderly, to create a barrier-free and warm interactive experience, and give an optimized design scheme for the operation interface of the smart washing machine.

Using the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method, through comprehensive evaluation and comparison among multiple candidate design schemes, the design scheme closest to the ideal solution and with the best overall performance is selected. Finally, according to the PUGH concept selection method (or Pros and Cons Charting), the selected optimal scheme is further verified and refined, and its potential advantages and disadvantages are deeply analyzed. Through iterative optimization, it is ensured that the design scheme is not only highly practical, but also smooth in actual operation, and finally, the best design scheme is determined and implemented.

4. Design and experiment

4.1. Demand acquisition

This study focuses on the elderly group aged 60 and above who have experience in using smart washing machines, and a total of 127 representative users were selected. Based on relevant research and authoritative reports on geriatric psychology and physiology, the target users are divided into four levels: young healthy period (60–64 years old), middle-aged self-care period (65–74 years old), elderly assistance period (75–84 years old) and super-elderly care period (over 85 years old). At the same time, differences in gender, region, economic level, and educational background are considered to ensure the diversity and representativeness of the sample.

Through questionnaires and in-depth interviews, the needs and usage habits of elderly users for smart washing machines are obtained. The Kawakita Jiro (KJ) method is used to classify the information, and 6 first-level needs and 18 second-level needs are obtained.

- (1) Operational requirements: Large font display, the laundry process is simplified, one-click laundry operation.
- (2) Security requirements: Anti-mistouch design, emergency stop.
- (3) Visually friendly needs: Height contrast, the icons are clear, and the color is mild.

- (4) Personalization: Customize your laundry routine and memory function.
- (5) Voice accessibility features: Voice control and verbal feedback.
- (6) Guidance and tips: How-to guide, error message, stability alerts.

4.2. Demand analysis and classification

The Kano model was used to classify the needs of elderly users. A total of 500 questionnaires were distributed, and 492 valid questionnaires were collected, with a collection rate of 98.4%. Based on quantitative analysis, essential needs, expected needs, and attractive needs were obtained.

- (1) Essential needs include: C11 Large font and clear interface, C12 Simplified operation process, C22 The icons are clear, C23 The color is mild, C41 Anti-mistouch design.
- (2) Expected needs include: one-dimensional requirements like C13 One-click laundry operation, C21 Height contrast, C31 Voice assistance function, C41 Anti-mistouch design, C43 Stability prompt, C44 Environmental protection and energy saving design, C42 Emergency stop button, C61 Operation guide, C62 Error prompt and solution.
- (3) Attractive needs include: C33 Intelligent interconnection function, C52 Memory function, C51 Personalized customization service, C53 Healthy washing mode.

There are no different needs and reverse requirements.

4.3. Design transformation and priority setting

Based on HCI interaction theory, QFD is used to transform user needs into design requirements and build a quality house model. Design requirements include six directions: basic operation optimization, auxiliary function enhancement, smart interconnection experience, health care, environmental protection and energy-saving design, and safety design.

The first-level design requirements are “D1 basic operation optimization direction,” including a series of style and appearance requirements of the operation interface, fonts, font sizes, icon clarity, interface layout style, etc. At the same time, the design of “D2 auxiliary function enhancement direction” is to enhance the user experience of the elderly. The addition of personalized settings, voice assistance functions, operation guides, and other functions is more in line with the operation and use habits of the elderly and better meet their daily use needs. The first-level design requirements of “D3 smart interconnection experience direction,” “D4 health care direction,” “D5 environmental protection and energy-saving design direction,” “D6 safety design direction,” and other requirements are aimed at improving the safety, convenience, comfort, and experience of the elderly during use, and increasing the user satisfaction of elderly users.

A relationship matrix was constructed to associate user needs with design requirements, and the design requirements were prioritized based on the scores. Simplified operation processes and voice assistance ranked high among the design requirements.

Table 1. Order of importance of design elements

Prioritization	Design elements	n_{ji}	v_{ij}
1	D12 Simplified operation process	2.35	0.1003
2	D22 Voice assistance function	2.26	0.0974
3	D23 Error prompts and solutions	1.96	0.0783

4	D52 Water-saving technology	1.93	0.0716
5	D61 Anti-accidental touch design	1.82	0.0685
6	D11 Large font and clear interface	1.74	0.0618
7	D13 Emergency stop button	1.63	0.0579
8	D24 Operation guide	1.58	0.0532
9	D21 Personalized settings	1.51	0.0513
10	D41 Healthy washing mode	1.46	0.0482
11	D42 Hightemperature disinfection function	1.41	0.0475
12	D51 Energy efficiency rating	1.39	0.0426
13	D53 Low noise design	1.38	0.0421
14	D62 Unbalance detection	1.32	0.0368
15	D63 Shockproof design	1.03	0.0257
16	D32 Smart interconnection	0.86	0.0212
17	D31 Wi-Fi connection function	0.69	0.0197

4.4. Design plan

Based on the analysis of design elements and the priority ranking of the smart washing machine interaction interface in the previous section, this section designs the smart washing machine interaction interface based on hierarchy, operability, clarity, readability, and ease of use. The four design schemes are shown in **Figure 1**.

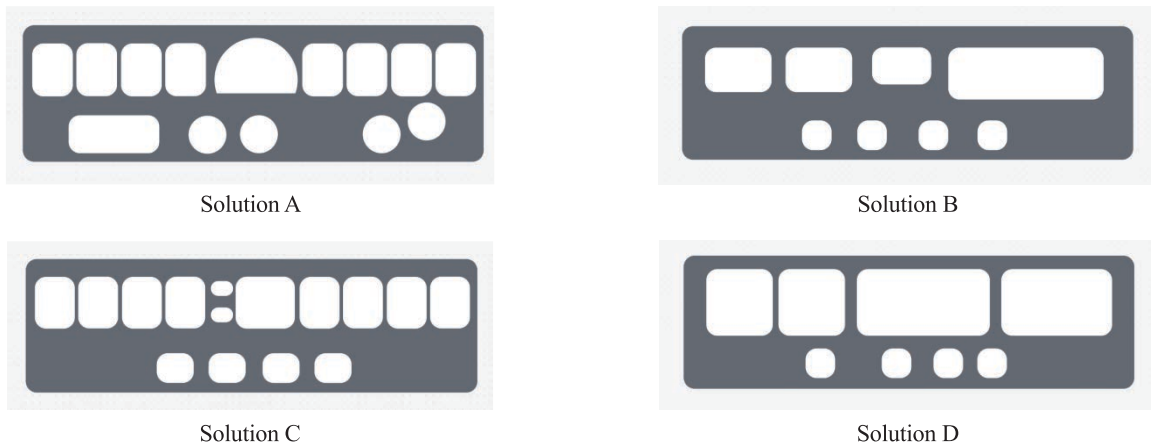


Figure 1. Four design options

- (1) Solution A (practical): focuses on meeting essential needs, with stable performance and reliable basic operating functions. The operation interface is intuitive and physical buttons are added.
- (2) Solution B (personalization and ease of use): On the basis of meeting the necessary needs, add personalized settings and optimized user interface. Provide adjustable options, allow users to customize the location of frequently used programs, and use clear and easy-to-understand icons and animations.
- (3) Solution C (innovative technology and environmental protection and energy saving): Focus on the realization of attractive needs, such as intelligent interconnection functions, environmental protection and energy-saving design, etc. Support Wi-Fi connection, automatically adjust the washing plan, and provide

energy-saving mode.

- (4) Solution D (comprehensive and balanced): Comprehensively consider all levels of needs and continuously optimize interface design and function settings through user research and feedback mechanisms.

4.5. Scheme evaluation

The TOPSIS method was used to evaluate the four design schemes. The relative closeness was calculated based on indicators such as practicality, personalization, ease of use, user feedback and adaptability, functionality, technological innovation, and cost-effectiveness, and Solution B was found to be the best.

The PUGH concept selection method was used to fine-tune Solution B, maintaining the current status of font size, simplifying operation steps and emergency stop function, adding voice control command options, and removing the interconnection function to reduce costs.

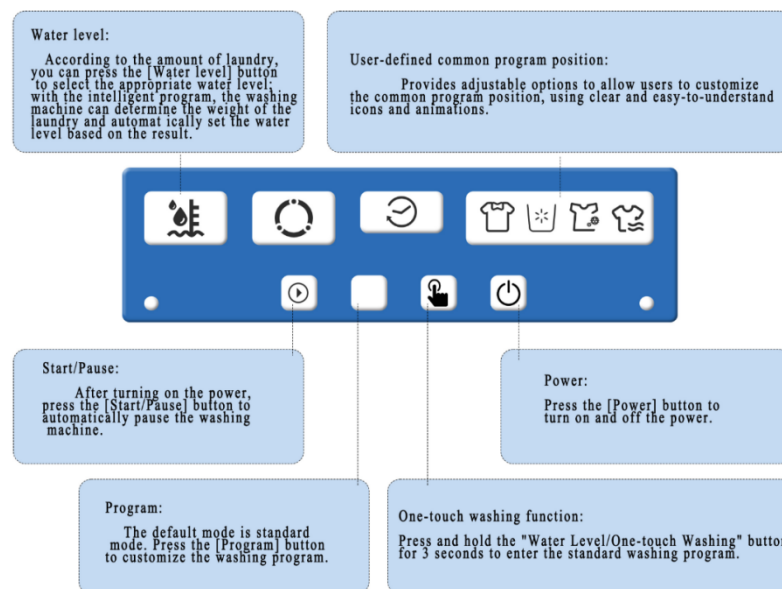


Figure 2. Specific design details of Solution B

- (1) Interface visual design: Use large fonts (Arial Bold, 28 pt or more) and high contrast color (black and white or dark blue and light white). Simplify the operation steps, set one-button operation mode, and intelligently recommend washing programs. Set emergency stop function and eye-catching emergency button. Support voice command input and result feedback, and provide operation guidance.
- (2) Advantages: The interface is simple and clear, and the operation steps are simple and easy to understand. Equipped with an emergency stop button and voice prompt function. Find a balance between functionality and cost-effectiveness.
- (3) Disadvantages: Compared with other solutions, it may lack some high-end intelligent or interconnected functions.

Through the above content deletion, the meaning of the article and the design results remain unchanged, and at the same time, it is more concise and clear.

5. Results and discussion

Under the evaluation of TOPSIS and PUGH methods, Solution B became the optimal design of the interface of the smart washing machine for the elderly. Its highlights include barrier-free reading, simplified operation, emergency safety guarantee, and voice assistance system, achieving a balance between ease of use, safety, and economy. Competitive product analysis shows that although Solution A is concise, the font is not optimized, Solution C is comprehensive but the operation is complicated, and Solution D is low-cost but lacks optimized design for the elderly. With the intensification of aging, the design of smart washing machines for the elderly is crucial^[14,15]. Solution B can improve the quality of life, safety, and family harmony of the elderly, and has guiding significance for the design of the smart washing machine industry and the entire smart home product for the elderly, promoting technological innovation, industrial upgrading, and enhancing social attention and respect for the elderly. This study provides strong support for the design of the elderly and promotes social progress.

6. Conclusion

This study integrates QFD and HCI theory, taking a smart washing machine as an example, to explore and practice a new path for the interface design of smart home products for the elderly. Through the combined application of the TOPSIS method and the PUGH model, the optimal design plan was innovatively evaluated and selected. This plan fully considered the special needs and usage habits of the elderly and significantly improved their quality of life, safety, and family harmony. The research not only provides practical guidance for aging-friendly design but also points out future research directions, including deepening research on elderly users, exploring new technology applications, and strengthening cross-field cooperation, providing strong support for the sustainable development of the smart home industry.

Disclosure statement

The authors declare no conflict of interest.

References

- [1] Ou JY, Zhang T, Research on Aging-Friendly Design Evaluation Model of Wearable Devices Based on Implicit Interaction Theory. ICMD: International Conference on Mechanical Design. Singapore: Springer Nature Singapore, 2023: 397–417.
- [2] Liu H, Wang W, Liu Y, et al., Study on the Differences of Icon Cognition of Graphical Interface for Age-Friendly Design. *Journal of Gerontological Social Work*, 66(5): 662–679.
- [3] Wang Y, Zhou Y, Chen X, et al., 2024, Operational Performance and Subjective Preferences of Elderly Users in Intelligent Interactive Interfaces: A Systematic Review. *International Journal of Human-Computer Interaction*, 2024: 1–15.
- [4] Kano N, 1984, Attractive Quality and Must-be Quality. *Hinshitsu Qual. J. Jpn. Soc. Qual. Control*, 14: 39–48.
- [5] Sirel Y, Kauffmann P, Ozan E, 2007, Integration of Kano's Model into QFD for Multiple Product Design. *IEEE Trans. Eng. Manag.*, 54: 380–390.
- [6] Cheng J, Wu Y, Huang H, et al., 2016, Study of Middle-Aged and Youth Users' Preference for Smart Homes. *Human-Computer Interaction. Novel User Experiences: 18th International Conference, Proceedings, Part III* 18. Springer

International Publishing, 2016: 483–493.

- [7] Liu Y, Tamura R, Song Y, 2020, Constructing a Smart Home for Future Elders Toward All-Around Happiness: Taking Connectivity as the Core Element. *Applied Sciences*, 10(16): 5690.
- [8] Huang YC, Wu KY, Liu YT, 2013, Future Home Design: An Emotional Communication Channel Approach to Smart Space. *Personal and Ubiquitous Computing*, 17: 1281–1293.
- [9] Zhou Y, Hu X, 2021, Internet of Things Intelligent Interaction Technology Using Deep Learning in Public Interaction Design. *IEEE Access*, 10: 3182–3191.
- [10] Reig S, Fong T, Forlizzi J, et al., 2022, Theory and Design Considerations for the User Experience of Smart Environments. *IEEE Transactions on Human-Machine Systems*, 52(3): 522–535.
- [11] Tapia EM, Intille SS, Larson K, 2004, Activity Recognition in the Home Using Simple and Ubiquitous Sensors. In *International Conference on Pervasive Computing*, Springer Singapore, 2004: 158–175.
- [12] Portet F, Vacher M, Golanski C, et al., 2013, Design and Evaluation of a Smart Home Voice Interface for the Elderly: Acceptability and Objection Aspects. *Pers. Ubiquitous Comput.*, 17: 127–144.
- [13] Epelde G, Valencia X, Carrasco E, et al., 2013, Providing Universally Accessible Interactive Services through TV Sets: Implementation and Validation with Elderly Users. *Multimed. Tools Appl.*, 67: 497–528.
- [14] Zhang X, 2021, Research on User Experience Design of Young and Old People Using Smartphones, thesis, Guangdong University of Technology.
- [15] Tural E, Lu D, Cole AD, 2021, Safely and Actively Aging in Place: Older Adults' Attitudes and Intentions Toward Smart Home Technologies. *Gerontol. Geriatr. Med.*, 7: 1–15.

Publisher's note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

High-Power Laser Technology and Industrial Development Research

Can Guo*

Hubei University of Education, Wuhan 430415, Hubei Province, China

*Corresponding author: Can Guo, 17317016132@163.com

Copyright: © 2025 Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY 4.0), permitting distribution and reproduction in any medium, provided the original work is cited.

Abstract: High-power laser technology is widely used in manufacturing processing, medical diagnosis, and treatment, and is one of the important fields of strategic high-tech competition in China at the moment. In the context of industrial upgrading, high-power laser technology plays an important role in leading the development of the manufacturing industry and industrial intelligence. Based on this, this paper carries out research on high-power laser technology and industry, summarizes the basic principle and classification of high-power laser technology, analyzes the current status of high-power laser technology industry, points out the opportunities and challenges faced by the industry development, puts forward suggestions to promote the development of high-power laser technology industry, and to provide an effective reference for the application and development of high-power laser technology.

Keywords: High-power laser technology; Industrial development; Research

Online publication: February 13, 2025

1. Introduction

With the rapid development of science and technology, high-power laser technology is increasingly widely used in industry, medical treatment, scientific research, and other fields. As one of the cores of modern optoelectronic technology, the development level of high-power laser technology is directly related to the competitiveness of related industries^[1]. Therefore, an in-depth study of high power laser technology and its industrial development is of great significance for promoting scientific and technological innovation and promoting industrial upgrading. This paper aims to comprehensively analyze the classification, industry status, challenges, and opportunities faced by high-power laser technology and put forward targeted development suggestions for relevant enterprises and policymakers to provide a reference^[2].

2. High-power laser technology related overview

High-power laser technology is the core component of modern optical and optoelectronic technology, and it plays

an important role in many fields such as scientific research, industry, medical treatment, and the military by using the coherence, directivity, and high intensity of the laser. With the progress of science and technology, high-power laser technology continues to break through, and its output power, wavelength stability, beam quality, and other performance indicators have been significantly improved, providing strong technical support for the development of related industries ^[3].

3. The category of high-power laser and its industry status

High-power lasers are mainly divided into gas lasers, semiconductor lasers, fiber lasers, and solid-state lasers according to their working principles and different media ^[4]. With the rapid development of science and technology, the high-power laser technology industry is experiencing unprecedented rapid development, attracting the attention of a large number of researchers, and promoting the transformation and upgrading of related industries.

3.1. Semiconductor laser

A semiconductor laser, also known as “direct semiconductor laser,” is where a semiconductor material is the working medium of the laser, using the electronic transition process in the semiconductor to produce a laser, with small size, lightweight, high efficiency, easy to modulate, and other advantages. In high-power applications, semiconductor lasers usually achieve high-power output by series or parallel multiple laser diodes and directly achieve power amplification through efficient beam combining technology, thus used in industrial applications. The laser is driven by electric power. The use of semiconductor materials as the gain medium, through the electro-optical conversion mechanism to stimulate the generation of laser, and finally integrate multiple lasers into the fiber to output high-power laser.

Compared with other types of lasers, it has many advantages such as high electro-optic conversion efficiency (up to more than 50%), long service life (more than 100,000 hours), superior direct electrical modulation performance, easy integration, small size, and compact structure. In the industrial field, high-power (up to kilowatt level) semiconductor lasers are mainly used in precision machining scenarios such as quenching and cladding. The hundred-watt semiconductor laser is often used as a pump source for fiber lasers and solid-state lasers. At present, China has achieved large-scale mass production in red laser diode (LD), and the output power can reach tens of watts, keeping pace with the international level, but in the field of blue LD, it still faces certain challenges ^[5].

At present, the international leading Blu-ray LD mass production power has broken through 5 W, and more top products are approaching 10 W, but the key technologies and processes are still highly confidential. In recent years, China has strengthened scientific and technological research and development, scientific research institutions such as Xiamen University and San'an Optoelectronics (Xiamen), and others have made significant progress in this field, achieving a breakthrough in output power such as 8.04 W, but compared with the international top level there is still room for improvement.

3.2. Fiber lasers

Fiber laser is where the fiber is the waveguide and gain medium of the laser, mainly by the gain medium, fiber grating, buncher, and other optical components, driven by the electrical control system, the use of doped ions in the fiber (such as ytterbium ions, erbium ions, etc.) under the action of the pump light energy level transition, resulting in laser. Ytterbium-doped (Yb^{3+}) fiber is good at the output of lasers in the 1,064 nm band, while erbium-doped (Er^{3+}) fiber is good in the 1,310 nm or 1,550 nm band.

Overall, the output of fiber lasers is mainly concentrated in the red band. Fiber lasers have the advantages of good beam quality, excellent heat dissipation performance, easy-to-achieve long-distance transmission, and amplification, and are widely used in the industrial field, among which continuous fiber lasers are mostly used in thick metal materials cutting, welding, and other macro processing fields. Pulsed fiber lasers are mostly used in solid state laser seed sources, which provides a solid foundation for the in-depth application of laser technology.

Currently, the technology has become the mainstay of China's Motor Control Center (MCC) laser. Relevant data show that in 2020, the proportion of fiber lasers in China's industrial laser market has reached 67%, and the total market sales have exceeded the 9.42 billion yuan mark. Shenzhen, Wuhan, and other places are the gathering of many fiber laser companies, forming an industrial agglomeration effect. In recent years, China has strengthened the research on the power of fiber lasers and obtained remarkable results, such as Wuhan Rayco and the University of South China jointly developed the first 100 kW fiber laser and its supporting equipment, and its output power has approached 120 kW level of IPG company in the United States, highlighting the strong strength of China's laser technology. However, China is still facing the bottleneck of core materials and devices in the field of high-power fiber lasers, such as special fiber, fiber grating, and other key components still need to rely on imports, to a certain extent, limiting the pace of development of high-power fiber lasers in China ^[6].

3.3. Solid-state laser

Solid-state laser is a kind of laser that can produce metal ions with excited radiation as the gain medium. It uses the electrons in the solid to make an energy level transition under the action of pumping light to produce a laser. Its structure is complex, including a pump source (commonly used semiconductor laser LD), seed source, amplification module (built-in gain medium), frequency conversion module (including nonlinear crystal), modulation module, and other key components. Compared with pulsed fiber lasers, it can realize ultra-fast pulse laser, and convert infrared light into green light, ultraviolet light, and deep ultraviolet light by frequency doubling crystals. The laser has the advantages of short wavelength, short pulse width (picosecond, nanosecond), and peak power, and is suitable for high-precision micro-machining fields, such as nanoparticle drilling and cutting of thin, brittle metals and non-metallic materials.

At the moment, most of the mainstream precision device board and pipeline-cutting equipment on the market use solid lasers, such as scientific research, medical processing, etc., especially in the medical field, it plays an important role in laser treatment, photodynamic therapy, and so on. However, China's development in the field of solid-state lasers started late, and there are fewer model enterprises. There is a significant gap between the domestic technical level and that of foreign countries. The high-end solid-state laser market is monopolized by foreign manufacturers, and the phenomenon of technical blockades and embargoes is serious, affecting the development of China's high-end manufacturing industry ^[7].

In summary, all kinds of lasers in high-power applications have shown unique advantages and challenges. With the continuous development of science and technology, the high power laser technology industry is still facing many challenges and opportunities.

4. Industrial development opportunities and challenges

4.1. Opportunities for industrial development

At present, the high-power laser technology industry is facing good development opportunities. On the one hand, the high-power laser market has good prospects for development. With the progress of science and technology,

high-power lasers have shown a wide range of application prospects in many fields. For example, in the field of manufacturing, it is used in material processing, precision manufacturing, and intelligent manufacturing, which can effectively improve the production efficiency of enterprises. In the medical field, it has been applied to laser therapy, photodynamic therapy, and other aspects to promote the innovation of medical technology. With the support of emerging industries such as new energy, the application fields of high power lasers are constantly expanding, and the market potential is huge. On the other hand, the international industrial situation accelerates the process of localization of lasers ^[8].

The change in the international industrial situation has provided a strong impetus for the localization process of high-power lasers, and domestic research institutions have strengthened the promotion of independent research, constantly breaking the international monopoly, promoting the localization of laser core materials and devices, and improving the core competitiveness of products. In addition, the support and guidance of national policies also provide a strong guarantee for the localization process of high-power lasers, and provide more development opportunities for domestic enterprises ^[9].

4.2. Industrial development challenges

Although China's high-power laser technology has made remarkable progress, it still faces several challenges. For example, the level of engineering technology requires further improvement, particularly in effectively controlling thermal effects and light damage during high-power output, as well as enhancing the stability and reliability of lasers. Additionally, optimizing the structure and design of lasers to reduce costs and improve production efficiency remains a priority. Since the development of engineering technology in China started relatively late, the adaptability of computer numerical control (CNC) systems and laser coordination during actual use also needs enhancement. These challenges require further research, development, and innovation to overcome ^[10].

5. High-power laser technology industry development suggestions

5.1. Strengthen research on key technologies and overcome difficulties in key materials and devices

In the process of industrial development, it is essential to prioritize the research, development, and innovation of key technologies to overcome challenges related to critical materials and devices. The core of high-power laser technology lies in high-performance materials and devices, necessitating efforts to address the technical and process challenges of industrializing pump semiconductor lasers, as well as resolving bottlenecks in high-performance artificial crystals, fibers, and other key materials. Strengthening research on critical materials and devices for high-power lasers, combining independent innovation with international cooperation, is crucial to overcoming these challenges swiftly.

For example, organizing cross-disciplinary research teams involving scientific research institutions, relevant departments, and enterprises can help tackle the challenges of key technologies and materials for high-power laser devices. Additionally, promoting international scientific and technological cooperation, learning from advanced international experiences and achievements, and enhancing the global competitiveness of China's high-power laser technology are vital steps forward ^[11].

The government and enterprises should increase the investment in the research and development of the key technologies of high-power laser, provide adequate financial support and policy guarantee, encourage scientific research institutions and enterprises to carry out long-term and stable cooperative research, achieve engineering

and industrialization, and ensure the independent production of key materials and devices.

5.2. Promote industry-university-research collaboration and promote the transformation of scientific and technological achievements

To promote the transformation and application of scientific research results and help industrial upgrading, relevant departments should actively carry out industry-university-research collaboration, break down barriers between scientific research, education, and industry, promote close cooperation among scientific research institutions, higher education institutions and enterprises, build a resource sharing system, and promote the transformation and application of scientific research results. Focusing on the technical dilemma of a high-power laser, scientific research institutions and institutions of higher learning should strengthen the promotion of cooperative research and development, the use of advanced experimental equipment and rich scientific research personnel, and constantly promote technological innovation and breakthroughs. Enterprises should assist and participate, combined with market demand and practical application scenarios, and promote the transformation of scientific and technological achievements into products with market competitiveness ^[12].

The government should take the lead in building an industry-university-research cooperation platform, promote information sharing and technical exchanges between multiple entities, encourage collaboration between various departments, support outstanding enterprises to achieve technological research through industry, open up the upstream and downstream industrial chain, and promote the process of localization of high-power lasers. Scientific research institutions and enterprises carry out project cooperation, jointly undertake the task of scientific research projects and transformation of results, promote the rapid transformation and industrialization of scientific research results, and bring economic and social benefits to enterprises ^[13].

The government should introduce relevant policies to support and incentivize industry-university-research collaboration and the transformation of scientific and technological achievements, such as providing research funding subsidies, tax incentives, and intellectual property rights protection, to stimulate the enthusiasm and creativity of all parties. In the whole process of research and development, talent is the first element. All parties should participate in the cultivation of talents, cultivate high-quality talents with innovative ability and practical experience, and promote the updating of knowledge and the dissemination of technology through the flow of talents and academic exchanges, to promote industrial upgrading and economic development ^[14].

5.3. Improve domestic production lines and expand domestic market layout

At present, with the fierce competition in the global manufacturing industry, China has paid more attention to improving the technical level and market share of domestic equipment. High-performance and high-power laser and laser equipment is an important support of the advanced manufacturing industry, its localization process is of great significance for breaking foreign technology monopoly, reducing production costs, and improving industrial competitiveness. Therefore, the relevant departments should pay attention to improving the production line, expanding the domestic market layout, and accelerating the realization of high-performance high-power laser and laser equipment engineering.

Firstly, strengthen policy support. To achieve industrial goals, policy guidance and support are particularly critical. Government departments should introduce relevant policies to encourage laser processing manufacturers to give domestic lasers and equipment online verification opportunities, through the actual production and application to test its performance and stability, to promote the process of localization of laser equipment, for

domestic laser equipment to provide valuable practical experience and improvement direction. Policy support can stimulate the vitality of enterprise innovation, promote its continuous efforts in the field of technology research and development and product upgrading, and then make breakthroughs.

Secondly, we should strengthen the linkage between upstream and downstream research and development (R&D) enterprises. In the process of technology research and development, upstream and downstream enterprises should form a joint effort to build a good ecology of collaborative innovation. The actual needs of the downstream application field are an important guide for the research and development of lasers and equipment, and the adaptation of lasers and equipment to application scenarios should be improved under the guidance of actual application scenarios. Through the close cooperation of upstream and downstream enterprises, the research and development cycle of products can be shortened, and the transformation and application of technological achievements can be accelerated ^[15]. In this process, the relevant enterprises should strengthen the exchange and cooperation with international advanced technology, the introduction of absorption and innovation, and constantly improve the core competitiveness of domestic laser equipment.

Finally, strengthen the market promotion. In the promotion of technology, the relevant departments should increase the publicity of domestic laser equipment, and improve its visibility and influence in the industry. For example, hold product exhibitions, technical exchange meetings, and other activities, so that more users understand the advantages and characteristics of domestic laser equipment, to enhance their trust in domestic equipment and purchase intentions. Establish a perfect after-sales service system, to provide users with timely and professional technical support and maintenance services, to ensure the stable operation of equipment and the interests of users. In addition, with the development of emerging industries, as the application demand for high-power lasers in intelligent manufacturing, aerospace, new energy, and other fields continues to grow, relevant departments should pay attention to expanding the domestic market layout, applying high-power laser technology to more fields and scenarios, and helping the transformation and upgrading of related industries.

6. Conclusion

In summary, high-power laser technology is a key field of modern optoelectronics technology. Its development level is directly related to the competitiveness of related industries. Currently, the high-power laser technology industry has broad prospects for development. To promote its sustainable and healthy development, relevant departments and personnel need to strengthen research on key technologies and overcome difficulties in key materials and devices, promote industry-university-research collaboration to promote the transformation of scientific and technological achievements, and improve domestic production lines and expand domestic market layout, to constantly improve the layout of high-power industries.

Disclosure statement

The author declares no conflict of interest.

References

- [1] Chen X, Wang P, Deng C, 2022, Research on Artificial Intelligence Control Method of High-power Laser. *Laser Journal*, 2022(12): 221.

- [2] Mu R, Zhang J, Longjing Y, et al., 2022, Research on Spectral Combining Technology of High-power Laser. *Applied Optics*, 43(04): 792–797.
- [3] Li J, 2022, Research on All-Fiber Mid-Infrared High-power Laser Based On Fiber End Coating Technology, thesis, Xiamen University.
- [4] Li Q, Yang Y, Liu S, et al., 2013, Application of Phase Conjugation Technique to Compensate Dynamic Wavefront Aberrations in High-power Lasers. *Laser Journal*, 34(01): 7–8.
- [5] Jiaxiao X, 2023, Study on the Influence of Laser Thermal Effect on Beam Quality of LD End-Pumped Solid-State Laser, thesis, Xi'an University of Electronic Science and Technology.
- [6] Du W, 2023, Analytical Study of Heat Transfer Equation of Laser Medium in Solid-State Lasers, thesis, Xi'an Technological University.
- [7] Qiu H, 2023, Design of Ring Spot Optical System for Laser Cutting, thesis, Huazhong University of Science and Technology.
- [8] Feng Y, 2024, Study on Preparation of YF3 Coating Material for High-power Laser System, thesis, Beijing General Research Institute of Non-Ferrous Metals.
- [9] Chen Y, 2017, Research on Electro-Optically Modulated Q946nm Solid-State Pulsed Laser, thesis, Northwest University.
- [10] Li X, 2022, Mechanism of Near-Infrared Laser Irradiation of Carbon Fiber Composites and its Application in Processing, thesis, Nanjing University of Science and Technology.
- [11] Yao T, Fan C, Hao X, et al., 2019, Research Progress of Raman Fiber Laser Power Enhancement and Wavelength Expansion. *Chinese Journal of Lasers*, 51(19): 182–200.
- [12] Shi F, Zhang J, Cai Y, et al., 2024, Design of Data Acquisition and Transmission Module for Wireless Laser Power Meter. *Journal of Quantum Electronics*, 41(05): 752–760.
- [13] Yi H, Qi Y, Suo X, et al., 2023, Progress Analysis of High Energy Laser Calibration and Amplification Program in the United States. *Journal of Applied Optics*, 44(06): 1167–1176.
- [14] Zhu J, 2024, Fabrication and Technology of DFB Semiconductor Laser Grating Based on Femtosecond Laser Technology, thesis, Changchun University of Science and Technology.
- [15] Zhao J, 2023, Research on Driving Technology of High-power Semiconductor Laser, thesis, Xi'an Technological University.

Publisher's note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Differential Privacy-Enabled TextCNN for MOOCs Fake Review Detection

Caiyun Chen*

School of Information Science and Technology, Tan Kah Kee College, Xiamen University, Zhangzhou 363105, Fujian Province, China

*Corresponding author: Caiyun Chen, chency@xujc.com

Copyright: © 2025 Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY 4.0), permitting distribution and reproduction in any medium, provided the original work is cited.

Abstract: The rapid development and widespread adoption of massive open online courses (MOOCs) have indeed had a significant impact on China's education curriculum. However, the problem of fake reviews and ratings on the platform has seriously affected the authenticity of course evaluations and user trust, requiring effective anomaly detection techniques for screening. The textual characteristics of MOOCs reviews, such as varying lengths and diverse emotional tendencies, have brought complexity to text analysis. Traditional rule-based analysis methods are often inadequate in dealing with such unstructured data. We propose a Differential Privacy-Enabled Text Convolutional Neural Network (DP-TextCNN) framework, aiming to achieve high-precision identification of outliers in MOOCs course reviews and ratings while protecting user privacy. This framework leverages the advantages of Convolutional Neural Networks (CNN) in text feature extraction and combines differential privacy techniques. It balances data privacy protection with model performance by introducing controlled random noise during the data preprocessing stage. By embedding differential privacy into the model training process, we ensure the privacy security of the framework when handling sensitive data, while maintaining a high recognition accuracy. Experimental results indicate that the DP-TextCNN framework achieves an exceptional accuracy of over 95% in identifying fake reviews on the dataset, this outcome not only verifies the applicability of differential privacy techniques in TextCNN but also underscores its potential in handling sensitive educational data. Additionally, we analyze the specific impact of differential privacy parameters on framework performance, offering theoretical support and empirical analysis to strike an optimal balance between privacy protection and framework efficiency.

Keywords: DP-TextCNN; Differential Privacy; Fake review; MOOCs

Online publication: February 13, 2025

1. Introduction

Massive Open Online Courses (MOOCs) have become important online platforms for learners to acquire knowledge. The evaluation of course quality has become particularly critical, not only in terms of the diversity and complexity of evaluation objectives but also in terms of the fairness and reliability of the evaluation process ^[1,2].

Course reviews and ratings, as key indicators to measure teaching quality and student learning experience, play a core role in the educational evaluation system^[3]. In-depth analysis of course ratings and reviews through machine learning and natural language processing technology can more accurately reflect the course situation^[4,5]. Natural language processing technology plays an important role in analyzing student feedback, extracting keywords and topics, sentiment analysis, and evaluating teaching effectiveness^[6].

However, fake review and rating data pose challenges to the accuracy of course evaluations, which may be caused by malicious operations, system errors, or data entry errors^[7-9]. In addition, review and rating data usually contain sensitive personal information and learning preferences, which may lead to serious privacy risks if not protected^[10]. Thus, the critical issue is how to effectively detect fake reviews and ratings while ensuring privacy and security.

In recent years, Differential Privacy (DP), as a powerful privacy protection technology, has received widespread attention. It can maintain the statistical properties of data and the accuracy of analysis results while providing data privacy protection^[11]. Differential privacy effectively protects privacy by adding an appropriate amount of random noise to the data set^[12]. On the other hand, sentiment analysis and data mining based on machine learning can help detect fake reviews and ratings, identify overall evaluations and discover evaluation anomalies^[13]. In particular, Text Convolutional Neural Network (TextCNN), as an important model of deep learning in the field of text processing, has been widely used in natural language processing, sentiment analysis, etc^[14].

Given the advantages of differential privacy and Text CNN, we propose a Differential Privacy-Enabled Text Convolutional Neural Network (DP-TextCNN) model, aiming to effectively identify course fake reviews and ratings while ensuring the security of user privacy. This model introduces a differential privacy mechanism in the data processing to protect the privacy of the review data and uses the DP-TextCNN model to detect fake reviews on the processed data. Our research not only enriches the application of differential privacy in the field of deep learning but also provides a new perspective and method for detecting course fake reviews.

2. Related work

2.1. Course fake reviews detection

With the development of online education platforms, the fairness and accuracy of course reviews and rating systems have become core issues in ensuring educational quality^[15-17]. Sentiment analysis of course reviews can reflect the adaptability of teaching design, student satisfaction, and learning effectiveness^[18-20]. By integrating learning records, course reviews, and ratings, more accurate course recommendation strategies can be implemented to optimize the learning experience^[21]. Review analysis is an important factor in revealing learner preferences and course selection^[22]. Li *et al.* provided a powerful tool for deep mining course reviews through a data-driven framework^[23]. Onan's research showed that the performance of deep learning in sentiment analysis surpasses traditional methods and has great potential in educational data mining^[24]. Course reviews and rating analysis play an irreplaceable role in improving education quality and promoting educational equity.

Fake reviews and ratings significantly impact users' decision-making, distorting fair competition and eroding trust in online evaluation systems^[25]. The development of deep learning methods, especially TextCNN in the field of text processing, has brought improvements in accuracy and effectiveness to the detection of fake reviews and ratings^[26]. Jain and Pamula introduced a supervised learning framework to bolster detection capabilities^[27], while

Salminen *et al.* leveraged GPT to create fake samples and integrated them with classifiers for effective recognition^[28]. The TextCNN model, with its robust feature extraction and automated processing, has excelled in identifying fake reviews and ratings^[29–31]. By employing sophisticated convolutional and pooling layers, the model precisely captures key semantic content, facilitating accurate classification and identification^[32].

However, despite TextCNN's advancements in detection accuracy and efficiency, research on privacy protection in this domain remains scant. When handling reviews and ratings containing sensitive user data, such as preferences and learning habits, many detection methods overlook the risks of information leakage, posing severe threats to user privacy and security. Consequently, ensuring detection accuracy while strengthening privacy protection has emerged as a pivotal challenge requiring urgent resolution.

2.2. Differential Privacy protection and deep learning models

Differential Privacy (DP) is a privacy-preserving framework that ensures that the output of a data analysis is insensitive to small changes in the input dataset. This is achieved by adding carefully calibrated random noise to the results of queries or computations performed on the dataset^[33,34]. The integration of Differential Privacy protection technology with deep learning models has become increasingly popular, especially in scenarios where user privacy is a concern. By incorporating Differential Privacy into the training process of deep learning models, it is possible to add noise to the gradients or other parameters in a way that preserves the overall utility of the model while providing strong privacy guarantees^[35,36].

TextCNN is a powerful text-processing model that is effective in various natural language processing tasks, including sentiment analysis, text classification, etc. By incorporating differential privacy, we can enhance the privacy protection of user data while maintaining the model's performance^[37,38]. Adding differential privacy noise to the convolutional layer, pooling layer, or fully connected layer of TextCNN can help obscure the influence of individual data on the model's weights, thereby protecting user privacy. While there have been some studies on the combination of differential privacy and deep learning, the specific application of differential privacy to the task, of course, fake reviews and rating detection is still relatively underdeveloped^[39].

We aim to design a TextCNN model combined with differential privacy protection, refining the noise addition strategy to minimize the impact on model performance while protecting user privacy. Constructing a rigorous experimental framework and conducting systematic experiments, verifying the specific impact of differential privacy protection on the performance of the TextCNN model in detecting course fake reviews and ratings. Finding the balance between privacy protection and model performance, conducting extensive experiments, and fine-tuning the noise addition strategy to achieve optimal results.

3. Differential Privacy-Enabled TextCNN model

3.1. Data preprocessing and analysis

We have conducted an extensive collection of course reviews and rating data from various MOOCs spanning multiple disciplines, including law, engineering, computer science, education and teaching, economic management, natural sciences, foreign languages, literature, history and philosophy, psychology, medicine, and health, as well as art and design. To guarantee the quality of our data, we implemented a thorough initial cleanup process, which involved eliminating duplicate, invalid, or significantly erroneous records. These records encompassed null values, extreme rating values, logically inconsistent ratings, meaningless reviews (like “666666” or “hahaha”), and

reviews that were not directly related to the course content (such as “sofa” or “reference books”).

Furthermore, we ensured the consistency between ratings and reviews by identifying and correcting any abnormal data where ratings were mismatched with the sentiment expressed in the reviews, thereby enhancing the logical rigor and accuracy of our dataset (**Figure 1**). Following the data preprocessing stage, we successfully constructed a MOOCs course reviews and ratings dataset, which comprises 10,000 positive and negative reviews along with their corresponding ratings. To enhance the dataset’s compatibility with the DP-TextCNN model, we conducted text segmentation. Utilizing the jieba Chinese word segmentation tool, we precisely divided continuous text strings into individual word sequences. This step is crucial for ensuring that the model can effectively process and understand the textual data, ultimately improving its performance in analyzing and predicting the sentiment of the course reviews.

After data preprocessing, a MOOCs course reviews and ratings dataset containing 10,000 positive and negative reviews and ratings was constructed. We performed text segmentation to improve the applicability of the data to the DP-TextCNN model. With the help of the Chinese word segmentation tool jieba, continuous text strings were accurately segmented into independent word sequences.

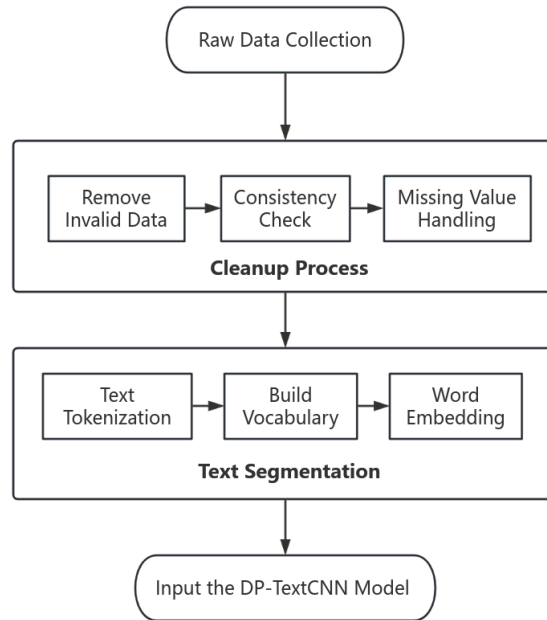


Figure 1. Data Cleaning and Transformation Process: the flowchart details the comprehensive steps involved in obtaining a high-quality dataset of reviews and ratings, starting from the raw data, through invalid record removal, consistency verification of ratings and reviews, and missing data processing

After word segmentation, we further refined the dataset by removing stop words and other invalid terms. This step significantly reduced the redundant information that the model needed to process and effectively decreased the dimensionality of the feature space. Subsequently, we established a comprehensive vocabulary and mapped each word into a fixed-dimensional vector space using word embedding techniques.

3.2. Differential Privacy protection technology

To safeguard data privacy while preserving the detection capabilities of the TextCNN model, we incorporate

differential privacy protection technology into its framework. Differential privacy minimizes the risk of information leakage from the training data by introducing noise and restricting gradient updates^[12]. By adding random noise to the data, differential privacy ensures that the model's output remains indistinguishable regardless of whether a specific sample is present in the dataset^[40].

(1) Gradient clipping: Gradient clipping using the L2 norm involves comparing the L2 norm (the Euclidean norm or magnitude) of the gradient vector with a predefined clipping threshold. If the L2 norm of the gradient exceeds this threshold, the gradient vector is scaled down proportionally so that its L2 norm equals the clipping threshold. This step ensures that the magnitude of the gradient update does not exceed a certain limit, thereby preventing potentially destabilizing large updates during model training. By applying this clipping operation, we limit the impact of individual training samples on the model's learning process, leading to a more stable and robust training experience. As shown in **Equation (1)**, the gradient is a vector representing the gradient calculated during model training, and `l2_norm_clip` is a scalar representing the threshold for gradient clipping. Compare the L2 norm of the gradient with a preset clipping threshold (`l2_norm_clip`). If the L2 norm of the gradient exceeds this threshold, it is scaled to be equal to the threshold.

$$\text{clipped_gradient} = \frac{\text{gradient}}{\max(1, \frac{\|\text{gradient}\|}{\text{l2_norm_clip}})} \quad (1)$$

(2) Adding noise: Adding Gaussian noise to the clipped gradient is a technique used to enhance privacy in model training, particularly in scenarios where protecting the confidentiality of training data is crucial. The noise is added to obscure the connection between gradient updates and specific training samples, thereby reducing the risk of information leakage. As shown in **Equation (2)**, where ϵ is a constant related to the privacy budget calculation, `noise_gradient` is a vector representing the gradient with Gaussian noise added, and `noise_multiplier` is used to control the amount of noise added to the gradient. The variance of the noise is proportional to the clipping threshold of the gradient and the privacy budget parameter (`noise_multiplier`). The addition of noise blurs the connection between gradient updates and specific training samples. Modify the gradients by adding appropriate Gaussian noise to allow model training without revealing too much information about data. Adjusting the values of `noise_multiplier`, `l2_norm_clip` and can find an appropriate balance between privacy protection and model performance.

$$\text{noisy_gradient} = \text{clipped_gradient} + \text{Gaussian_noise}(0, \text{noise_multiplier} \times \text{l2_norm_clip} \times \sigma) \quad (2)$$

3.2. DP-TextCNN model

The DP-TextCNN model is a Differential Privacy-Enabled TextCNN model designed for detecting course fake reviews and ratings^[40]. It converts the input integer index into high-dimensional dense vector representations via an embedding layer, effectively mapping the information into a vector space. Subsequently, the model employs multiple one-dimensional convolutional layers with varying convolution kernel sizes to extract local features from the input sequence. These convolutional layers are capable of capturing contextual information of different lengths, thereby enriching the model's feature representation capabilities. To reduce the feature dimension while retaining the most crucial information, the model applies a global max pooling layer after each convolutional layer. Global maximum pooling achieves feature dimensionality reduction by selecting the maximum value on each feature map. This process not only minimizes computational complexity but also enhances the model's generalization capabilities. During the training process, the model incorporates differential privacy technology to ensure model performance while bolstering data privacy protection. It utilizes a differential privacy-compatible optimizer,

such as DPKerasSGDOptimizer, which considers the allocation of privacy budget when adding Gaussian noise to the model gradient. By adjusting the noise intensity and the privacy budget threshold, the model can restrict information leakage, thereby providing robust privacy protection (**Figure 2**).

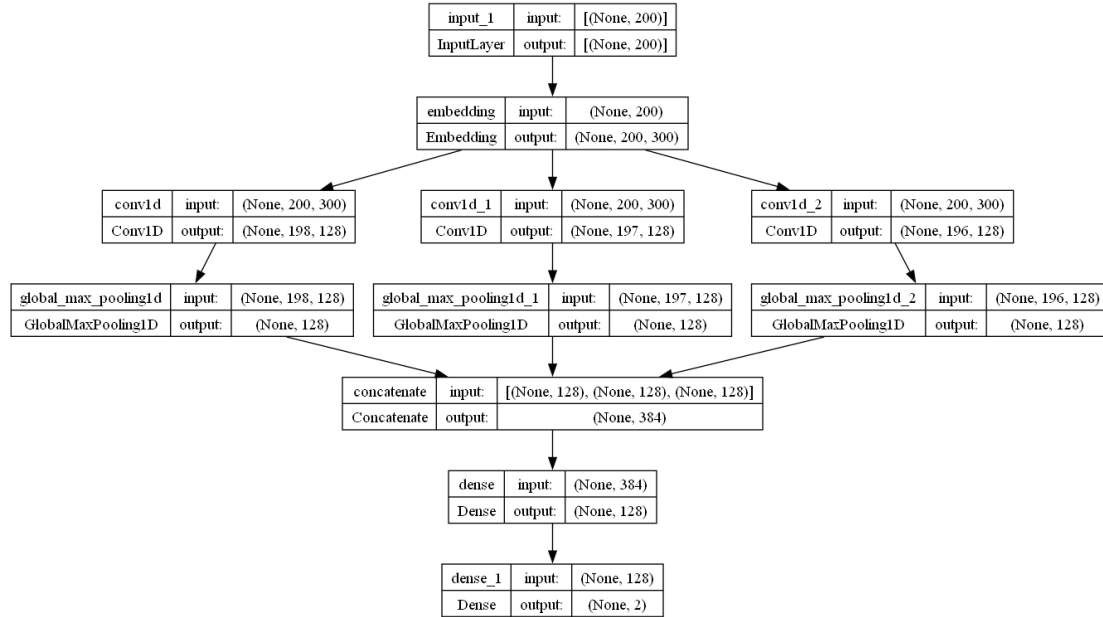


Figure 2. Structure of the DP-TextCNN Model, including the input layer, convolution layer, pooling layer, fully connected layer, as well as the connection methods and parameter settings between each layer

3.3. DP-TextCNN model

The training of the DP-textCNN model focuses on enhancing its performance in text classification tasks by iteratively adjusting its parameters. Initially, the model's weights are randomly initialized. Subsequently, the training data is fed into the model, which undergoes a series of transformations and processing steps. To assess the model's performance and update its parameters, a loss function is employed to quantify the discrepancy between the predicted and actual labels. The backpropagation algorithm is activated to efficiently compute the gradient of the loss function concerning the model parameters. This gradient information guides the optimization process, indicating how the model parameters should be adjusted to minimize losses and enhance performance.

The differential privacy SGD optimizer leverages gradient information to update model parameters while ensuring training efficiency and data privacy. It achieves this by incorporating gradient clipping and adding noise. The model parameters are updated in each epoch, and the training process is closely monitored to prevent overfitting. Both the training set and validation set are evaluated for loss and accuracy (**Figure 3**).

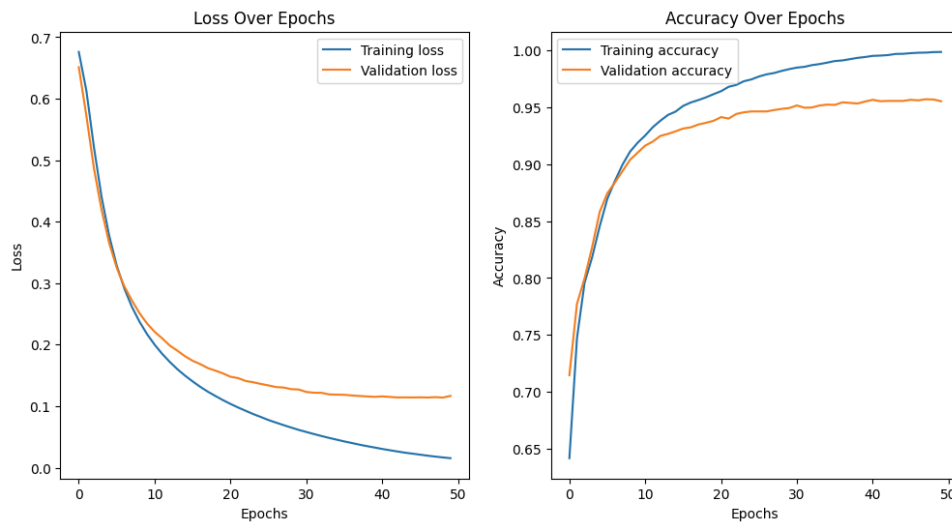


Figure 3. Loss function and recognition rate of different epochs, as the number of training epochs increases, the loss on the training set decreases, and accuracy improves until the training epoch reaches 30, which suggests that the model has begun to overfit

4. Results and analysis

We evaluated the DP-TextCNN model on a test dataset comprising fake reviews and ratings of courses across multiple disciplines on a MOOCs platform. This dataset encompasses diverse review information and is designed to assess the model's performance in fake review classification. The results show that the DP-TextCNN model demonstrates exceptional performance on this dataset, achieving an accuracy rate for fake review classification exceeding 95% (**Figure 4**).

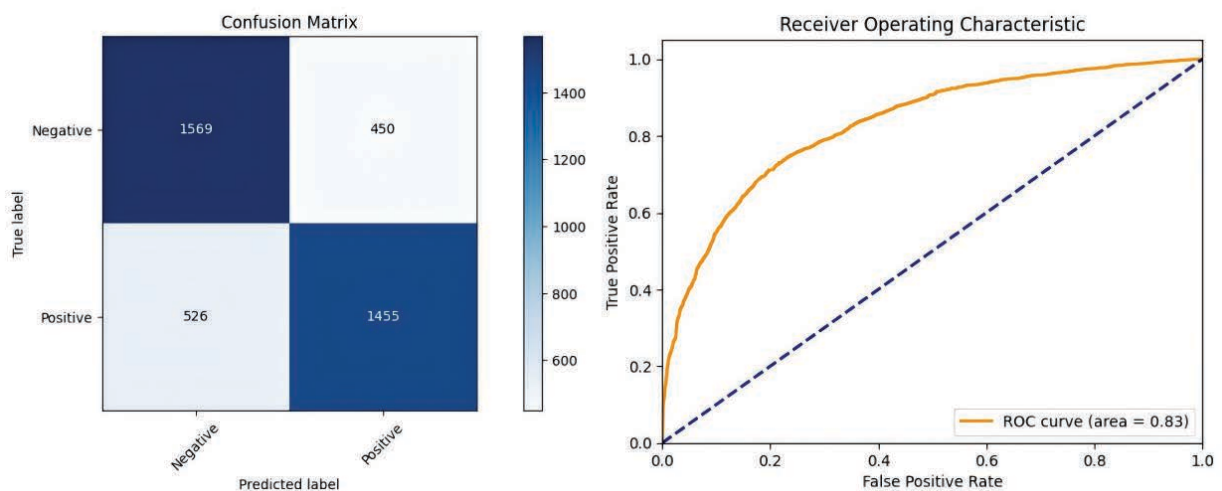


Figure 4. The Confusion Matrix and ROC of the DP-TextCNN model, the proportions of false positives (FP) and false negatives (FN) are relatively low, indicating a minimal misjudgment rate by the model. The Receiver Operating Characteristic (ROC) curve of the DP-TextCNN model closely aligns with the upper left corner, signifying high sensitivity and specificity in classifying fake reviews and ratings

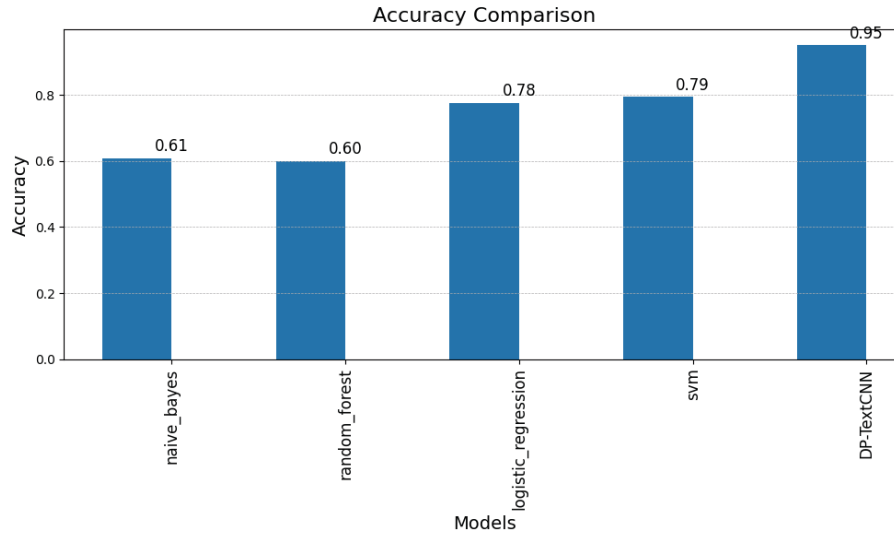


Figure 5. Comparison of accuracy among different models, including Naive Bayes, Random Forest, Logistic Regression, and Support Vector Machine (SVM).

We conducted a comparative analysis of various machine learning and deep learning models, as shown in **Figure 5**. In text classification tasks, the Random Forest’s effectiveness is limited by the quality of features and its capacity to capture interactions among complex text features. Logistic Regression exhibits relatively limited classification capabilities when dealing with text data characterized by nonlinear relationships. SVM incurs high training costs for large-scale text datasets and struggles to capture the intricate structure of text data. In contrast, DP-TextCNN excels at extracting high-level features from text data, capturing dependencies and semantic information within the text. It performs exceptionally well when processing large-scale, high-dimensional text datasets. While maintaining a high classification accuracy, DP-TextCNN incorporates differential privacy protection to safeguard the privacy of data processing. Experimental results demonstrate that DP-TextCNN achieves a classification accuracy of over 95%, surpassing other comparison models. DP-TextCNN exhibits superior classification performance and robustness in the task of identifying course fake reviews and ratings.

5. Conclusion

We proposed a DP-TextCNN model based on differential privacy protection for data privacy protection of course fake reviews and ratings classification on online MOOCs platforms. This model integrates the robust feature extraction capabilities of TextCNN with differential privacy protection, ensuring efficient classification of fake course reviews and ratings while preserving data privacy. Experimental results show that DP-TextCNN achieves a fake review classification accuracy of over 95% on a dataset comprising course reviews across multiple disciplines on the MOOCs platform, outperforming traditional methods.

Our work not only validates the application of differential privacy within the DP-TextCNN model framework but also opens up possibilities for establishing a fair evaluation system on online education platforms. Looking ahead, it is imperative to refine the implementation of differential privacy to strike an optimal balance between privacy protection and model performance. Additionally, we aim to explore the fusion of differential privacy with other privacy protection technologies and broaden the application of the DP-TextCNN model to new domains.

Disclosure statement

The author declares no conflict of interest.

References

- [1] Wei X, Saab N, Admiraal W, 2021, Assessment of Cognitive, Behavioral, and Affective Learning Outcomes in Massive Open Online Courses: A Systematic Literature Review. *Computers & Education*, 163: 104097.
- [2] Wu B, 2021, Influence of MOOC Learners Discussion Forum Social Interactions on Online Reviews of MOOC. *Education and Information Technologies*, 26: 3483–3496.
- [3] Alturkistani A, Lam C, Foley K, et al., 2020, Massive Open Online Course Evaluation Methods: Systematic Review. *Journal of Medical Internet Research*, 22: e13851.
- [4] Alger W, Doan M, Caporusso N, 2024, Student Evaluations of Teaching: Using Big Data Visualization to Explore Challenges and Opportunities. In *Proceedings of the 2024 47th MIPRO ICT and Electronics Convention (MIPRO)*, IEEE, 2024: 508–513.
- [5] Soheli A, Hossain MR, Mostofa ZB, et al., 2023, Sentiment Analysis Based on Online Course Feedback Using Textblob and Machine Learning Techniques. In *Proceedings of the 2023 26th International Conference on Computer and Information Technology (ICCIT)*, IEEE, 2023: 1–6.
- [6] Shaik T, Tao X, Li Y, et al., 2022, A Review of the Trends and Challenges in Adopting Natural Language Processing Methods for Education Feedback Analysis. *IEEE Access*, 10: 56720–56739.
- [7] Alexandron G, Ruipérez-Valiente JA, Lee S, et al., 2018, Evaluating the Robustness of Learning Analytics Results Against Fake Learners. In *Proceedings of the European Conference on Technology Enhanced Learning*, Springer, 2018: 74–87.
- [8] Graf P, 2024, Making Sense of Today's Use of Student Evaluations of Teaching (SET). *Human Arenas* 7: 446–450.
- [9] Paul H, Nikolaev A, 2021, Fake Review Detection on Online E-Commerce Platforms: A Systematic Literature Review. *Data Mining and Knowledge Discovery*, 35: 1830–1881.
- [10] Zigomitros A, Casino F, Solanas A, 2020, et al., 2020, Survey on Privacy Properties for Data Publishing of Relational Data. *IEEE Access*, 8: 51071–51099.
- [11] Qin Y, Li M, Zhu J, 2023, Privacy-Preserving Federated Learning Framework in Multimedia Courses Recommendation. *Wireless Networks*, 29: 1535–1544.
- [12] Dong J, Roth A, Su WJ, 2022, Gaussian Differential Privacy. *Journal of the Royal Statistical Society: Series B (Statistical Methodology)*, 84: 3–37.
- [13] Shaik T, Tao X, Dann C, et al., 2023, Sentiment Analysis and Opinion Mining on Educational Data: A Survey. *Natural Language Processing Journal*, 2: 100003.
- [14] Zhang T, You F, 2021, Research on Short Text Classification Based on Textcnn. In *Proceedings of the Journal of Physics: Conference Series*. IOP Publishing, 1757: 012092.
- [15] Moore RL, Blackmon SJ, 2022, From the Learner's Perspective: A Systematic Review of MOOC Learner Experiences (2008–2021). *Computers & Education*, 190: 104596.
- [16] Peng X, Xu Q, 2020, Investigating Learners' Behaviors and Discourse Content in MOOC Course Reviews. *Computers & Education*, 143: 103673.
- [17] Qi C, Liu S, 2021, Evaluating On-Line Courses via Reviews Mining. *Ieee Access*, 9: 35439–35451.
- [18] Bulusu A, Rao KR, 2021, Sentiment Analysis of Learner Reviews to Improve Efficacy of Massive Open Online Courses (MOOC's)—A survey. In *Proceedings of the 2021 Fifth International Conference on I-SMAC (IoT in Social,*

Mobile, Analytics and Cloud) (I-SMAC), IEEE, 2021: 933–941.

- [19] Kastrati Z, Imran AS, Kurti A, 2020, Weakly Supervised Framework for Aspect-Based Sentiment Analysis on Students' Reviews of MOOCs. *IEEE Access*, 8: 106799–106810.
- [20] Yang P, Liu Y, Luo Y, et al., 2024, Text Mining and Multi-Attribute Decision-Making-Based Course Improvement in Massive Open Online Courses. *Applied Sciences*, 14: 3654.
- [21] Fan J, Jiang Y, Liu Y, et al., 2022, Interpretable MOOC Recommendation: A Multi-Attention Network for Personalized Learning Behavior Analysis. *Internet Research*, 32: 588–605.
- [22] Gomez MJ, Calderón M, Sánchez V, et al., 2022, Large Scale Analysis of Open MOOC Reviews to Support Learners' Course Selection. *Expert Systems with Applications*, 210: 118400.
- [23] Li H, Gu H, Hao X, et al., 2024, Data-Driven Analytics for Student Reviews in China's Higher Vocational Education MOOCs: A Quality Improvement Perspective. *Plos One*, 19: e0298675.
- [24] Onan A, 2021, Sentiment Analysis on Massive Open Online Course Evaluations: A Text Mining and Deep Learning Approach. *Computer Applications in Engineering Education*, 29: 572–589.
- [25] Wu Y, Ngai EW, Wu P, et al., 2020, Fake Online Reviews: Literature Review, Synthesis, and Directions for Future Research. *Decision Support Systems*, 132: 113280.
- [26] Mohawesh R, Xu S, Tran SN, et al., 2021, Fake Reviews Detection: A Survey. *Ieee Access*, 9: 65771–65802.
- [27] Jain PK, Pamula R, Srivastava G, 2021, A Systematic Literature Review on Machine Learning Applications for Consumer Sentiment Analysis Using Online Reviews. *Computer Science Review*, 41: 100413.
- [28] Salminen J, Kandpal C, Kamel AM, et al., 2022, Creating and Detecting Fake Reviews of Online Products. *Journal of Retailing and Consumer Services*, 64: 102771.
- [29] Chen X, Li Z, Zou D, et al., 2024, Leveraging Deep Learning for Classifying Learner-Generated Course Evaluation Texts. In *Proceedings of the International Conference on Blended Learning*. Springer, 2024: 311–321.
- [30] Wang J, Xie H, Au OTS, et al., 2020, Attention-Based CNN for Personalized Course Recommendations for MOOC Learners. In *Proceedings of the 2020 International Symposium on Educational Technology (ISET)*. IEEE, 2020: 180–184.
- [31] Liu T, Hu W, Liu F, et al., 2021, Sentiment Analysis for MOOC Course Reviews. In *Proceedings of the Data Science: 7th International Conference of Pioneering Computer Scientists, Engineers and Educators, ICPCSEE 2021*, Springer, 2021: 78–87.
- [32] Liu J, Yan Z, Chen S, et al., 2023, Channel Attention TextCNN with Feature Word Extraction for Chinese Sentiment Analysis. *ACM Transactions on Asian and Low-Resource Language Information Processing*, 22: 1–23.
- [33] Bu Z, Dong J, Long Q, et al., 2020, Deep Learning with Gaussian Differential Privacy. *Harvard Data Science Review*, 2(3).
- [34] Ha T, Dang TK, Le H, 2020, Security and Privacy Issues in Deep Learning: A Brief Review. *SN Computer Science*, 1: 253.
- [35] Boulemtafes A, Derhab A, Challal Y, 2020, A Review of Privacy-Preserving Techniques for Deep Learning. *Neurocomputing*, 384: 21–45.
- [36] Doleck T, Lemay DJ, Basnet RB, et al., 2020, Predictive Analytics in Education: A Comparison of Deep Learning Frameworks. *Education and Information Technologies*, 25: 1951–1963.
- [37] Ghazi B, Golowich N, Kumar R, et al., 2021, Deep Learning with Label Differential Privacy. *Advances in Neural Information Processing Systems*, 34: 27131–27145.
- [38] Vasa J, Thakkar A, 2023, Deep Learning: Differential Privacy Preservation in the Era of Big Data. *Journal of*

Computer Information Systems, 63: 608–631.

- [39] Liu G, Sun X, Li Y, et al., 2023, An Automatic Privacy-Aware Framework for Text Data in Online Social Network Based on a Multi-Deep Learning Model. *International Journal of Intelligent Systems*, 2023: 1727285.
- [40] Dong M, Li Y, Tang X, et al., 2020, Variable Convolution and Pooling Convolutional Neural Network for Text Sentiment Classification. *IEEE access*, 8: 16174–16186.

Publisher's note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

U-Net-Based Medical Image Segmentation: A Comprehensive Analysis and Performance Review

Aliyu Abdulfatah^{1*}, Zhang Sheng¹, Yirga Eyasu Tenawerk¹

¹School of Information Engineering, Nanchang Hangkong University, Nanchang, 330063, China

*Corresponding author: Aliyu Abdulfatah, Abdulfatahaliyu77@gmail.com

Copyright: © 2025 Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY 4.0), permitting distribution and reproduction in any medium, provided the original work is cited.

Abstract: Medical image segmentation has become a cornerstone for many healthcare applications, allowing for the automated extraction of critical information from images such as Computed Tomography (CT) scans, Magnetic Resonance Imaging (MRIs), and X-rays. The introduction of U-Net in 2015 has significantly advanced segmentation capabilities, especially for small datasets commonly found in medical imaging. Since then, various modifications to the original U-Net architecture have been proposed to enhance segmentation accuracy and tackle challenges like class imbalance, data scarcity, and multi-modal image processing. This paper provides a detailed review and comparison of several U-Net-based architectures, focusing on their effectiveness in medical image segmentation tasks. We evaluate performance metrics such as Dice Similarity Coefficient (DSC) and Intersection over Union (IoU) across different U-Net variants including HmsU-Net, CrossU-Net, mResU-Net, and others. Our results indicate that architectural enhancements such as transformers, attention mechanisms, and residual connections improve segmentation performance across diverse medical imaging applications, including tumor detection, organ segmentation, and lesion identification. The study also identifies current challenges in the field, including data variability, limited dataset sizes, and issues with class imbalance. Based on these findings, the paper suggests potential future directions for improving the robustness and clinical applicability of U-Net-based models in medical image segmentation.

Keywords: U-Net architecture; Medical image segmentation; DSC; IoU; Transformer-based segmentation

Online publication: February 13, 2025

1. Introduction

Medical image segmentation plays a crucial role in enabling automated diagnosis and treatment planning in the healthcare industry^[1]. With the advent of deep learning, especially convolutional neural networks (CNNs), the segmentation process has become more efficient and accurate^[2]. One of the key architectures that has been widely adopted in medical imaging is U-Net, introduced by Ronneberger *et al.* in 2015^[3]. U-Net revolutionized the field with its encoder-decoder architecture, where skip connections link the encoder and decoder layers, facilitating

precise segmentation with fewer annotated samples ^[4].

Despite the success of the original U-Net, several challenges remain, such as class imbalance, the need for multi-modal data processing, and the integration of global and local image features ^[5]. To address these issues, researchers have proposed several enhanced versions of U-Net. These variants include HmsU-Net, which integrates transformers for better feature extraction, CrossU-Net, which uses a cross-attention mechanism to handle multi-modal data, and mResU-Net, which incorporates residual connections for improved feature propagation.

The primary aim of this paper is to systematically review these U-Net variants, assess their performance across different medical image segmentation tasks, and provide a comparative analysis of their strengths and weaknesses ^[6]. The study also highlights potential areas for further improvement in U-Net-based architectures to enhance clinical applicability.

2. Related work

Over the last few years, significant progress has been made in the field of medical image segmentation, particularly with the development of U-Net-based models. These architectures have been adopted for various applications, including brain tumor segmentation, liver segmentation, and even lesion detection in gastric cancer ^[7].

2.1. U-Net architecture

The original U-Net architecture consists of two main parts: the contracting path (encoder) and the expansive path (decoder) ^[8]. The contracting path follows the typical architecture of a convolutional network, with each step progressively reducing the spatial dimensions of the feature maps. The expansive path then increases the spatial dimensions, aiming to generate pixel-wise predictions for segmentation. Crucially, skip connections between the encoder and decoder layers help retain fine-grained spatial information, allowing U-Net to achieve high segmentation accuracy, even with relatively small datasets ^[9].

2.2. U-Net variants and enhancements

Numerous improvements to the original U-Net architecture have been proposed to address specific challenges in medical image segmentation.

- (1) HmsU-Net: This variant incorporates transformers alongside convolutional layers to capture both local and global features. The inclusion of a hybrid CNN-transformer model enhances the model's ability to focus on both fine details and broader patterns in images. This approach has been shown to improve segmentation accuracy in brain tumor and liver segmentation tasks ^[10].
- (2) CrossU-Net: CrossU-Net introduces a cross-attention mechanism, making it particularly effective for multi-modal segmentation tasks, such as the identification of gastric cancer lesions. By leveraging information from different image modalities, CrossU-Net can more accurately segment structures in complex multi-modal datasets ^[11].
- (3) mResU-Net: The mResU-Net model adds residual connections and channel attention mechanisms, improving the flow of information through the network and ensuring that relevant features are prioritized during segmentation. These modifications have led to significant improvements in segmentation accuracy, particularly in the segmentation of brain tumors and other small lesions ^[12].

2.3. Performance metrics

The key metric used for evaluating the performance of medical image segmentation models is the DSC, which measures the overlap between the predicted segmentation and the ground truth. Another important metric is IoU, which quantifies the overlap between predicted and true regions. Both metrics provide insight into the model's ability to accurately delineate regions of interest ^[13].

3. Methodology

3.1. Systematic review approach

This study follows a systematic review methodology to assess and compare the performance of U-Net and its variants in medical image segmentation tasks. We performed a comprehensive literature search across databases such as PubMed, IEEE Xplore, and Scopus using keywords such as “U-Net,” “medical image segmentation,” and “deep learning.” The search was limited to studies published from 2015 to 2024, ensuring that we captured the most recent advancements ^[14].

3.2. Inclusion and exclusion criteria

- (1) Inclusion: Studies that evaluate U-Net and its variants in medical image segmentation tasks, published in English, and provide quantitative performance metrics (e.g., DSC, IoU).
- (2) Exclusion: Studies that lack original research, non-English publications, and editorials.

3.3. Performance metrics

We evaluate the performance of each model variant using the following metrics.

$$DSC = \frac{2 \times |A \cap B|}{|A| + |B|} \quad (1)$$

Where A represents the predicted segmentation. B represents the ground truth segmentation.

The DSC measures the overlap between the predicted and actual segmentations, with values closer to 1 indicating better segmentation accuracy.

$$IOU = \frac{|A \cap B|}{|A \cup B|} \quad (2)$$

IoU evaluates the ratio of the intersection to the union of the predicted and ground truth regions, making it effective for assessing overlap precision.

4. Results and discussion

4.1. Performance of U-Net variants

We compiled the performance results of various U-Net variants across different medical image segmentation tasks. The results are summarized in **Table 1**, which shows the Dice Similarity (DSC) for each variant across several segmentation tasks, including brain tumor, liver, pancreas, gastric lesions, and tympanic membrane segmentation.

Table 1 Performance of U-Net variants

Model variant	Brain tumor	Liver	Pancreas	Gastric lesions	Tympanic membrane	Left ventricle
U-Net (Original)	0.85–0.90	0.88	0.91	0.90	0.88	0.92
HmsU-Net	0.92–0.95	0.91	0.92	0.96	0.91	0.95
CrossU-Net	0.91–0.96	0.91	0.91	0.96	0.92	0.93
mResU-Net	0.92–0.93	0.92	0.92	0.91	0.90	0.94
3D U-Net	0.86–0.88	0.87	0.88	0.88	0.85	0.89
EAR-U-Net	0.92	0.91	0.90	0.92	0.93	0.92
MFP-U-Net	0.95	0.93	0.94	0.95	0.94	0.95

4.2. Discussion of results

From **Table 1**, it is clear that HmsU-Net and CrossU-Net performed exceptionally well in multi-modal and complex tasks like brain tumor and gastric lesion segmentation, with DSC values reaching up to 0.96. mResU-Net, with its residual connections, provided solid performance across multiple tasks, particularly in brain tumor segmentation, where the model was able to achieve a DSC value of 0.93. The following formulas help with measurements.

Measures the proportion of correctly predicted positives

$$Precision = \frac{TruePositives(TP)}{TP + FalsePositives(FP)} \quad (3)$$

Measures the proportion of actual positives correctly predicted

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

Harmonic mean of precision and recall, used for imbalanced datasets

$$F1 = 2 \times \frac{Precision \times Recall}{Precision + Recall} \quad (5)$$

Measures the proportion of correctly predicted negatives

$$Specificity = \frac{TrueNegatives(TN)}{TN + FalsePositives(FP)} \quad (6)$$

Measures overall correctness of predictions

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN} \quad (7)$$

4.3. Performance of CrossU-Net across medical imaging applications

The CrossU-Net architecture, which integrates a cross-attention mechanism for better multi-modal learning, was evaluated across several medical imaging applications. This variant showed significant improvements in tasks such as precancerous lesion detection in gastric cancer and brain tumor segmentation.

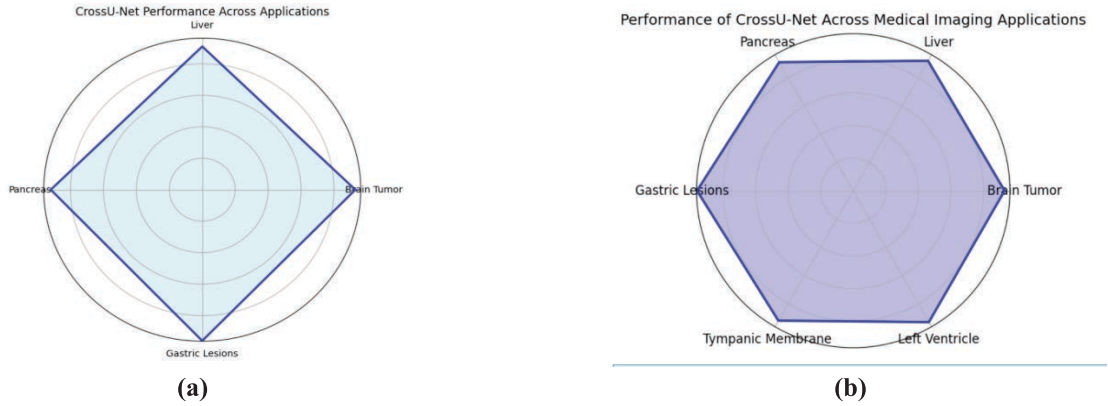


Figure 1. (a) CrossU-Net performance across applications, (b) CrossU-Net performance across medical imaging applications

Figure 2 visually represents the performance of CrossU-Net across different medical imaging tasks, highlighting its strength in dealing with multi-modal data. The model demonstrated superior results in gastric lesion segmentation with a DSC of 0.96, outperforming other U-Net variants. CrossU-Net also exhibited high performance in brain tumor and pancreatic tumor segmentation, with DSC values of 0.91–0.94. The details of **Figure 2** are as follows.

- (1) X-Axis: Various medical imaging applications (e.g., Gastric Lesions, Brain Tumor, Pancreas Tumor, etc.)
- (2) Y-Axis: DSC value
- (3) Bars: Show the DSC values for CrossU-Net in each application

The CrossU-Net architecture excels in segmentation tasks where the combination of features from multiple modalities is critical. The cross-attention mechanism allows the network to focus on relevant features from each modality, thereby increasing the model’s robustness in these applications.

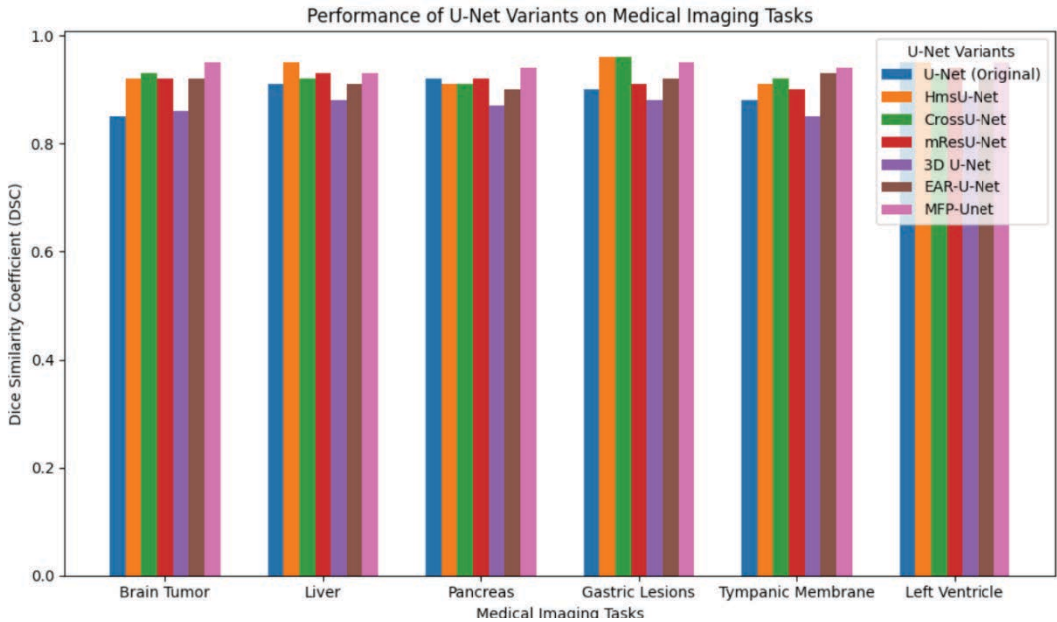


Figure 2. Performance bar chart

4.4. Discussion of CrossU-Net performance

From **Figure 1**, we can observe that CrossU-Net consistently outperforms other U-Net variants in multi-modal applications. The architecture's ability to handle complex data types—such as combining CT and MRI images for brain tumor segmentation—has been a key strength. This cross-attention mechanism enables the model to identify key features in one modality while aligning them with complementary features from another modality, enhancing overall segmentation performance.

Additionally, CrossU-Net achieved the highest performance in gastric cancer lesions, with a DSC of 0.96, which is a significant improvement over standard U-Net models. This demonstrates the potential of CrossU-Net in handling clinical applications where accurate lesion detection is paramount.

5. Conclusion and future directions

5.1. Conclusion

This study systematically reviews the performance of various U-Net-based models in medical image segmentation tasks. Our results indicate that architectural modifications such as attention mechanisms, residual connections, and transformer integration offer substantial improvements in segmentation accuracy. HmsU-Net and CrossU-Net were found to be particularly effective for complex and multi-modal segmentation tasks.

5.2. Future directions

While U-Net-based models have made significant strides, challenges remain in improving generalization, handling class imbalance, and enhancing the models' ability to process multi-modal data effectively. Future research should explore hybrid models that combine U-Net with other advanced architectures such as Generative Adversarial Networks (GANs) or Graph Neural Networks (GNNs) for even more.

Disclosure statement

The authors declare no conflict of interest.

References

- [1] Razzak MI, Naz S, Zaib A, 2018, Deep Learning for Medical Image Processing: Overview, Challenges and the Future. *Classification in BioApps: Automation of Decision Making*, 2018: 323–350.
- [2] Guo Y, Liu Y, Georgiou T, et al., 2018, A Review of Semantic Segmentation Using Deep Neural Networks. *International Journal of Multimedia Information Retrieval*, 7: 87–93.
- [3] Ronneberger O, Fischer P, Brox T, 2015, U-net: Convolutional networks for Biomedical Image Segmentation. In *Medical Image Computing and Computer-Assisted Intervention–MICCAI 2015: 18th International Conference, Proceedings*, Springer International Publishing, part III, 18: 234–241.
- [4] Neha F, Bhati D, Shukla DK, et al., 2024, U-Net in Medical Image Segmentation: A Review of Its Applications Across Modalities. *arXiv preprint: arXiv:2412.02242*.
- [5] Punns NS, Agarwal S, 2022, Modality Specific U-Net Variants for Biomedical Image Segmentation: A Survey. *Artificial Intelligence Review*, 55(7): 5845–5889.
- [6] Taha AA, Hanbury A, 2015, Metrics for Evaluating 3D Medical Image Segmentation: Analysis, Selection, and

Tool. BMC Medical Imaging, 15: 1–28.

- [7] Hariharan S, Anandan D, Krishnamoorthy M, et al., 2025, Advancements in Liver Tumor Detection: A Comprehensive Review of Various Deep Learning Models. CMES-Computer Modeling in Engineering & Sciences, 142(1).
- [8] Siddique N, Paheding S, Elkin CP, et al., 2021, U-Net and its Variants for Medical Image Segmentation: A Review of Theory and Applications. IEEE Access, 9: 82031–82057.
- [9] Azad R, Aghdam EK, Rauland A, et al., 2024, Medical image segmentation review: The success of U-Net. IEEE Transactions on Pattern Analysis and Machine Intelligence. Eess.IV, 2022: arXiv:2211.14830v1.
- [10] Bilic P, Christ P, Li HB, et al., 2023, The Liver Tumor Segmentation Benchmark (LITS). Medical Image Analysis, 84: 102680.
- [11] Feng D, Haase-Schütz C, Rosenbaum L, et al., 2020, Deep Multi-Modal Object Detection and Semantic Segmentation for Autonomous Driving: Datasets, Methods, and Challenges. IEEE Transactions on Intelligent Transportation Systems, 22(3): 1341–1360.
- [12] Nalepa J, Marcinkiewicz M, Kawulok M, 2019, Data Augmentation for Brain-Tumor Segmentation: A Review. Frontiers in Computational Neuroscience, 13: 83.
- [13] Cheng B, Girshick R, Dollár P, et al., 2021, Boundary IoU: Improving Object-Centric Image Segmentation Evaluation. In Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition, 2021: 15334–15342.
- [14] Nandal N, Bordoloi D, Sanyal S, et al., 2024, Unlocking the Potential of Knowledge Management in Harnessing Technological Advancements for Design and Development. International Journal of Knowledge Management Studies, 15(2): 171–192.

Publisher's note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Design of Universal Platform Architecture for Complex Discrete Storage System

Yangyang Zhang, Haiting Xu, Dong Wang*, Bo Xu

Tianjin Institute of Aerospace Mechanical and Electrical Equipment, Tianjin 300000, China

*Corresponding author: Dong Wang, zyy199200@126.com

Copyright: © 2025 Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY 4.0), permitting distribution and reproduction in any medium, provided the original work is cited.

Abstract: The flexible satellite batch production line is a complex discrete production system with multiple cross-disciplinary fields and mixed serial parallel tasks. As the source of the satellite batch production line process, the warehousing system has urgent needs such as uncertain production scale and rapid iteration and optimization of business processes. Therefore, the requirements and architecture of complex discrete warehousing systems such as flexible satellite batch production lines are studied. The physical system of intelligent equipment is abstracted as a digital model to form the underlying module, and a digital fusion framework of “business domain + middleware platform + intelligent equipment information model” is constructed. The granularity of microservice splitting is calculated based on the dynamic correlation relationship between user access instances and database table structures. The general warehousing functions of the platform are divided to achieve module customization, addition, and configuration. An open discrete warehousing system based on microservices is designed. Software architecture and design develop complex discrete warehousing systems based on the SpringCloud framework. This architecture achieves the decoupling of business logic and physical hardware, enhances the maintainability and scalability of the system, and greatly improves the system’s adaptability to different complex discrete warehousing business scenarios.

Keywords: Satellite batch production line; Complex discrete production; Warehousing system; Architecture design; Flexibility; Microservices

Online publication: February 14, 2025

1. Introduction

In recent years, with the intensification of competition among aerospace powers, satellite mass production lines have become a key focus of research on high-speed satellite networking and production. The flexible satellite batch production line is a complex discrete production system that integrates multiple professional technical fields and involves a mixture of serial and parallel tasks. As the source of the production process, the warehousing system has urgent needs such as uncertain production scale, rapid iteration and optimization of business processes, high degree of customization, and short development cycle. It is urgent to design and package flexible warehousing

systems with business needs as the core, to achieve on-demand use and on-demand adaptation ^[1,2].

In response to the shortcomings of existing methods, this article studies the requirements and architecture of complex discrete warehousing systems such as flexible satellite batch production lines. Based on the idea of digital systems, the physical system of intelligent equipment is abstracted as a digital model to form the underlying module. The platform's warehousing general functions are segmented to achieve module customization, addition, and configuration. An open software architecture for an intelligent warehousing system based on microservices is designed. This architecture fully utilizes the flexibility and scalability of microservices, enabling the system to automatically configure according to changes in business requirements and enhance the generalization capability of the warehousing platform ^[3,4].

2. Architecture design

According to the organization and deployment structure of the system, the evolution process of software architecture can be roughly divided into the following stages: monolithic architecture, Service Oriented Architecture (SOA), and microservice architecture ^[6], as shown in **Table 1** for comparison. The monolithic architecture integrates all business logic and control logic into one program, which is suitable for all simple applications. As business becomes increasingly complex, a module failure can cause the entire system to crash. The vertical splitting of monolithic architecture has evolved into Service Oriented Architecture (SOA). The microservice architecture emphasizes componentization and servitization, with services that can interact and integrate with each other.

The flexible satellite batch production line is a highly integrated complex discrete production system, specialized in producing high-quality and high-precision complex products such as satellites. As the source of the satellite batch production line process, the warehousing system has challenges such as multiple varieties, small batches, and flexible production processes. It is required that the warehouse system architecture has good scalability and reconfigurability to flexibly respond to various demand changes. The modular, independent deployment and easy scalability advantages of microservice architecture can meet the requirements and become the best choice for flexible warehousing.

2.1. Standard information model

To cope with the continuous evolution of business processes and build a flexible warehousing system, there is an urgent need for an open and highly scalable business domain model. The objects that the current business model can describe are fixed and difficult to flexibly expand ^[5]. Therefore, a solution of “business domain + middleware platform + intelligent equipment information model” is proposed, as shown in **Figure 1**. At the same time, it can flexibly adjust and optimize the deployment of microservice architecture according to the actual scale and business complexity of the production line. The middleware platform is a bridge for information exchange between business domains and intelligent equipment. It digitizes the information model of intelligent equipment and interacts with business data to ensure unified and accurate data standards, providing support for subsequent traceability analysis and visual display, building a reusable and standardized intelligent equipment information model, solving the problems of diverse, non-open or non-standard communication protocols, and achieve interconnection and intercommunication of on-site devices ^[5,6].

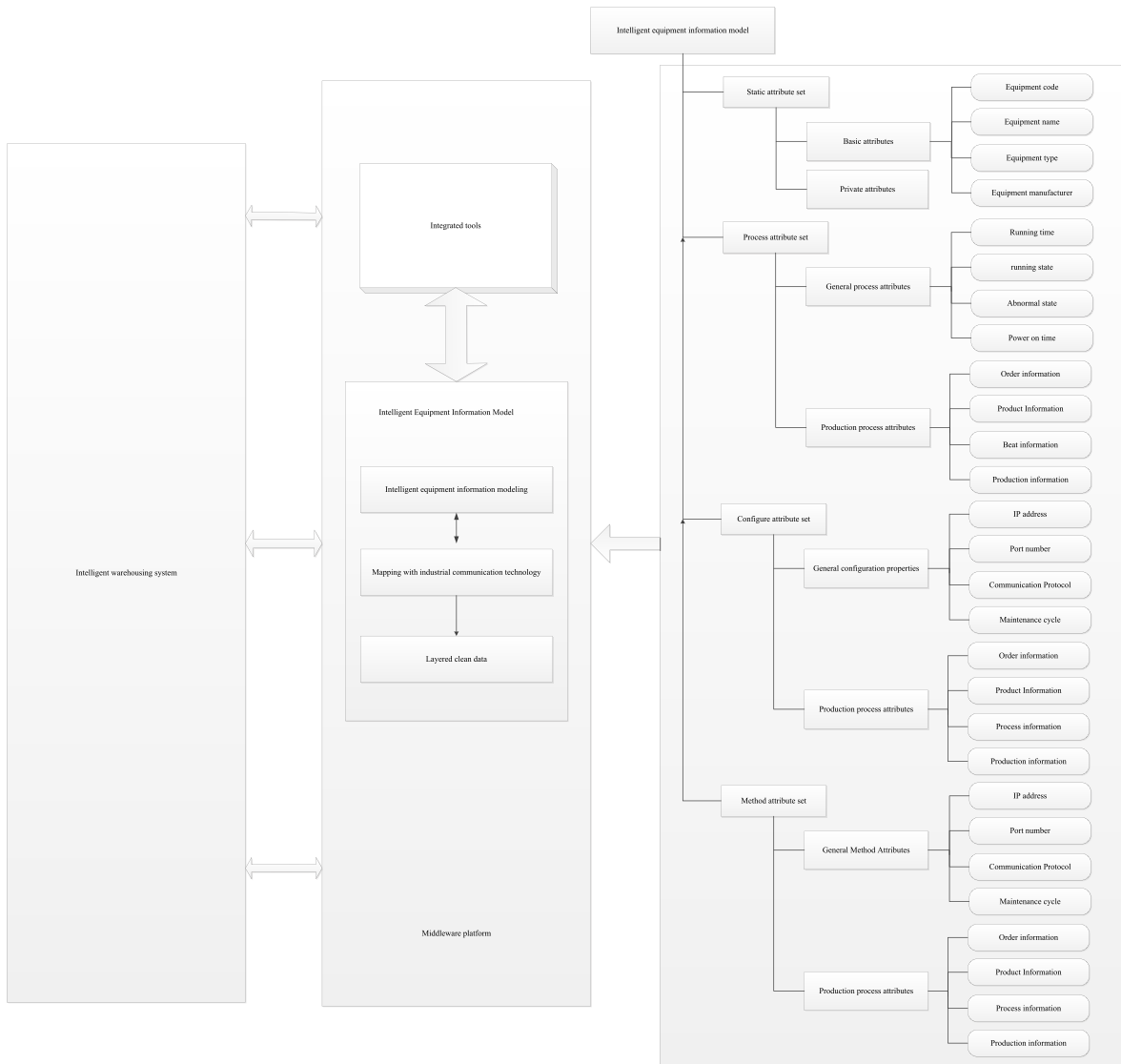


Figure 1. System standard model

2.2. Functional architecture design

The general platform for complex discrete warehousing systems realizes the management of inbound and outbound inventory for different warehouses, and can also adapt to changes in complex discrete scenarios. The functional architecture is shown in the following **Figure 2**. This platform has functions such as warehouse management, inventory management, report management, kanban management, basic information management, permission management, system configuration, and many more^[7].

It includes the equipment layer, data layer, business layer, interface layer, and upper layer applications. The equipment layer is composed of multiple intelligent devices, each of which is independent of the other. The device control layer mainly controls the actions of each device through protocols. The business layer consists of a middleware platform, a Warehouse Management System (WMS), and a monitoring display module. The middleware platform mainly completes the reception, parsing, decomposition, and process control of upstream system instructions, and distributes the decomposed instructions to various intelligent devices in sequence according to the process. At the same time, it completes functions such as different interfaces, data standardization,

and data collection, monitoring, and analysis for each intelligent device. The system configuration function of WMS includes a rule engine and process configuration. The rule engine includes coding rules, shelving rules, and picking rules, and supports custom configuration and extension. Process configuration can be used to configure processes such as receiving, acceptance, and shelving. The interface layer is responsible for integrated communication with upper-layer applications.

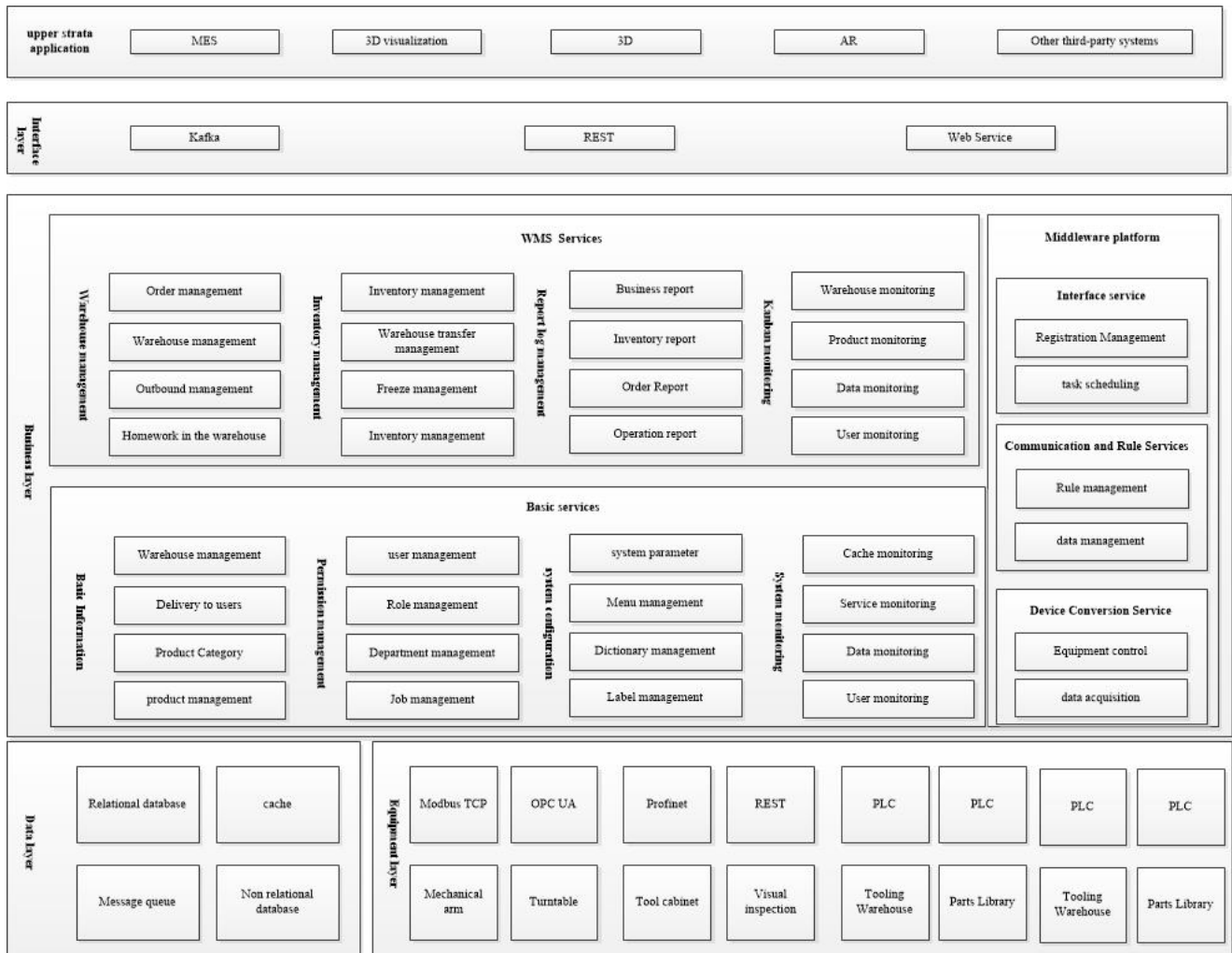


Figure 2. Function architecture

2.3. Microservice segmentation

According to the “business domain + middleware platform + intelligent equipment information model,” the middleware platform organizes services into four categories based on system scalability: interface services, device protocol conversion services, communication services, and rule services. Based on system reusability, services are divided into basic services and query services. Furthermore, based on business functions, services are categorized as inbound services, outbound services, and inventory services, as shown in **Figure 3**.

The interface service provides Representational State Transfer Application Programming Interface (REST API) and Kafka queue communication methods to communicate with upper-level application systems, and call device protocol conversion modules and business management modules according to the specific types of tasks ^[8]. The basic service is the fundamental data part of the middleware platform, and all operational data of the business is

based on the current module. Business data processing is carried out based on the data in this module. The device protocol conversion service includes a protocol adaptation and conversion engine, as well as a data unification engine. The protocol adaptation and conversion engine is based on the communication connection of multi-source heterogeneous devices. Simultaneously, the protocol can be converted into more universal Application Programming Interface (API) or Software Development Kit (SDK) interfaces, enabling compatibility with the scheduling and control of multi-source heterogeneous devices. The data unification engine processes JSON (JavaScript Object Notation) data parsed from the intelligent equipment information model and standardizes it into a unified format before pushing it to the message queue. Communication and rule services are the core components of middleware platforms. These services handle subscribing to incoming data from message queues and performing various processing and analysis tasks, including communication management, rule management, data analysis, alarm management, device predictive maintenance, and other critical functions.

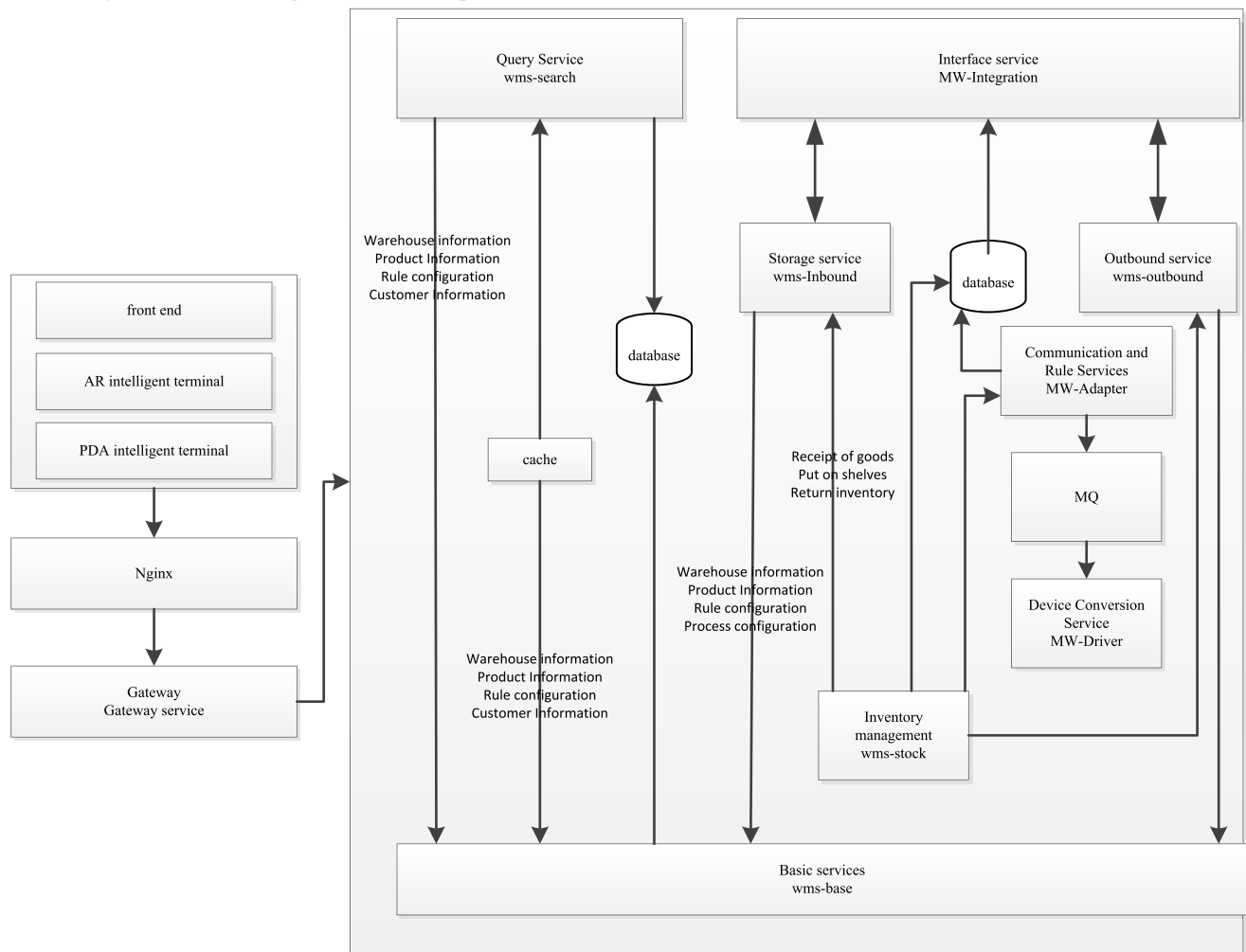


Figure 3. Microservice segmentation

3. System software design

3.1. Warehouse management

As a key link in the warehousing system, inventory management covers the entire process from generating inbound orders to updating inventory, ensuring efficient product warehousing, and real-time monitoring of

inventory status. **Figure 4** shows the operational process of the system's inbound business.

- (1) Inbound order management includes generating inbound orders, printing inbound orders, and storing inbound orders. The incoming order is imported into the system by the process personnel, and the incoming order is automatically generated, with detailed records of the incoming order number.
- (2) Inspection management conducts receiving and preliminary product inspections based on the inspection tasks generated from the incoming orders to prevent the storage of non-conforming products.
- (3) Shelf management will safely and efficiently place products that have passed inspection in designated storage locations, and update inventory information in real-time. The system intelligently recommends or manually allocates shelf locations, and the recommended shelf locations are allocated according to the preset shelf strategy.

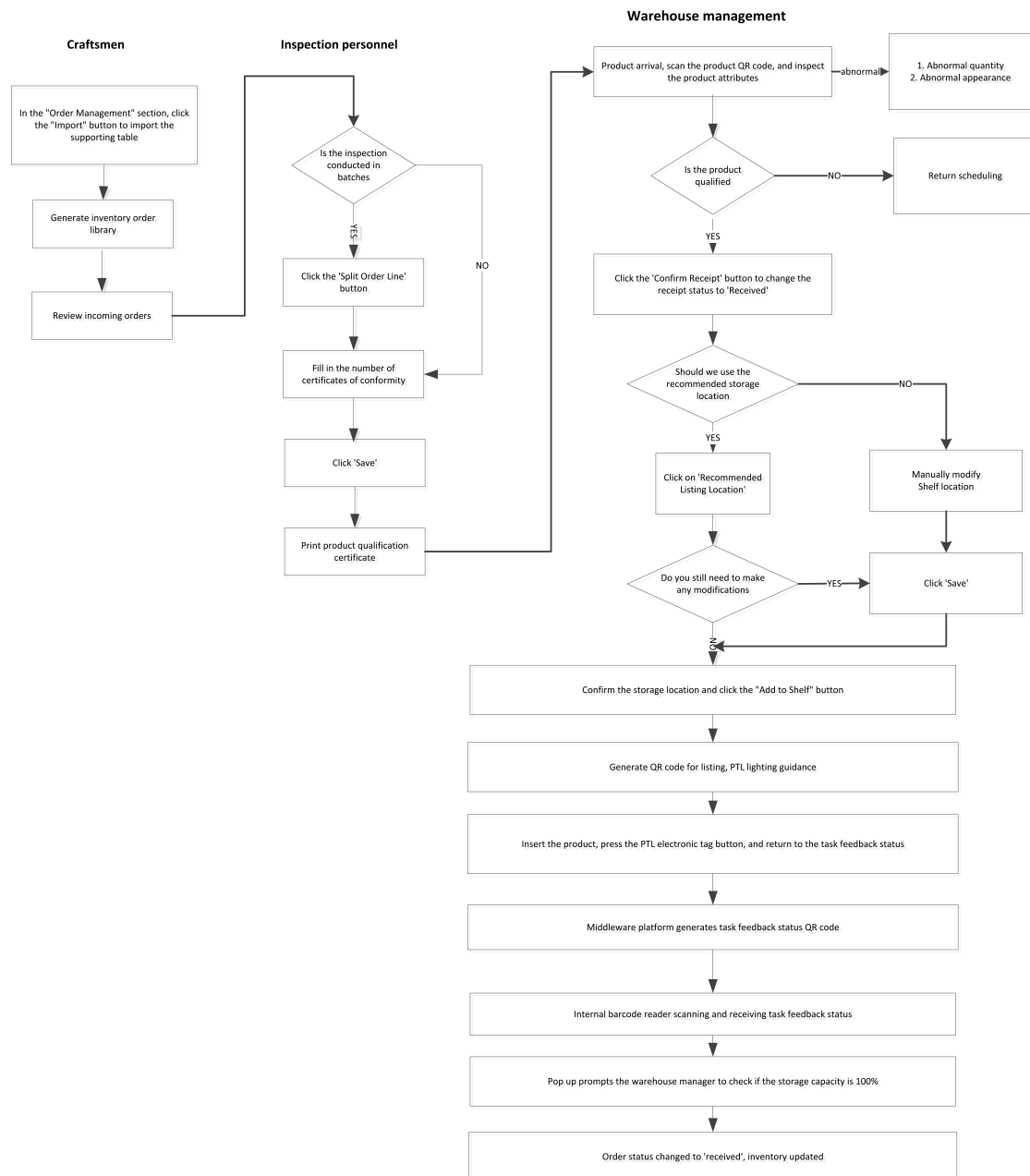


Figure 4. Inventory process

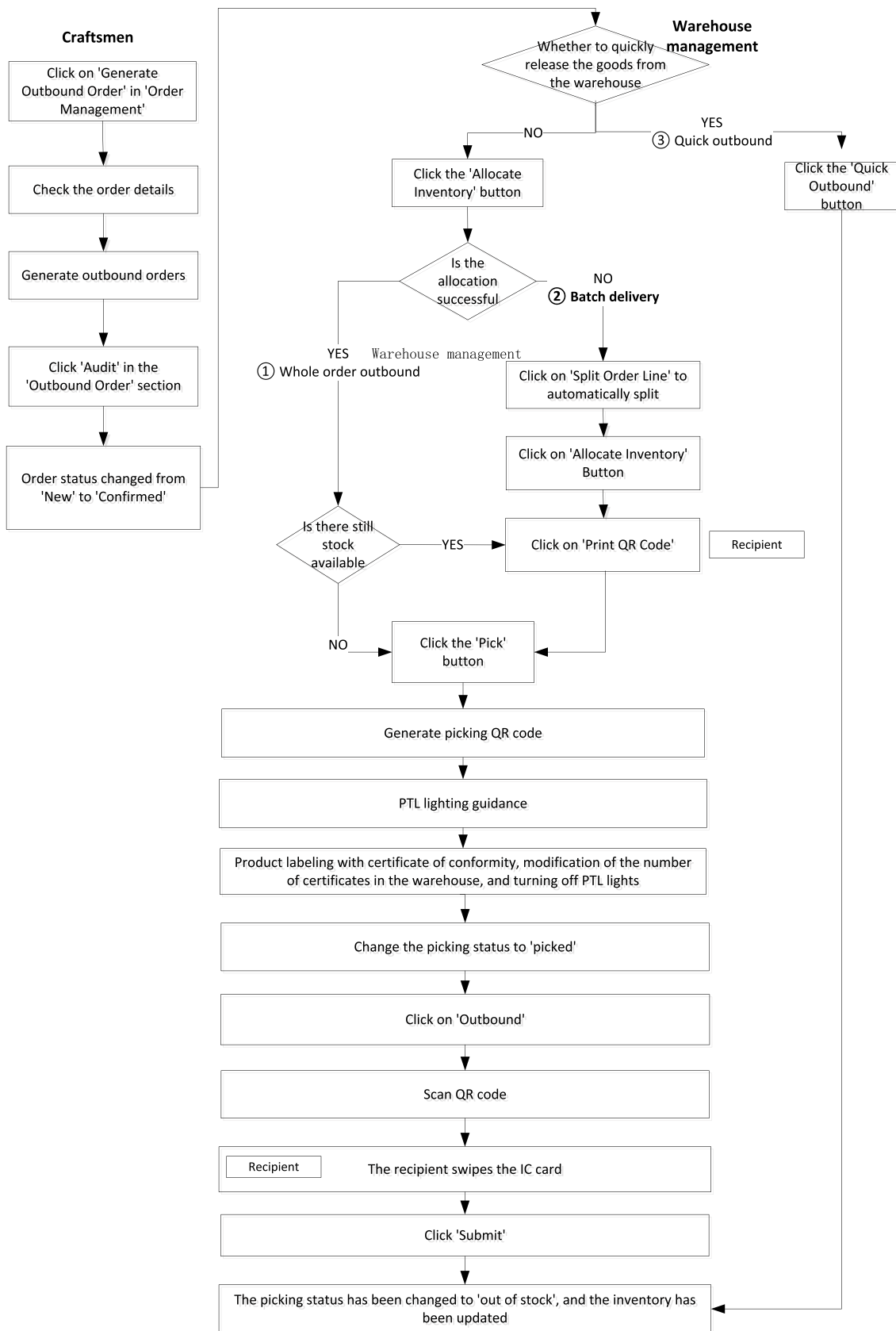


Figure 5. Outbound process

3.2. Outbound management

Outbound management mainly includes outbound order management, inventory turnover rule setting, picking management, and outbound record query, ensuring accurate and efficient product outbound process. When the product is released from the warehouse, a release order is generated in the system, inventory turnover rules are set, release is allocated, release picking tasks are generated, and automatic release is executed. After the release is completed, a release record is automatically generated to update the product inventory. **Figure 5** shows the operation process of outbound business.

- (1) Outbound order management, where process personnel generate outbound orders in the system based on the outbound plan. Outbound orders include key information such as outbound order number, task number, batch number, part drawing number, part name, outbound quantity, and whether mixed batch outbound is required. After the outbound order is generated, it needs to go through an audit process to ensure the accuracy and legality of the order information. Before executing the outbound operation, the outbound order can be modified or canceled to meet the corresponding requirements.
- (2) Picking management allows the system to remove and locate products that need to be shipped based on outbound orders and preset inventory turnover rules. The warehouse management personnel carry out picking operations according to the designated storage location and quantity indicated by the system, ensuring accurate and error-free picking and shipping of products.

4. Conclusion

The general platform for complex discrete warehousing systems based on microservices has been successfully applied to multiple complex discrete scenario projects such as aerospace. The system adopts a microservice architecture, with each service deployed and upgraded independently, achieving a high degree of modularity and loose coupling, significantly improving the maintainability and flexibility of the system. The digital integration framework of “business domain + middleware platform + intelligent equipment information model” has seamlessly integrated business logic and underlying devices, greatly improving job accuracy and efficiency. The system has functions such as equipment management, inbound and outbound management, and inventory management, which can quickly adapt to different complex discrete warehousing business scenarios, promote the automation and intelligence of business processes, and ensure the precision and efficiency of warehousing operations.

Disclosure statement

The authors declare no conflict of interest.

References

- [1] Wang J, Du Y, 2019, Design and Implementation of Intelligent Warehouse Management System. *Computer Technology and Development*, 29(12): 189–193.
- [2] Zhen L, Haolin LI, 2022, A Literature Review of Smart Warehouse Operations Management. *Frontiers of Engineering Management*, 9(1): 25.
- [3] Zhao Q, Liu M, Zou Y, et al., 2023, Research and Application of Special Loading Warehouse Storage Management

System. *Aerospace Industry Management*, 2023(09): 64–68.

- [4] Revillot-Narvaez D, Perez-Galarce F, Alvarez-Miranda E, 2020, Optimizing the Storage Assignment and Order-Picking for the Compact Drive-In Storage System. *International Journal of Production Research*, 58(22): 6949–6969.
- [5] Sharma R, 2021, Intelligent Warehousing Based on the Internet of Things Technology. *Computing Reviews*, 2021(4): 162–163.
- [6] Ye S, 2023, Research on Dynamic Adjustment and Quality Optimization of IoT Perceived Service Composition, thesis, North China University of Technology.
- [7] Leng JW, Yan DX, Liu Q, et al., 2019, Digital Twin-Driven Joint Optimization of Packing and Storage Assignment in Large-Scale Automated High-Rise Warehouse Product-Service System. *International Journal of Computer Integrated Manufacturing*, 09(29): 1–18.
- [8] Leung E, Lee C, Ouyang Z, 2022, From Traditional Warehouses to Physical Internet Hubs: A Digital Twin-Based Inbound Synchronization Framework for Pi-order Management. *International Journal of Production Economics*, 2022: 244–259.

Publisher's note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Design for Improving the Architectural Capabilities of Complex Network Intensive and Scalable Early Warning Release System

Ruiliang Ma^{1*}, Yao Wang², Guan Chao Peng¹

¹Huake Guoxin International Cultural (Beijing) Co., Ltd., Beijing 101119, China

²Beijing T&S Technology Co., Ltd., Beijing 100094, China

**Corresponding author:* Ruiliang Ma, ruiliang.ma@163.com

Copyright: © 2025 Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY 4.0), permitting distribution and reproduction in any medium, provided the original work is cited.

Abstract: In order to solve the problems of high coupling and poor scalability of the traditional monomer early warning release system architecture, multi-level deployment in a complex network environment will lead to high investment in software and hardware and cannot achieve intensive multi-level deployment. This paper realizes the goal of system scalability by introducing micro service architecture and technology stack and realizes the goal of resource intensification by introducing the idea of a data forwarding agent. The designed architecture scheme has been practically applied in the “Jiangxi emergency early warning information release system software platform (phase I) project” (hereinafter referred to as “provincial emergency”), which meets the needs of flexible deployment of multi-level applications across meteorological wide area network (WAN), business private network of other commissions, offices, and bureaus, government extranet, Internet and other complex networks, and fully verifies the scientificity and rationality of the scheme. It has achieved the goal of intensive and scalable construction of provincial emergencies under the complex network environment, greatly improved the early warning capacity and communication capacity of emergencies and comprehensive disasters, provided a reliable guarantee for disaster prevention and reduction, and provided a reference for the construction of current and future early warning release system and capacity improvement project.

Keywords: Early warning; Architecture; Microservices; Intensification; Extensible; Power enhanced

Online publication: February 13, 2025

1. Overview

In the past two decades, an average of more than 200 million people around the world have been affected by natural disasters every year^[1], and natural disasters have led to frequent workplace safety accidents, which have caused long-term negative impacts on society, economy, and the environment. The emergency early warning information release platform has provided a good guarantee and support for disaster prevention, mitigation, and relief.

On the international front, the book *Institutional Partnership for Multi-Hazard Early Warning Systems* documents seven examples of hydrometeorological and other hazard early warning systems, covering a variety of climate regimes and stages of economic development, from industrialized countries such as Germany, France, Japan and the United States of America. Bangladesh, the island nation of Cuba, and the megacity of Shanghai ^[2], demonstrated good practice in multi-hazard Early Warning systems (EWS) ^[3].

Domestically, the governments of 31 provinces (autonomous regions and municipalities directly under the central government) have successively formulated measures for the release and management of emergency early warning information at the provincial level ^[4]. The governments of many provinces (autonomous regions and municipalities), including Beijing, Shanghai, Guangdong, and Tianjin, have set up emergency warning information release centers, completed or are under construction provincial emergency warning information release systems, and incorporated their operation and maintenance into local financial security ^[5].

2. Early warning microservice architecture design

2.1. Overall requirements

Considering the current state of the network, the emergency early warning information distribution center (hereinafter referred to as the early warning center) operates within the meteorological wide area network (WAN). The provincial, municipal, and county (district/city) networks are interconnected, while private networks of other commissions and offices are physically isolated, and there is isolation between government networks outside provinces and cities. The network architecture design scheme connects provincial, municipal, and county (district/city) horizontal commissions, offices, and bureaus through the government extranet. Meanwhile, the early warning centers at the provincial, municipal, and county (district/city) levels access the meteorological WAN vertically for the production and release of emergency early warning information.

The final implementation scheme includes deploying a set of applications and databases in the information center of the provincial Meteorological Bureau to support three-level applications at the provincial, municipal, and county (district/city) levels. Additionally, a set of applications is deployed in the Demilitarized Zone (DMZ) of the provincial and municipal Meteorological Bureau information center to enable two-level deployments for provincial and municipal multi-agency applications while meeting the isolation requirements of provincial and municipal government external networks.

2.2. Functional design

Several business function subdomains are identified through domain decomposition, and each business function domain corresponds to a subsystem. Subprocesses are generated by the re-decomposition of the subsystem and then gradually decomposed and refined iteratively, and the subprocesses that finally reach the level of user interaction are called atomic processes ^[6,7]. Functional design mainly includes eight subsystems, as shown in **Figure 1**.

2.3. Microservice architecture design and implementation

Integrated Development Environment (IDE) using Eclipse has been adopted to streamline software development processes, leveraging the numerous advantages of the Java programming language. Java's strengths include high development efficiency, robust running speed, support for distributed transaction processing, scalability, object-oriented design, robustness, security, platform independence, portability, compatibility, multi-threading, and dynamic features.

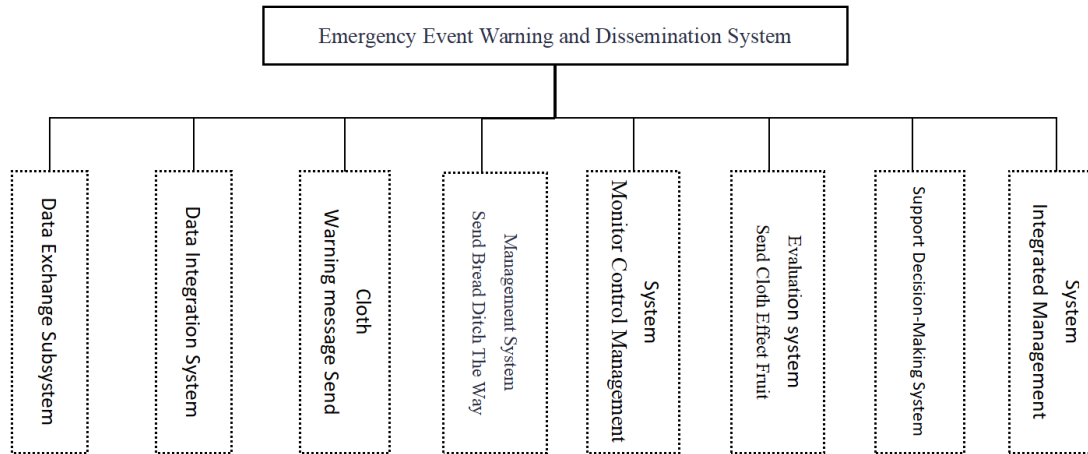


Figure 1. Functional structure

For front-end development, the framework utilizes Vue.js and HTML5, while the back-end development is based on the Spring Cloud Alibaba^[8] distributed one-stop development solution. This back-end framework integrates Spring Boot^[9], SpringMVC, and MyBatis^[10] to implement the control layer, data model layer, business logic layer, and data storage object microservice development^[11]. The architecture uses Spring Cloud Gateway as the API gateway^[12], OAuth 2.0^[13] for unified authentication, Sentinel^[14] for flow control and service degradation, Nacos^[15] for service registration and discovery, a distributed configuration center, and Seata^[16] for distributed transaction processing.

The system also incorporates advanced tools to handle data and monitoring. Canal enables real-time incremental data transmission of MySQL in a containerized environment powered by Docker, while Redis is used for real-time incremental data and basic resource storage of MySQL. Zabbix ensures visual monitoring of system services, software, network, and hardware resources.

For messaging and logging, Kafka is utilized for subscription message storage, while Logstash collects, analyzes, and filters log messages for formatting purposes. Elasticsearch supports data search, analysis, and storage, and Nginx provides load balancing to optimize system performance.

The development pipeline is further enhanced through the integration of Jenkins, Kubernetes, Git, Maven, and Docker repositories to implement a robust DevOps workflow. This combination ensures efficient, automated processes for continuous integration, deployment, and management of microservices. **Figure 2** shows the microservice architecture.

3. Intensive scalable deployment architecture implementation

The system is deployed on the provincial and municipal private cloud infrastructure, as well as the government network, to achieve vertical integration of applications across the provincial, prefecture, and county levels. It also facilitates the horizontal integration of a multi-department joint warning and release platform. This deployment ensures unified resource management, standardized development environments, and application support, thereby enhancing system efficiency and security.

To support Internet-based microservices, resources such as websites, apps, microblogs, WeChat, Doudou, emails, and direct emergency reporting systems are deployed within the DMZ's Internet resource pool. This setup

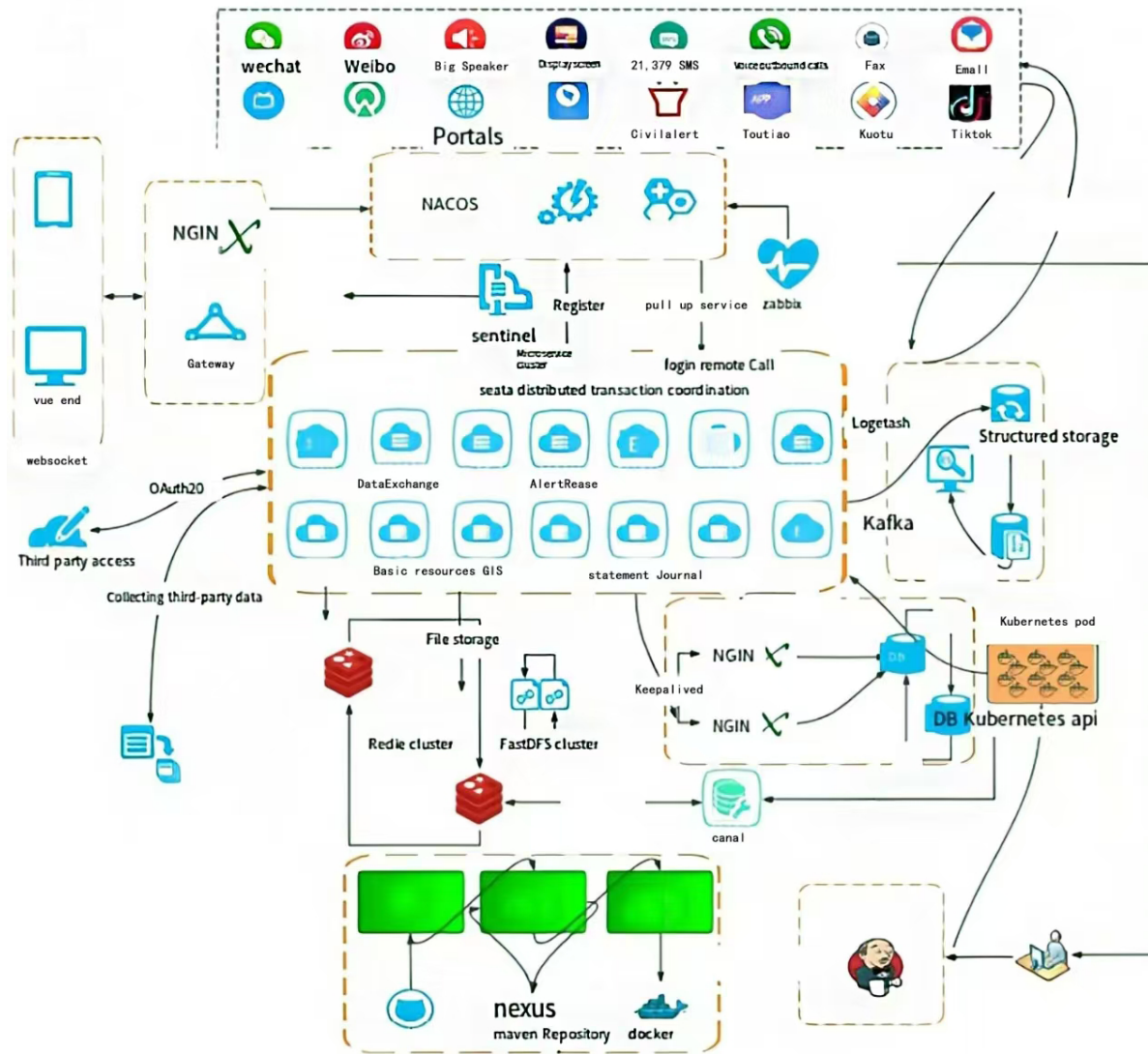


Figure 2. SaaS microservice architecture

enables resource sharing across provincial, city, and county levels.

The nodes at both provincial and municipal levels adhere to the requirements for information security level protection and national e-government engineering construction projects. They are designed to comply with the system's third-level protection standards, ensuring robust security measures are in place^[16]. The architecture for the new deployment is illustrated in **Figure 3**.

4. System operation effect

From January 1, 2022, to September 13, 2022, the municipal and county commissions and bureaus of XXX Province released statistical reports on the types of early warning information issued by the province, as shown in **Table 1**.

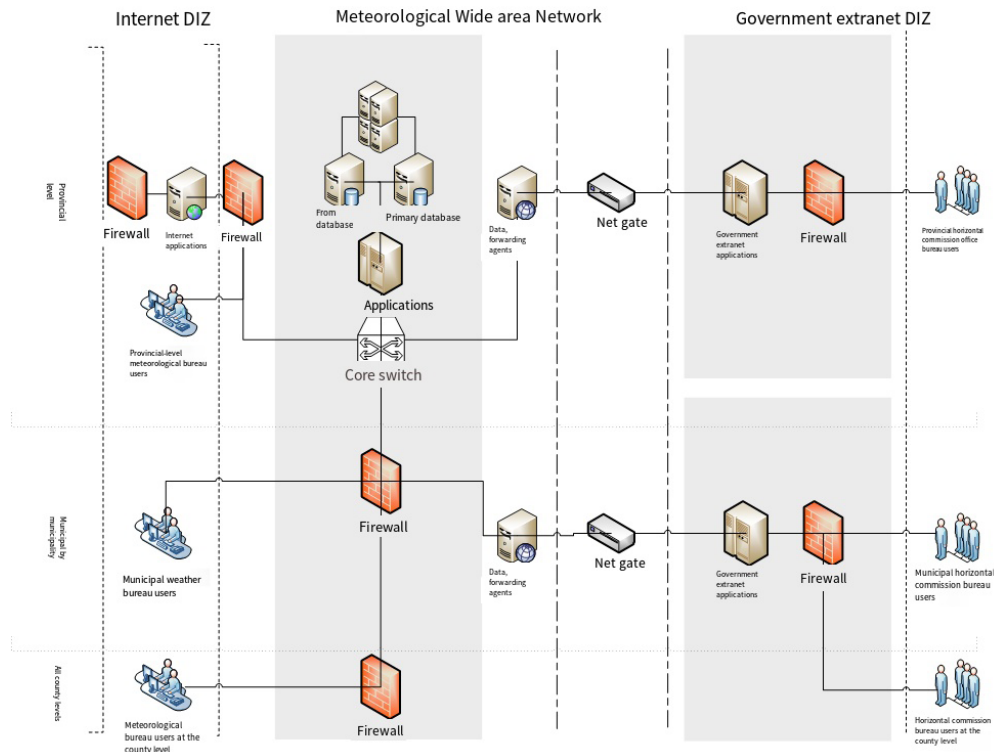


Figure 3. Intensive deployment

Table 1. Statistical reports on the types of early warning information issued

Information Type	Early Warning Information					Text messages	WeChat	Microblog	Mail	Outbound	Loudspeaker	Display screen
	red	orange	yellow	blue	Total		Number of Follows	Number of Fans				
Fog	7	352	1,261	0	1,620	579,918	888,050	7,521,634	230	8	81	149
High winds	0	2	221	1,701	1,924	791,902	1,587,368	13,162,952	761	143	0	0
Heavy snow	2	5	23	142	172	78,397	172,044	871,720	24	1	0	0
Thunder	0	376	23	0	399	4,161,942	4,093,761	39,975,673	3,420	198	0	0
Hailstone	0	30	23	0	53	9,554	16,561	639,100	11	0	0	0
Heavy Rain	95	674	23	677	1,469	1,453,376	1,267,287	20,058,410	1,230	2,503	0	0
High temperatures	438	4,023	23	0	4,484	3,412,831	2,653,870	15,143,004	1,992	2,987	0	0
Total	542	5,462	1,597	2,520	10,121	10,487,920	10,678,941	97,372,493	7,668	5,840	81	149

5. Conclusion

This architecture has been applied in 16 prefectural cities, 27 municipal districts, 12 county-level cities, and 83 counties in Ningxia and Jiangxi. The practice proves that the provincial surge architecture meets the requirements of intensification, scalability, and security in a complex network environment.

Disclosure statement

The authors declare no conflict of interest.

References

- [1] Chen J, Wang X, Li H, 2013, Analysis of the Development of Carbon Emission Trading Market in the Asia-Pacific Region under the Doha Climate Summit. *Pacific Economy*. 2013(2): 42–48.
- [2] Tian G, Jiang K, Hu K, 2002, Research on Real-Time Warning System of Financial Crisis of Listed Companies. *Contemporary Economic Science*, 2002(04): 78–83 + 96.
- [3] Zhang B, 2012, Establishing Emergency Early Warning System to Improve Disaster Prevention and Reduction Ability. *China Emergency Management*, 2012(12): 23–25.
- [4] Ran Z, 2021, Research on Construction of Public Opinion Risk Early Warning Prevention and Control System from the Perspective of Ping An Henan Construction. *Zhengzhou Municipal Party Committee of the Communist Party of China Party School Journal*, 2021(02): 92–95.
- [5] Jia G, He C, Chen Y, et al., 2019, Early Warning of Construction Workers' Safety Behavior from Cross-Level Perspective. *Journal of Tongji University (Natural Science Edition)*, 47(04): 568–574.
- [6] Guijun, Shen Y, 2021, Design and Application of ERP Based on Microservice Architecture in Enterprises. *Computer Systems Applications*, 30(08): 82–83.
- [7] Watts K, 2015, *Microservices Architecture: Deep Exploration Of Microservices*. CreateSpace Independent Publishing Platform, North Charleston.
- [8] Fan J, Zhou T, Lu J, et al., 2013, Application and Improvement of Digital Monitoring and Early Warning System for Major Crop Pests and Diseases. *Yunnan Agriculture*, 2013(12): 61–62.
- [9] Sun J, Zhang P, 2013, Research on Logistics Traceability and Early Warning System of Shaanxi Apple Industry. *Logistics Technology*, 32(19): 247–249 + 253.
- [10] Luo X, 2009, Enterprise Leaders Facing the Challenge of Crisis Management. *Construction Enterprise Management*, 2009(11): 37–39.
- [11] Xu W, Gao J, 2012, Research on Web Application Framework Based on Spring_MVC and MyBatis. *Microcomputer Applications*, 28(07): 1–10.
- [12] Lu Y, Jiang X, Zhai Z, 2007, Research on the Solution of Virus Outbreak in Network. *Information Security and Communication Security*, 2007(12): 91–93.
- [13] Liu T, 2024, Application Research of Data Information Security Assurance Technology in Information Communication Network. *Instrument User*, 31(12): 86–88.
- [14] Li X, Hong Y, 2008, Risk Warning System of Enterprise Logistics Service Outsourcing based on BP Neural Network. *China Market*, 2008(23): 13–15.
- [15] Zhang W, He J, Ding D, 2009, Research on Comprehensive Risk Early Warning System of Property Insurance Company based on BP Neural Network Expert System. *Journal of Xi'an University of Electronic Science and Technology (Social Science Edition)*, 2009(01): 27–32.
- [16] Xue Y, Zhang M, 2009, Research on Early Warning System of Coordinated Development of Urbanization and Ecological Environment in China. *Statistical Education*, 2009(08): 7–12.

Publisher's note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

A Multi-Scale Attention-Based Pedestrian Detection Method for Roadways Using the YOLOv5 Framework

Ruihan Wang*, Boling Liu, Tingyu Liao

School of Software Engineering, Chongqing University of Posts and Telecommunications, Chongqing 400065, China

*Corresponding author: Ruihan Wang, s221201032@stu.cqupt.edu.cn

Copyright: © 2025 Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY 4.0), permitting distribution and reproduction in any medium, provided the original work is cited.

Abstract: Due to multi-scale variations and occlusion problems, accurate traffic road pedestrian detection faces great challenges. This paper proposes an improved pedestrian detection method called Multi Scales Attention-YOLOv5x (MSA-YOLOv5x) based on the YOLOv5x framework. Firstly, by replacing the first convolutional operation of the backbone network with the Focus module, this method expands the number of image input channels to enhance feature expressiveness. Secondly, we construct C3_CBAM module instead of the original C3 module for better feature fusion. In this way, the learning process could achieve more multi-scale features and occluded pedestrian target features through channel attention and spatial attention. Additionally, a new feature pyramid detection layer and a new detection channel are embedded in the feature fusion part for enhancing multi-scale pedestrian detection accuracy. Compared with the baseline methods, experimental results on a public dataset demonstrate that the proposed method achieves optimal detection accuracy for traffic road pedestrian detection.

Keywords: YOLOv5; Pedestrian; Detection; Feature; Fusion

Online publication: February 13, 2025

1. Introduction

Pedestrian object detection plays a crucial role in the field of autonomous driving. It utilizes road images captured by vehicle-mounted camera equipment to identify pedestrians and accurately determine their locations by the use of computer vision techniques.

Traditional pedestrian detection methods, such as Histogram of Oriented Gradients (HOG) ^[1], Local Binary Pattern (LBP) ^[2], and Scale-Invariant Feature Transform (SIFT) ^[3], mainly rely on manually designed feature extraction methods. However, these methods always suffered from low accuracy performance and limited generalization ability in practice.

Object detection algorithms based on deep learning were first proposed by Girshick *et al.* in 2014, where

the Region-CNN (RCNN) ^[4] was introduced. Subsequently, two-stage detectors such as Fast R-CNN ^[5], Faster R-CNN ^[6], and Mask R-CNN ^[7], as well as single-stage detectors like You Only Look Once (YOLO) ^[8] and Single Shot MultiBox Detector (SSD) ^[9], have emerged in the following ten years. Among these algorithms, YOLO performs significant performance in the field of pedestrian target detection due to its outstanding contributions to balance detection accuracy and processing speed. However, when facing multi-scale and occlusion scenarios, the YOLO method also suffers from issues such as increased leakage and false detection rates, resulting in poor detection results.

In real traffic road scenes, pedestrian object detection techniques are greatly affected by multi-scale and occlusion issues. Large-scale pedestrians often provide richer information, facilitating better detection. However, small-scale pedestrians usually reveal the following characteristics, such as reduced pixel sizes, blurred outlines, and appearances, resulting in limited information extraction effectiveness. Moreover, occlusion occurs when an object or a portion of an object obstructs another object, causing partial or complete invisibility in images or videos. Occlusion complicates the recognition of pedestrian parts, substantially increasing the difficulty of pedestrian detection.

To solve the above issues, this paper proposes MSA-YOLOv5x, an enhanced multi-scale attention network based on YOLOv5x, specifically designed to improve pedestrian detection accuracy in multi-scale and occluded scenarios.

2. Related work

2.1. Occlusion and multiscale studies in pedestrian detection

In recent years, pedestrian detection has made significant advancements in terms of detection accuracy and speed, owing to the continuous efforts and works of researchers. To address the challenge of occlusion, researchers have explored various techniques. For instance, Tian *et al.* ^[10] proposed DeepParts, which tackles occlusion by utilizing different partial detectors. By incorporating features from specific body parts, DeepParts aims to improve the detection of partially occluded pedestrians with higher robustness. Another technique that has been employed to address occlusion is center point detection. This approach transforms pedestrian detection into advanced semantic feature detection, which helps enhance accuracy in occlusion scenarios. One example of such a method is OAF-Net, proposed by Qiming *et al.* ^[11] in 2022. OAF-Net incorporates an occlusion-aware detection head, which consists of three independent centroid prediction branches along with scale and offset prediction branches.

Recently, incorporating attention mechanisms and contextual information has been widely used to further promote the detection performance of occluded pedestrians. In 2019, Chi *et al.* proposed Context-Aware Feature Learning Networks (CAFL) ^[12]. CAFL utilizes pixel-level contextual embedding modules to integrate contextual information from multiple surrounding regions into the feature layer. Considering the context, CAFL enhances the discriminative ability of detectors and improves the robustness of occlusions. In 2021, Jin *et al.* proposed the Mask-Guided Attention Network (MGAN) ^[13].

Researchers have proposed various solutions for addressing the multi-scale problem of pedestrian detection. Some studies focused on enhancing multiscale pedestrian detection by incorporating contextual information and enabling the model to adapt to pedestrians at different scales more effectively. For instance, in 2019, Xie *et al.* introduced the inverse convolution and porous module into Faster R-CNN networks to enrich the feature map with semantic contextual information ^[14]. This augmentation resulted in a synthesized feature map that provided more

detailed visual information and semantic contextual representation. Besides, the attention mechanism has been employed to identify the correlation between raw data and emphasize significant features. Integrating the attention mechanism into pedestrian detection facilitates the fusion of different features and improves the robustness of pedestrian detection across various scales. In 2020, Lin *et al.* proposed a granularity-aware deep feature learning method (CAGDFL) that utilizes a convolutional backbone to generate multiple feature maps representing pedestrian targets at different scales ^[15]. Subsequently, a scale-aware pedestrian attention module is employed to generate attention maps. Moreover, the fusion of multi-scale features has been utilized to enhance the robustness of pedestrian detection. In 2022, Chao *et al.* introduced RSSD based on the SSD algorithm ^[16]. This approach fuses feature maps of different scales during the feature fusion process, generating six prediction layers from varying depths. Additionally, residual blocks are incorporated into each prediction layer of the SSD to enhance prediction performance.

2.2. YOLOv5

YOLOv5 is one of the most popular deep learning-based object detection algorithms. Compared to its predecessor, YOLOv4, YOLOv5 introduces Adaptive Anchor Frames and Adaptive Picture Scaling. These improvements enable the model to adapt to objects of varying sizes and proportions, thereby improving its generalization ability. Additionally, YOLOv5 incorporates the Cross Stage Partial Network (CSPNet) structure into the Backbone and Neck components, effectively reducing the number of parameters and computation required, thereby enhancing the model's efficiency ^[17]. In terms of post-processing, YOLOv5 utilizes the weighted Non-Maximum Suppression (NMS) approach, which effectively handles overlapping targets and eliminates duplicate detection results, leading to improved model accuracy ^[18]. YOLOv5 consists of the input side, Backbone structure, Neck structure, and prediction side, as depicted in **Figure 1**.

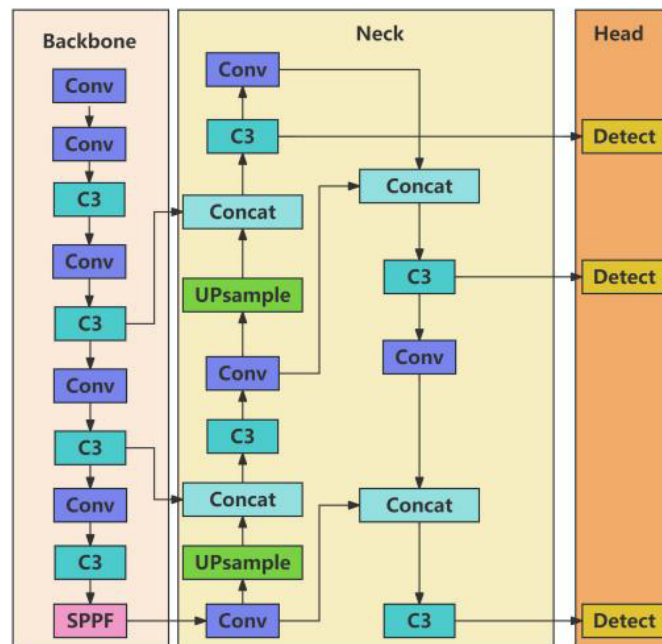


Figure 1. Yolov5x network structure

3. Method

This paper proposes a roadways pedestrian detection method with multi-scale attention based on the YOLOv5 Framework, abbreviated as MSA-YOLOv5x. The method aims to improve the accuracy of detecting partially occluded and differently-sized pedestrian targets. The structure of MSA-YOLOv5x is illustrated in **Figure 2**.

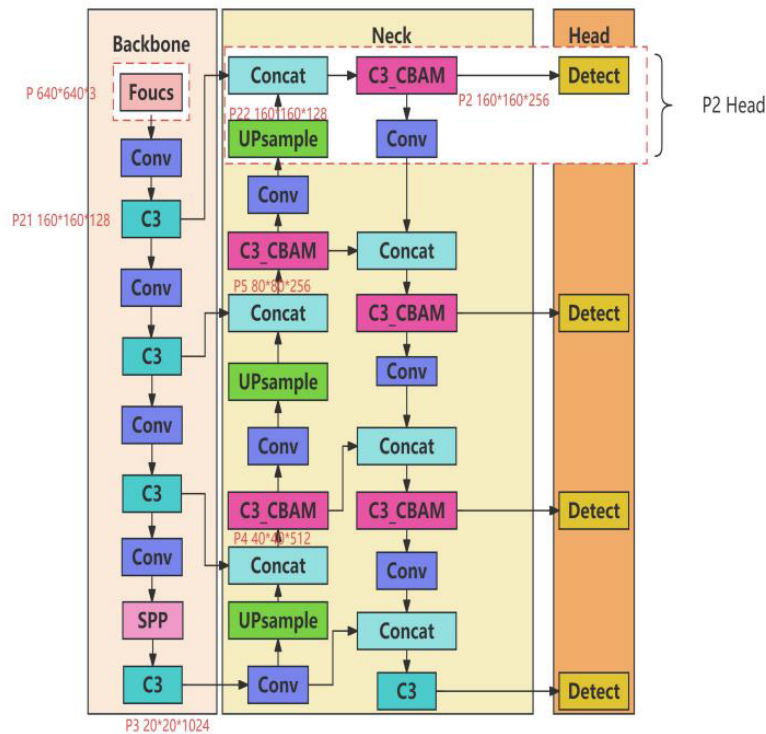


Figure 2. MSA-YOLOv5x network architecture

Within the neck network, the C3_CBAM module is constructed by incorporating the CBAM attention mechanism to replace the C3 module in the feature fusion part^[19]. The feature maps are further processed by the successive up-sampling and C3_CBAM modules. They are then fused with the feature maps corresponding to the same scale in the backbone network to generate the output detection results. Additionally, to further enhance the multi-scale pedestrian detection accuracy, this method introduces a P2 feature pyramid detection layer in the feature fusion part and establishes a new detection channel in combination with the C3_CBAM module^[20].

3.1. Image preprocessing

Compared to the traditional Convolution (Conv), we replace the first convolution operation of the backbone network with the Focus module. This replacement enhances the model's ability to capture local features. The Focus module performs a slicing operation on the input image within the backbone network.

3.2. C3_CBAM feature extraction module

We introduce the Convolutional Block Attention Module (CBAM) attention mechanism block to reconstruct C3_CBAM feature extraction module, enhancing the C3 structure of YOLOv5x. The C3_CBAM feature extraction module is depicted in **Figure 3(b)**. This module combines channel attention and spatial attention, significantly

enhancing the method's perceptual ability. By adaptively learning these two attention types, the module enriches feature map representations, thereby improving the detection of small-scale pedestrians and partially occluded pedestrian targets. C3_CBAM introduces a CBAM attention mechanism module at the end of each C3 structure in the original YOLOv5x, with the same number of channels as the C3 structure. This new module enables the method to adaptively learn channel attention and spatial attention. It enhances the feature map representation while preserving the original feature map channels. The specific operation of C3_CBAM is as follows: For the input feature map of the C3 module, H and W denotes as with dimensions and C indicates the number of channels. It undergoes two parallel branches. In the first branch, a 3×3 convolution kernel is applied to generate a shallower feature map. In the second branch, the input shallow feature map is divided into two sub-branches within a BottleNeck module^[21]. One sub-branch remains unchanged, while the other sub-branch is further processed by two 3×3 .

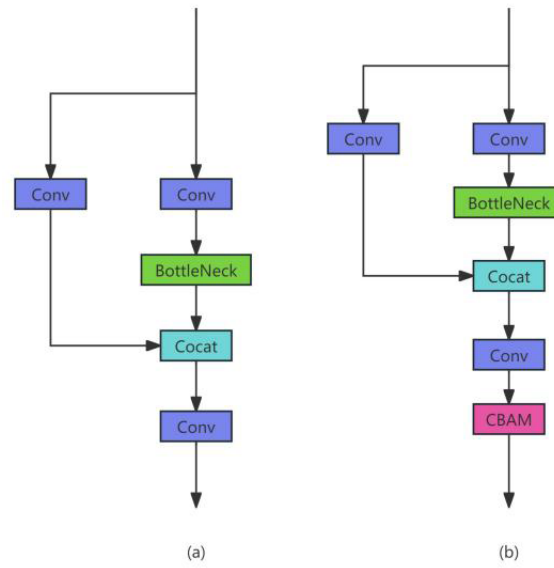


Figure 3. C3_CBAM module: (a) the original C3 module; (b) the improved C3 module with the introduction of CBAM convolution kernels

The resulting two sub-branches within the BottleNeck module are then combined using residual connections to produce a deeper feature map $F_{12} \in R^{H*W*C/2}$. The shallow feature map and the deeper feature map are concatenated to obtain the feature map F_2 , which can be calculated using the following formula:

$$F_2 = \text{Concat}(F_{11}, F_{12}) \in R^{H*W*C} \quad (1)$$

The F_2 feature map integrates the information from the shallower and deeper feature maps, facilitating cross-layer feature fusion. This fusion enables the model to gain a better understanding of targets at various scales, thereby enhancing the accuracy of detection. Subsequently, the F_2 feature map is passed through the CBAM attention block. The CBAM attention block consists of two components: channel attention and spatial attention. First, the channel attention mechanism calculates the importance of each channel. It achieves this by employing global average pooling and fully connected layers to compute the weights for each channel. These weights indicate the significance of each channel in extracting valuable features. The weights are then multiplied with the corresponding feature maps of each channel, resulting in a one-dimensional channel attention feature map

that contains channel attention information. The formula for the one-dimensional channel attention feature map, denoted as F_C , is as follows:

$$F_C = \sigma (MLP (Avg (F_2)) + MLP (Max (F_2))) \otimes F_2 \quad (2)$$

The one-dimensional channel attention feature map, F_C , obtained from the channel attention block, is then passed into the spatial attention block to calculate the spatial attention. The spatial attention mechanism aims to learn the significance of each spatial location in the feature map. It utilizes channel max pooling and fully connected layers to compute the weights for each spatial location. These weights indicate the importance of each location in extracting valuable features. Subsequently, the weights are multiplied by the corresponding locations of the feature map, resulting in a 2D spatial attention feature map, F_s , that incorporates both channel attention and spatial attention information. The formula for the 2D spatial attention feature map, F_s , is presented below:

$$F_s = \sigma (f^{7*7} ([Avg (F_C)]; [Max (F_2)])) \otimes F_C \quad (3)$$

3.3. P2 feature pyramid detection layer

To detect pedestrians at multiple scales in traffic road scenes, a new $P2$ feature pyramid detection layer and a new detection channel are embedded in the feature fusion part of YOLOv5x for enhancing multi-scale pedestrian detection accuracy. The structure of this module is illustrated in **Figure 2**.

Down-sampling the original image $P \in R^{640*640*3}$ by the use of both the Focus module and Conv, we can get a new feature map after passing through the first C3 module. This feature map is denoted as $P21 \in R^{160*160*128}$. Subsequently, $P3$ is obtained through successive down-sampling of the feature map $P21$ using Conv in the backbone network. This process is facilitated by employing the Spatial Pyramid Pooling (SPP) feature pyramid^[22]. At this stage, the feature map is referred to as $P3 \in R^{20*20*1024}$.

The $P3$ feature map is fed into the neck feature pyramid, where it undergoes up-sampling and is then combined with feature maps of the same scale from the backbone network. This fusion process results in the generation of a new feature map. This feature map is denoted as $P4 \in R^{40*40*512}$.

The $P4$ feature map is up-sampled and further fused with feature maps of the same scale from the backbone network, resulting in the generation of a new feature map $P5 \in R^{80*80*256}$. In this paper, we introduce a $P2$ feature pyramid layer, as an addition to the feature fusion structure of the neck network. This layer is formed by concatenating the feature map $P2 \in R^{160*160*128}$, obtained from up-sampling $P5$, with $P21$ from the backbone network. The calculation formula of the $P2$ feature map is as follows:

$$P2 = Concat (P21, P22) \in R^{160*160*256} \quad (3)$$

4. Experimentation

4.1. Dataset and experimental setup

The CityPersons dataset comprises over 3,000 high-resolution real-world images, which depict diverse urban scenarios such as roads, sidewalks, intersections, and more^[23]. It provides a comprehensive representation of urban environments, capturing various elements like different weather conditions (sunny, cloudy, rainy, etc.), periods (daytime, nighttime), and population densities (busy city centers, suburbs, etc.). In this paper, the experimental evaluation metrics include mAP and GFLOPS.

4.2. Experiment 1: ablation study

In this paper, we introduce the CBAM attention mechanism to enhance the feature extraction structure of the

YOLOv5x backbone network. Additionally, we incorporate an extra $P2$ feature pyramid detection layer to reduce the false positives and false negatives of pedestrian targets at various scales. To evaluate the effectiveness of these improvements, we conduct three sets of ablation experiments using the CityPersons dataset. The experimental results are presented in **Table 1**.

4.3. Experiment 2: comparative analysis

To validate the detection performance of the improved method, this paper compares and analyzes MSA-YOLOv5x with the baseline methods in terms of mAP, GFLOPS, and the number of parameters on the CityPersons test set. **Table 2** presents the baseline methods utilized in the experiments, comprising the two-stage target detection method Faster R-CNN^[6], the one-stage target detection method SSD^[9], YOLOv3^[21], YOLOv4^[10], YOLOv5x, and YOLOv8x. These methods are evaluated for their detection accuracy on the CityPersons dataset specifically for pedestrian detection.

Table 1. Results of ablation experiments on the CityPersons dataset

Methods	Params	GFLOPS	mAP50 (%)	mAP50:95 (%)
YOLOv5X	86.21M	203.9	59.7	35.5
YOLOv5X+P2	90.88M	313.2	64.2	39.5
MSA-YOLOv5x	91.22M	314.1	65.3	40.4

Table 2. Comparative results of various algorithms on the CityPersons dataset

Methods	Params	GFLOPS	mAP50 (%)	mAP50:95 (%)
Faster-RCNN	41.5M	207.1	43.9	19.0
SSD	34.3M	386.2	31.4	11.3
YOLOv3	103.69M	283	64.8	40.5
YOLOv4-CSP	52.52M	119.8	64.6	40.4
YOLOv5x	86.21M	203.9	59.7	35.5
YOLOv8x	68.15M	258.1	62.8	40.8
MSA-YOLOv5x(ours)	91.22M	314.1	65.3	40.4

5. Discussion

The MSA-YOLOv5x method demonstrated significant improvements in pedestrian detection, especially for occluded and multi-scale pedestrians, thanks to the integration of the CBAM attention mechanism and the $P2$ feature pyramid detection layer. The CBAM module helped the model focus on the most relevant features by applying channel and spatial attention, while the $P2$ layer enhanced multi-scale detection. When compared to other models like Faster R-CNN and SSD, MSA-YOLOv5x outperformed them in both detection accuracy (mAP) and computational efficiency (GFLOPS). The results suggest that the model is well-suited for real-time pedestrian detection in complex urban settings, such as in smart city applications or autonomous vehicles.

6. Conclusion

This study introduced MSA-YOLOv5x, a novel pedestrian detection model that enhances YOLOv5x with the CBAM attention mechanism and a P2 feature pyramid detection layer. Experimental results on the CityPersons dataset showed that MSA-YOLOv5x improves detection accuracy, particularly in challenging environments with occlusions and varying pedestrian sizes. Compared to baseline models, MSA-YOLOv5x achieved higher performance in both mAP and GFLOPS, making it a promising approach for real-time pedestrian detection in urban scenarios. Future work can focus on further optimizations and testing in diverse environments.

Disclosure statement

The authors declare no conflict of interest.

References

- [1] Dalal N, Triggs B, 2005, Histograms of Oriented Gradients for Human Detection. 2005 IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR'05), Vol. 1. IEEE, 2005: 886–893.
- [2] Ahonen T, Hadid A, Pietikainen M, 2004, Face Recognition with Local Binary Patterns. Computer Vision-ECCV 2004: 8th European Conference on Computer Vision, Proceedings, Part I 8, Springer, 2004: 469–481.
- [3] Lowe DG, 2004, Distinctive Image Features from Scale-Invariant Keypoints. International Journal of Computer Vision, 60: 91–110.
- [4] Girshick R, Donahue J, Darrell T, et al., 2014, Rich Feature Hierarchies for Accurate Object Detection and Semantic Segmentation. Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition, 2014: 580–587.
- [5] Girshick R, 2015, Fast r-cnn. Proceedings of the IEEE International Conference on Computer Vision, 2015: 1440–1448.
- [6] Ren S, He K, Girshick R, et al., 2015, Faster r-cnn: Towards Realtime Object Detection with Region Proposal Networks. Advances in Neural Information Processing Systems, 28: 2015.
- [7] He K, Gkioxari G, Dollár P, et al., 2017, Mask r-cnn. Proceedings of the IEEE International Conference on Computer Vision, 2017: 2961–2969.
- [8] Redmon J, Divvala S, Girshick R, et al., 2016, You Only Look Once: Unified, Real-Time Object Detection. Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition, 2016: 779–788.
- [9] Liu W, Anguelov D, Erhan D, et al., 2016, SSD: Single Shot Multibox Detector. Computer Vision-ECCV 2016: 14th European Conference Proceedings, Part I 14. Springer, 2016: 21–37.
- [10] Tian Y, Luo P, Wang X, et al., 2015, Deep Learning Strong Parts for Pedestrian Detection. Proceedings of the IEEE International Conference on Computer Vision, 2015: 1904–1912.
- [11] Li Q, Su Y, Gao Y, et al., 2022, Oaf-Net: An Occlusion-Aware Anchor-Free Network for Pedestrian Detection in a Crowd. IEEE Transactions on Intelligent Transportation Systems, 23(11): 21291–21300.
- [12] Fei C, Liu B, Chen Z, et al., 2019, Learning Pixel-Level and Instance-Level Context-Aware Features for Pedestrian Detection in Crowds. IEEE Access, 7: 94944–94953.
- [13] Xie J, Pang Y, Khan MH, et al., 2020, Mask-Guided Attention Network and Occlusion-Sensitive Hard Example Mining for Occluded Pedestrian Detection. IEEE Transactions on Image Processing, 30: 3872–3884.
- [14] Xie H, Chen Y, Shin H, 2019, Context-Aware Pedestrian Detection Especially for Small-Sized Instances with Deconvolution Integrated Faster Rcn (dif r-cnn). Applied Intelligence, 49: 1200–1211.

- [15] Lin C, Lu J, Wang G, et al., 2018, Graininess-Aware Deep Feature Learning for Pedestrian Detection. Proceedings of the European conference on Computer Vision (ECCV), 2018: 732–747.
- [16] Yan C, Zhang H, Li X, et al., 2022, R-ssd: Refined Single Shot Multibox Detector for Pedestrian Detection. Applied Intelligence, 52(9): 10430–10447.
- [17] Wang CY, Liao HYM, Wu YH, et al., 2020, Cspnet: A New Backbone that can Enhance Learning Capability of Cnn. Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition Workshops, 2020: 390–391.
- [18] Felzenszwalb PF, Girshick RB, McAllester D, et al., 2009, Object Detection with Discriminatively Trained Part-Based Models. IEEE Transactions on Pattern Analysis and Machine Intelligence, 32(9): 1627–1645.
- [19] Woo S, Park J, Lee JY, et al., 2018, Cbam: Convolutional Block Attention Module. Proceedings of the European Conference on Computer Vision (ECCV), 2018: 3–19.
- [20] Redmon J, Farhadi A, 2018, Yolov3: An Incremental Improvement. arXiv Preprint, arXiv:1804.02767.
- [21] He K, Zhang X, Ren S, et al., 2016, Deep Residual Learning for Image Recognition. Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition, 2016: 770–778.
- [22] He K, Zhang X, Ren S, et al., 2015, Spatial Pyramid Pooling in Deep Convolutional Networks for Visual Recognition,” IEEE Transactions on Pattern Analysis and Machine Intelligence, 37(9): 1904–1916.
- [23] Zhang S, Benenson R, Schiele B, 2017, Citypersons: A Diverse Dataset for Pedestrian Detection. Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition, 2017: 3213–3221.

Publisher’s note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Path Planning for Thermal Power Plant Fan Inspection Robot Based on Improved A* Algorithm

Wei Zhang*, Tingfeng Zhang

College of Electrical Engineering, Liaoning University of Technology, Jinzhou, 121001, China

*Corresponding author: Wei Zhang, 1326001933@163.com

Copyright: © 2025 Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY 4.0), permitting distribution and reproduction in any medium, provided the original work is cited.

Abstract: To improve the efficiency and accuracy of path planning for fan inspection tasks in thermal power plants, this paper proposes an intelligent inspection robot path planning scheme based on an improved A* algorithm. The inspection robot utilizes multiple sensors to monitor key parameters of the fans, such as vibration, noise, and bearing temperature, and upload the data to the monitoring center. The robot's inspection path employs the improved A* algorithm, incorporating obstacle penalty terms, path reconstruction, and smoothing optimization techniques, thereby achieving optimal path planning for the inspection robot in complex environments. Simulation results demonstrate that the improved A* algorithm significantly outperforms the traditional A* algorithm in terms of total path distance, smoothness, and detour rate, effectively improving the execution efficiency of inspection tasks.

Keywords: Power plant fans; Inspection robot; Path planning; Improved A* algorithm

Online publication: February 17, 2025

1. Introduction

At present, thermal power plants require staff to inspect equipment at multiple points. This process is physically demanding and inefficient^[1,2]. Intelligent inspection robots can replace manual inspections^[3]. They collect and monitor equipment data in real-time, reducing labor and improving efficiency. Path planning is key to enabling autonomous robot inspections^[4,5]. Commonly used algorithms include A* and Dijkstra. The A* algorithm uses heuristic search to quickly find optimal paths in finite graphs, making it widely studied and applied^[6]. However, in complex environments, A* often gets stuck in local optima, leading to inefficient paths and excessive turns^[7,8]. Researchers have proposed improvements, including optimizing heuristic functions, integrating local planning algorithms such as Dynamic Window Approach (DWA), and combining intelligent search methods like genetic or ant colony algorithms^[9-15]. This paper enhances the A* algorithm with obstacle penalties, path reconstruction, and smoothing techniques to improve path planning efficiency.

2. Design scheme of an intelligent inspection robot for thermal power plants

This intelligent inspection robot is controlled by an STM32 microcontroller. It uses Mecanum wheel drive technology for flexible and efficient motion control. The system design includes multiple functional modules. These modules cover temperature detection, gas detection, navigation, video monitoring, and image processing. The main functional modules are shown in **Figure 1**.

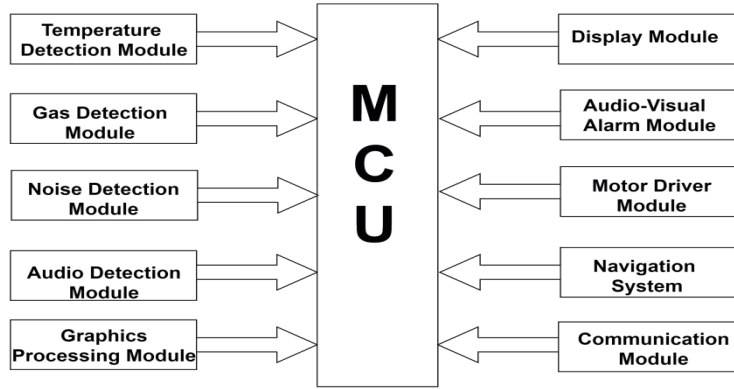


Figure 1. Overall system design

3. Research on path planning algorithm

3.1. Operating principle of traditional A* algorithm

The A* algorithm combines the advantages of Breadth-First Search and Greedy Best-First Search. It determines the search order by calculating the total cost $f(n)$ for each node. This ensures the optimal path from the start to the goal can be found in the shortest time. The total cost $f(n)$ is calculated using the following formula:

$$f(n) = g(n) + h(n) \quad (1)$$

In the formula, $g(n)$ represents the actual cost from the start node to the current node n . It is the total length of the path traveled so far. $h(n)$ represents the estimated remaining cost from the current node n to the goal node. The heuristic function $h(n)$ is expressed using the Manhattan distance as follows:

$$h(n) = |x_1 - x_2| + |y_1 - y_2| \quad (2)$$

In the formula, x_1 and x_2 represent the horizontal coordinates of two points in the plane, while y_1 and y_2 represent the vertical coordinates corresponding to x_1 and x_2 respectively.

3.2. Working principle of improved A* algorithm

To address the aforementioned issues, this paper introduces obstacle penalty terms and employs the Bresenham algorithm for path reconstruction based on the traditional A* algorithm. Additionally, gradient descent is utilized to achieve path smoothing.

3.2.1. Improvement and optimization of heuristic function

The improved heuristic function incorporates an obstacle penalty term on top of the traditional heuristic value $h(n)$ to enhance the flexibility and obstacle avoidance capability of path planning. The specific formula is as follows:

$$H(n) = h(n) + \lambda \frac{1}{d_{obstacle} + \varepsilon} \quad (3)$$

In the formula, λ is the weight of the hazard penalty factor. $d_{obstacle}$ is the distance from the current node to the nearest obstacle. ε is the minimum positive number to prevent dividing zero errors. $h(n)$ is an estimate of the residual cost from the current node n to the target node. $H(n)$ is an improved heuristic function. To adapt to the complexity of different environments, the penalty factor λ is dynamically adjusted. The specific adjustment formula is as follows:

$$\lambda = K \times \frac{\text{number of obstacles}}{\text{total number of grids}} \quad (4)$$

In the formula, K is a scaling constant with a value range of 5 to 10. It is used to amplify or reduce the impact of the obstacle penalty. To adapt to complex environments in practical inspection tasks, the improved A* algorithm adopts the Euclidean distance to enhance the accuracy of path planning. The Euclidean distance is a standard method for calculating the straight-line distance between the current node and the goal node. Its formula is as follows:

$$h(n) = \sqrt{(x_{goal} - x_n)^2 + (y_{goal} - y_n)^2} \quad (5)$$

In the formula, (x_{goal}, y_{goal}) is the coordinate of the target node. (x_n, y_n) is the coordinates of the current node.

3.2.2. Path reconstruction and path optimization

After the A* algorithm completes the path search, the initial path often contains redundant nodes and sharp turns. This affects the simplicity of the path and the robot's movement efficiency. To address this, this paper introduces the Bresenham algorithm and gradient descent to optimize the path. These methods eliminate redundant nodes and smooth the path.

- (1) The Bresenham algorithm is used to reconstruct the path and remove redundant nodes. The path reconstruction process is illustrated in **Figure 2**.

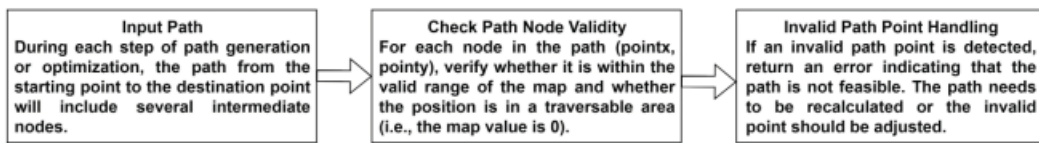


Figure 2. Path reconstruction process

- (2) Gradient descent is used to smooth the path. It adjusts the positions of intermediate nodes to make the path as close to a straight line as possible. This reduces turns and improves path smoothness. The path-smoothing steps are as follows:
 - (i) Initial path input: The path optimized by the Bresenham algorithm is used as the input for gradient descent optimization.
 - (ii) Smoothing optimization: Intermediate nodes (excluding the start and end nodes) are selected. Their positions are adjusted using the following formula:

$$\text{current} = \text{prev} + \alpha \times (\text{next} - \text{prev}) \quad (6)$$

In the formula, *current* refers to the current point on the path, which is the point to be optimized, *prev* is the previous point of the current point, *next* is the next point of the current point, and α (alpha) is the learning rate, which controls the step size.

3.2.3. Path planning legality check

Ensure that every point on the path lies within the valid area. This avoids the path-crossing obstacles or exceeding the map boundaries. The validity of each path point is determined by the following formula:

$$\begin{aligned} 0 < \text{point}_x &\leq \text{rows} \\ 0 < \text{point}_y &\leq \text{cols} \\ \text{matrix}(\text{point}_x, \text{point}_y) &= 0 \end{aligned} \quad (7)$$

In the formula, *point_x* and *point_y* are the coordinates of the current path point, *rows* and *cols* represent the number of rows and columns in the map matrix, defining the valid range of the map, *matrix(point_x, point_y)* is the value of the corresponding point in the map.

3.3. Implementation process of the improved A* algorithm

This paper improves the traditional A* algorithm by introducing obstacle penalty terms to optimize the heuristic function, combining path reconstruction and optimization techniques, and implementing a dynamic update mechanism. These enhancements enable more efficient and precise path planning in complex environments. Below is the complete implementation process of the improved A* algorithm.

- (1) Step 1: Initialize the start point. Define the open list and closed list. Set the cost of the start node to $g(n) = 0$ and its parent node to null. Add the start node to the open list.
- (2) Step 2: Search and expand. Select the node with the smallest $f(n)$ from the open list and move it to the closed list. If it is the goal node, proceed to path reconstruction. Otherwise, expand its neighboring nodes.
- (3) Step 3: Process neighboring nodes. Skip nodes that are outside the map boundaries, obstacles, or in the closed list. Calculate the cost for the remaining nodes.
- (4) Step 4: Path reconstruction and optimization. Trace back from the goal node to generate the initial path. Use the Bresenham algorithm to straighten the path and remove redundant points. Further optimize the path using gradient descent.
- (5) Step 5: Legality check. Ensure all points on the path are within the map boundaries and not obstacles. If any point fails the check, recalculate the path.
- (6) Step 6: Return the optimized path. If the open list is empty and the goal node is not found, report that the path is unreachable.

3.4. Simulation experiments and performance analysis of traditional A* algorithm vs improved A* algorithm

3.4.1. Establishment of the map model

In the autonomous navigation of inspection robots, grid maps are a commonly used method for environmental representation. They are typically generated by combining Light Detection and Ranging (LiDAR) sensor data with Simultaneous Localization and Mapping (SLAM) algorithms to create a 2D grid map. The resulting grid map of

the power plant fans is shown in **Figure 3**.

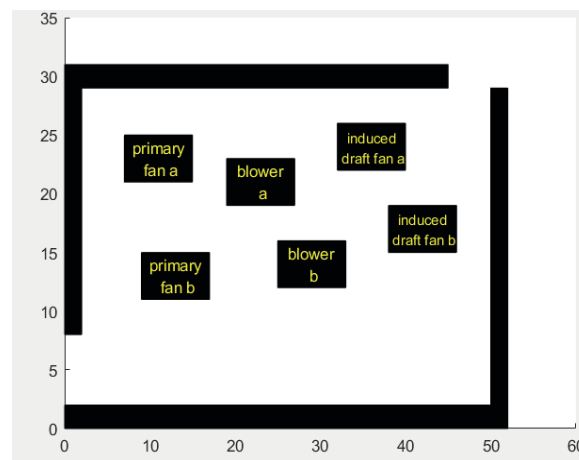


Figure 3. Grid map

3.4.2. Simulation comparison

The effectiveness of the improved A* algorithm for path planning is verified based on the generated 2D grid map. The path planning results of the traditional A* algorithm and the improved A* algorithm for the inspection robot are shown in **Figure 4**.

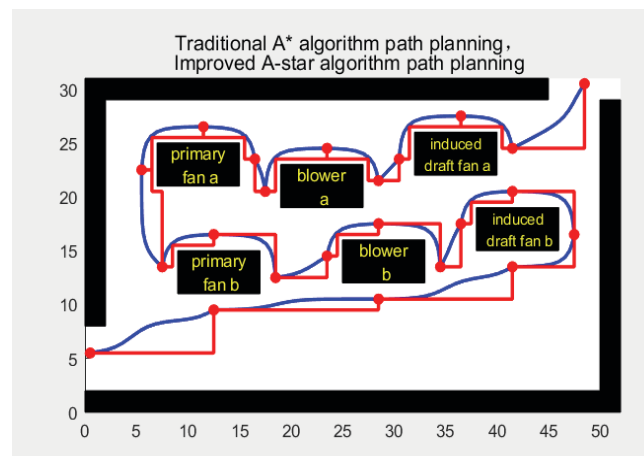


Figure 4. Path planning comparison between traditional A* algorithm and improved A* algorithm

The differences between the traditional A* algorithm and the improved A* algorithm in key metrics are statistically analyzed. These metrics include obstacle avoidance capability and path optimization performance. The results are shown in **Table 1**.

Table 1. Data comparison of path planning between traditional A* algorithm and improved A* algorithm

Metrics	Traditional A* algorithm	Improved A* algorithm
Total steps	211	211
Total distance (m)	200.3m	198.7m
Computation time (s)	0.1234s	0.1402s
Smoothness	2.95	1.85
Detour rate	1.25	1.05
Obstacle proximity	3.72	4.23
Directional angle change (°)	320.5	180.2

The experimental results show that the improved A* algorithm significantly outperforms the traditional A* algorithm. It achieves better performance in path smoothness, detour rate, and obstacle avoidance. This enhances the efficiency and safety of path planning for inspection robots in complex environments.

4. Conclusion

This paper proposes an intelligent inspection robot path planning scheme for fans based on an improved A* algorithm. The goal is to enhance the efficiency and accuracy of path planning for fan inspection tasks in thermal power plants. By introducing obstacle penalty terms, path reconstruction, and smoothing optimization techniques, the improved A* algorithm increases path flexibility, obstacle avoidance capability, and smoothness in complex environments. Simulation results show that the improved A* algorithm outperforms the traditional A* algorithm in total path distance, smoothness, and detour rate. It significantly improves path planning efficiency and safety. This research provides a theoretical foundation and technical support for the design of intelligent inspection systems. It also promotes the development of unmanned inspection systems.

Disclosure statement

The authors declare no conflict of interest.

References

- [1] Zhou Y, Wang W, Li Z, et al., 2020, Application Research on Path Planning of Mobile Robots Based on A Algorithm. *Computer Knowledge and Technology*, 2020, 16(13): 1–3 + 10.
- [2] Delobel L, Aufrere R, Debain C, et al., 2019, A Real-Time Map Refinement Method Using a Multi-Sensor Localization Framework. *IEEE Transactions on Intelligent Transportation Systems*, 20(5): 1644–1658.
- [3] Lin H, Dan X, Jian O, et al., 2021, Review of Path Planning Algorithms for Mobile Robots. *Computer Engineering and Applications*, 57(18): 38–48.
- [4] Ouyang M, Ma Y, 2020, Path Planning for Gravity Aided Navigation Based on Improved A* Algorithm. *Chinese Journal of Geophysics*, 63(12): 4361–4368.
- [5] Lai R, Dou L, Wu Z, et al., 2024, Fusion of Improved A* and Dynamic Window Approach for Mobile Robot Path Planning. *Journal of System Simulation*, 36(08): 1884–1894.

- [6] Chen X, Ren G, 2020, Key Technologies and Development Trends of Intelligent Manufacturing and Robot Application. IOP Conference Series: Earth and Environmental Science, 461(1): 1–4.
- [7] Patle BK, Babu LG, Pandey A, et al., 2019, A Review: On Path Planning Strategies for Navigation of Mobile Robot. Defence Technology, 15(4): 582–606.
- [8] Jin S, Kou Z, Wu J, 2022, Research on Path Planning and Tracking Algorithm for Coal Mine Fan Inspection Robot. Coal Science and Technology, 50(5): 253–262.
- [9] Zhao J, Feng S, Sun T, et al., 2020, Functional Design and Application of Intelligent Robot Technology in Coal-Fired Smart Power Plants. Energy Technology, 2020(4): 35–42.
- [10] Liu X, Li X, Wang J, 2018, Research on Mobile Robot Path Planning Based on Improved A* Algorithm. Computer Applications and Software, 35(10): 194–199.
- [11] Cai X, Xu J, Zhao F, 2019, Research on Path Planning for Intelligent Robots Based on Improved A* Algorithm. Robotics, 41(6): 809–818.
- [12] Wang X, Wang S, Wang X, 2017, Path Planning Optimization Based on Genetic Algorithm and A* Algorithm. Computer Engineering and Design, 38(7): 1679–1684.
- [13] Han J, Zhang Y, Sun X, 2020, Path Planning Research Based on Improved Dijkstra Algorithm. Automation Technology and Application, 39(2): 102–106.
- [14] Chen X, Zhu D, Tian F, 2021, A Robot Path Planning Method Based on Dynamic Weight A* Algorithm. Robotics Technology and Applications, 46(2): 40–47.
- [15] Wang J, Zhang H, Li Y, 2021, Optimization of Path Planning Based on Genetic Algorithm and A* Algorithm. Computer Science and Exploration, 15(6): 1122–131.

Publisher's note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Research on Innovation and Application of Integrated Media Content Generation Based on Artificial Intelligence

Xiu Wang*

Shanghai Zhongqiao Vocational And Technical University, Shanghai 201514, China

*Corresponding author: Xiu Wang, 18321702017@163.com

Copyright: © 2025 Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY 4.0), permitting distribution and reproduction in any medium, provided the original work is cited.

Abstract: As an emerging form of media, integrated media not only enriches the expression and dissemination of information, but integrates various forms, both online and offline, to enable resource flow and cross-platform communication. With the development and application of information technology and 5G technology, the information needs of the broad audience have undergone a shift from a single media format to more diversified and personalized integrated media content. The rapid development of Artificial Intelligence (AI) technology has provided strong support for the generation and innovation of integrated media content. Through automation, multimodal content generation, immersive experience, and other ways, the application of Artificial Intelligence technology can not only improve the efficiency of content creation and enrich creative expression forms, but also provide users with more diversified and personalized information.

Keywords: Integrated media content; Artificial Intelligence technology; Dissemination of information

Online publication: February 14, 2025

1. Introduction

At present, with the rapid development of computer technology and scientific advancements, Artificial Intelligence (AI) technology has made significant breakthroughs in the fields of academia, media, and technology, gradually becoming the driving force behind the new wave of socio-economic development. By its inherent advantages, AI technology has driven industry innovation, technological breakthroughs, and information dissemination, and has been widely applied in various fields of society. In the new era, traditional forms of media creation and communication are facing unprecedented challenges. As the product of the convergence of various media types, integrated media effectively presents information through diversified expressions, which is consistent with people's needs for information in the context of the new era. Therefore, AI technology brings more possibilities and development space for the innovation and application of integrated media content.

2. The advantages of AI technology in the generation of integrated media content

2.1. The improvement of content generation efficiency

The rapid development of AI technology has driven openness and innovation of content creation in the media era. Through the application of AI technology, the integrated media industry can improve the speed and efficiency of content creation, reduce cumbersome workflows, and promote the positive development ^[1] of content generation and dissemination under the support of massive resources. At the same time, with the application of AI technology, integrated media can not only handle many labor-intensive tasks, such as content editing, proofreading, and formatting adjustments but also enable automated content generation and reduce the consumption of manual operation processes and related energy. AI-driven content creation and data organization ensure the effective utilization of massive resources, further reducing resource and energy waste.

2.2. The enhancement of user interaction experience

Through intelligent algorithms and machine learning technology, AI technology can integrate multiple types of data and resources, such as text, images, and audio, to create more diverse and vivid media content and enhance users' immersive experiences. In the process of analyzing input textual data, AI assistants and language processing technology enable the system to automatically process and generate the required content, and adapt to different expressions and user needs ^[2]. Image recognition technology and intelligent algorithms can extract the required content, images, and audio from vast resource databases and integrate them with creative content, thereby enhancing the visual expression of the content and improving the user experience. Furthermore, with the application of AI technology, the input text can also be transformed into natural, smooth, and logical speech, which makes the creation of content more diversified, to enhance the practicability of content and user interactivity ^[3]. By searching and integrating various data, AI technology not only improves the efficiency of integrated media content generation but also provides users with customized content through autonomous operation, driving convergent media content toward more innovative and personalized directions.

2.3. The creativity and diversity of content creation

With its superior computational power, recognition abilities, and monitoring capabilities, AI technology can analyze and monitor ^[4] behavioral data of users from multiple perspectives and all-around aspects. By monitoring and analyzing users' information needs and behavioral data, AI systems are capable of identifying automatically users' preferences and related content, thereby promoting the optimization and filtering of content. Using machine learning algorithms and data analysis tools, AI technology extracts keywords for content creation from various data of users, including indicators such as search interests, viewing time, and comment forms. The application of this technology allows creators to adapt the direction and quality of content generation in real-time according to changes of the times and users' information needs, facilitating the innovative development of integrated media. Furthermore, it is AI technology that can automatically adjust the generation patterns, themes, and editing ^[5] of the content based on the audience's acceptance and click-through rates. By analyzing the characteristics of the era and popular trends, AI technology can quickly capture potential patterns in data or emerging viewpoints, enabling it to be integrated and published to some extent, and identify innovative opportunities at the forefront of technology, driving intelligent development and fostering new business breakthroughs.

3. The challenges faced by AI technology in the generation of integrated media content

3.1. Technical challenges

Currently, although AI technology is extensively applied across various fields, ensuring consistently high standards and quality of results remains challenging ^[6]. There are still some difficulties in dealing with more complex and high-quality content, especially in the field of integrated media content generation. For example, It is difficult to understand and generate texts with deep connotations in processing and analyzing text for AI technology, due to the unique expressive techniques and logic of language. Moreover, while AI technology can preprocess image data through deep learning algorithms, it is still difficult to generate high-quality images or visuals due to the influence of image format, size, audio, and other factors, which harms the application range of AI technology in integrated media content creation.

3.2. The bottleneck of creation

Although AI technology is widely applied in the media industry, the content it generates is largely based on existing data and materials from databases, often lacking innovation, which results in high repetition rates. Additionally, the content generated by AI technology lacks a certain level of depth. Specifically, while AI technology can extract and combine qualified data, it lacks human creativity and emotional expression, making it difficult to simulate human activities or thoughts in the form of programs, resulting in the lack of a certain depth of the final content. Furthermore, the content generated by AI technology may contain errors or biases due to biases in the database content, which may lead to transmission accidents of information ^[7].

3.3. Ethical and social responsibility issues

As Artificial Intelligence technology expands within the integrated media sector, ethical dilemmas and social responsibility concerns have become increasingly prominent. On the one hand, AI-generated content is highly likely to involve issues related to copyright and privacy. For example, it is difficult for AI technology to distinguish between copyright and non-copyright content, making it prone to copyright disputes when extracting content. Additionally, extracting others' privacy or related data without their consent may lead to legal disputes ^[8]. On the other hand, AI technology can't filter information, making it prone to generating misleading content, such as unethical material or content that could destabilize society, potentially triggering major information incidents. Moreover, the widespread use of AI technology has greatly reduced labor and resource costs, causing major changes in the job market and increasing employment competition.

4. The innovation in AI-driven content creation for integrated media

4.1. Promoting the creation of multimodal content and innovation in presentation forms and enhancing communication effectiveness

- (1) Application of Natural Language Processing (NLP) technology: As an important application technology of AI, Natural Language Processing (NLP) technology plays an essential role in content generation and creation, which has brought great changes to the creation of integrated media content. Firstly, sentiment analysis, a technique within NLP technology, can deeply identify and analyze attitudes and emotional tendencies in data during content creation, providing users with more authentic feedback of the public. This allows users to refine and customize content more effectively, enabling them to address the diverse

and evolving needs of their audience with greater precision and relevance. Secondly, NLP technology can also organize and analyze extracted texts or images, helping creators quickly filter valuable content to enhance its depth and professionalism. Finally, virtual robots have emerged as vital tools in media content creation, facilitating real-time interaction with users and enabling the timely collection of user feedback, which helps in delivering content that effectively meets user demands.

- (2) The technology of text generation based on deep learning: In the creation of integrated media content, deep learning technology plays a crucial role in text summarization, text translation, and text generation, which significantly enriches the means and methods of integrated media creation ^[9]. Deep learning technology is capable of autonomously extracting the core content from data or text, generating concise and coherent summaries, and enabling users to rapidly access and comprehend key information. Additionally, it can process massive amounts of data and break language barriers, allowing readers worldwide to access and comprehend published content.
- (3) The vivid generation and optimization of video content: The system of automatic video content generation usually consists of multiple modules, including text-to-speech, text-to-graphics, image-to-video conversions, and so on. Under the guidance of instructions, the automatic video generation technology can prioritize and select character images, text backgrounds, action scenes, and expressions based on textual information, ultimately producing high-quality short video content.

4.2. Strengthening the creation and innovation of integrated media content and providing personalized intelligent services

With the rapid advancement of AI technology, the creation of integrated media content has gradually undergone a significant transformation, evolving from single-modal to multi-modal in content generation, which not only enables basic content generation but contributes to the creation of innovative and creative content. For example, AI technology can automatically generate images, design proposals, and short video scripts, greatly expanding the boundaries of content creation and providing new inspiration and tools for content creators. The introduction of multimodal models for AI technology enhances the capability to process and manage complex content, allowing media professionals to automatically generate summaries based on the use of visual data and multimedia tools, generating more enriched and scientifically-backed content, providing readers with immersive video experiences ^[10].

Speech synthesis technology, another crucial technology driving the advancement and innovation of integrated media creation, is capable of converting text automatically into natural, fluent speech, enabling machines to perform speech broadcasting like humans. Firstly, the multimedia system can automatically generate news broadcast audio by applying speech synthesis technology, allowing media professionals to easily download and utilize the content. The application of automatic speech synthesis technology not only enhances the efficiency of news production but also generates diverse news broadcasts to meet the varied needs of the audience.

Secondly, speech synthesis technology can support broadcasts in multiple languages, offering the potential for international integrated media organizations with greater long-term development ^[11]. Through speech synthesis technology, integrated media agencies can quickly expand overseas markets and provide personalized news broadcast services to users worldwide.

Finally, speech synthesis technology can customize personalized news broadcasts, thereby enhancing user engagement and frequency of interaction, which ultimately contributes to an improved user experience.

4.3. Optimizing distribution paths of content, achieving intelligent communication, and content delivery

- (1) User profile-based content recommendation algorithms: By utilizing user profiles, AI-driven content recommendation algorithms technology can more accurately analyze users' needs and preferences, thereby offering more targeted and relevant content. For instance, media platforms can recommend relevant news or articles based on their reading habits and saved content preferences^[12]. Video platforms can recommend video content of interest based on their viewing history and time spent watching. Users no longer need to invest significant time in searching for content of interest. Instead, they can directly access content that has been carefully curated for them by the recommendation system.
- (2) Keyframe-based video editing technology: Keyframe is a fundamental tool in both video editing and content analysis. Keyframe-based video editing technology can automatically extract the keyframes in the video and improve the editing speed and quality of the video based on the association and transition effects of content^[13]. Traditional video editing requires users to manually select frames for editing, however, with the application of AI technology, this process can be fully automated, allowing for the swift extraction and editing of keyframes, greatly improving the editing efficiency.
- (3) Sentiment analysis-based video editing technology: As an important technology in the field of Artificial Intelligence, sentiment analysis is typically used to filter and analyze the key content and emotional trends in text, speech, or images^[14]. In the work of video editing, AI-driven sentiment analysis technology can automatically detect the emotional trend in the video, and adjust the proportion of the frames, the integrity of the storyline, and the state of the characters according to the content and plot changes. Additionally, sentiment analysis-based video editing technology plays an important role in the creation and production of video advertisements. Through the collection and analysis of data, AI technology can more accurately grasp the needs of audiences, provide data support for advertising production and delivery, and improve the communication efficiency of advertisement distribution.

4.4. Strengthening innovative interaction and communication models of media integration and enhancing the sense of user participation

Firstly, 3D modeling technology, under the framework of AI technology, has been widely applied in integrated media, with virtual host designs being particularly popular among media professionals. Through 3D modeling technology, media workers can create vivid and realistic virtual hosts, including facial details, expressions, height, and other aspects. Additionally, the design of virtual hosts can be altered according to the scene or the theme, allowing for effective integration into work settings and creating more realistic and engaging media content, thereby enhancing the users' sense of participation and immersion.

Secondly, in the creation of integrated media content, images, and illustrations are essential parts of the article, serving as key factors in improving the efficiency of information dissemination and enhancing users' interaction. In the traditional work of content creation, images and illustrations need to be manually searched and analyzed. However, with the support of AI technology, news systems can autonomously generate images and illustrations based on the textual content, and publishers can also use AI to automatically insert relevant illustrations^[15]. With the assistance of AI, animation companies can reduce the investment of manpower, improve the efficiency and quality of creation, and promote the customization and personalization of media content.

Lastly, AI technology can expand the forms and scope of integrated media content expression. By utilizing

new algorithms, AI technology is capable of adding creative effects to the original text based on hot topics or trends, making it more engaging and captivating. For example, AI can automatically generate visual animations that match the scene content, and it can also create music works that perfectly blend with the video content. This greatly improves the innovation of the content, which is conducive to enhancing the users' sense of experience and participation.

5. Conclusion

In conclusion, within the realm of Artificial Intelligence, the ongoing advancements in information technology and the development of intelligent systems have led to increasingly diversified user information demands. This has rendered the innovation of integrated media content an urgent priority for the contemporary media industry. Artificial Intelligence not only broadens the scope of expression for integrated media content, enhancing its innovation and diversity, but also significantly improves user experience. To achieve this, promoting the innovation of multi-modal content creation and presentation methods, reinforcing the creation and innovation of integrated media content, optimizing content dissemination pathways, and enhancing the innovative interaction and dissemination models of integrated media can maximally promote the innovation and application of integrated media content, thereby optimizing content creation and dissemination.

Disclosure statement

The author declares no conflict of interest.

References

- [1] Tang J, 2024, Practice Analysis of Artificial Intelligence in Media Content Production and Communication—Taking the Evolution of Cover News Client Version 10.0 as an Example. *Media Review*, 2024(10): 19–21.
- [2] Xu Z, 2024, Research on Empowering Content Production of County-Level Integrated Media with Intelligent Virtual Anchors. *Radio and Television Technology*, 51(10): 68–72.
- [3] Chen Z, Zeng Z, Xu G, et al., 2024, Design and Implementation of AI-Powered Platform for Media Content Security Perception and Control. *Modern Television Technology*, 2024(03): 75–78.
- [4] Ma X, Zou Q, 2024, A New Stage of Media Evolution: The Transformation of Intelligent Media Ecology Driven by Artificial Intelligence. *China Television*, 2024(02): 22–29.
- [5] Lv Y, 2023, Research on Media Content Production in the Wave of Generative Artificial Intelligence: A Case Study of ChatGPT. *Science and Technology Communication*, 15(24): 123–126 + 130.
- [6] Shi D, Gu G, 2023, Design and Implementation of a New Generation of Intelligent Media Asset System Based on “Center + Edge” Cloud Architecture. *Modern Television Technology*, 2023(10): 80–86.
- [7] Liu G, 2023, The Implementation of Artificial Intelligence in the Production and Operation of Ultra-Clean Media Content. *Radio and Television Information*, 30(01): 39.
- [8] Sun Q, Gu G, 2022, Exploration of Integrated Media Intelligent Content Management System Based on “Cloud + Edge” Architecture. *Radio and Television Information*, 29(10): 36–39.
- [9] Cai H, 2021, Exploration and Practice of Intelligent Production System of Changjiang Cloud Integrated Media Content Production Platform. *Film and Television Production*, 27(05): 67–69.

- [10] Ye X, 2020, Content Development and Pathways for Enhancing Communication Power in Smart Integrated Media. *Southeast Communication*, 2020(10): 17–19.
- [11] Wu K, 2020, Analysis of the Transformation of Grassroots Traditional Media News Production in the Era of Integrated Media. *Journal of Journalism Research*, 11(16): 181–182.
- [12] Duan P, 2020, On the Practical Pathways for Building China’s Intelligent All-Media Communication System: Content, Framework and Mode. *Modern Publishing*, 2020(03): 11–18.
- [13] Yang BD, Liu JW, 2020, Technology, Product and Content: Key Issues and Approaches of Current Media Integration. *Journal of Social Sciences*, 35(03): 93–97.
- [14] Cao SS, 2019, Innovative Development Pathways for Intelligent Integrated Media in the Context of an All-Media Landscape. *Leadership Science Forum*, 2019(16): 60–81.
- [15] Zeng X, Qi H, 2019, A Preliminary Study on the Development of Intelligent Media Under the Background of 5G Technology. *Television Research*, 2019(06): 14–17.

Publisher’s note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Study on Bionic Fabrication and Morphology of the Two Wings of the Tiger Papilio

Fuming He, Yaxuan Wang, Zhenyu Xiong, Yang Li*

Hunan Applied Technology University, Changde 415000, China

*Corresponding author: Yang Li, liyang5862022@163.com

Copyright: © 2025 Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY 4.0), permitting distribution and reproduction in any medium, provided the original work is cited.

Abstract: Based on research into bionic butterflies for environmental detection and ecological management, a scheme was proposed to develop and manufacture a bionic aircraft with two wings inspired by specific butterfly species. A flapping-wing aircraft with a simple structure was designed, and its two-wing design was optimized. The research focused on several key areas: the design and optimization of the wings, the development of the transmission mechanism, hardware design and fabrication, and 3D printing for component manufacturing. This resulted in the bionic replication of the wing shape and structure of the Tiger Papilio butterfly. The final bionic butterfly features a wingspan of 29.5 cm and a total weight of 13.8 g. This project integrates mechatronic principles and provides a valuable reference for advancements in the field of bionic butterflies. Future research could explore the aerodynamic characteristics of wings and innovative design approaches in greater depth.

Keywords: Bionic butterfly flying vehicle; Two wing design; Bionic design

Online publication: February 17, 2025

1. Introduction

Currently, there are specific research projects focused on bionic butterflies ^[1]. However, the application of bionic butterflies for environmental detection and ecological management remains in its early stages. Most bionic butterfly materials are lightweight, expensive, and technically demanding, limiting their widespread adoption in society. Despite these challenges, bionic butterflies hold significant market potential in areas such as environmental monitoring and biology education. However, their complex flight principles and the low Reynolds number aerodynamic mechanism have resulted in limited attention to their application in environmental supervision.

On the other hand, as traditional fixed-wing aircraft and rotorcraft technologies continue to mature, flapping-wing aircraft have demonstrated better adaptability to complex environments due to their superior maneuverability and control performance. These characteristics offer unique advantages in specific application scenarios ^[2]. As a result, a growing number of researchers have been drawn to the study of flapping-wing bionic butterfly aircraft, leading to significant advancements in recent years. However, despite their outstanding performance

and development potential, flapping-wing aircraft face persistent challenges. Notably, insufficient lift remains a key issue, preventing stable flight over extended periods. To address these challenges and ensure the necessary flapping deformation and lift during flight, the design of the wings and the selection of appropriate materials have become critical areas of research.

2. Research and design of bionic butterfly wings

2.1. Two-wing design

Butterflies possess exceptional flight capabilities, which are closely related to their wing geometry, vein structure, and mass distribution ^[3]. Butterfly flight typically involves the periodic up-and-down flapping of their two wings, forming an arc shape. Based on studies of fluid-structure coupling in flapping-wing aircraft and butterfly flight dynamics, the Tiger Papilio butterfly was selected as the research subject for designing and analyzing the two-wing profile. Research into the Tiger Papilio's wings revealed the following: during unpowered level flight, the butterfly demonstrated greater stability in straight flight due to its flat front wing and pronounced arc shape. Additionally, its smooth wings exhibited favorable stall characteristics at high angles of attack and optimal lift-to-drag performance at small to medium angles of attack ^[4].

Accordingly, the front wing of the butterfly-inspired aircraft in this project is designed with a larger arc, similar to most natural butterfly wings, while the rear wing features a smoother edge, akin to an elliptical wing found in fixed-wing designs. The vein skeleton structure of the wings mimics the vein distribution of the Tiger Papilio butterfly. The experimental design will be further optimized and refined in future studies.

The model created in CAD software was imported into SolidWorks for preliminary simulation and optimization, resulting in a finalized three-dimensional model. The edge line of the two wings should ideally be parallel to the longitudinal axis of the torso or fall within an optimal range of -30° to $+30^\circ$, ensuring that the trunk axis forms an acute angle relative to the wings. The inner edge line of the wing and the spar typically range between 70° and 110° , with the optimal range being between 80° and 100° ^[6].

2.2. The arrangement and distribution of carbon rods inside the two wings

Referring to the butterfly wing structure, this project uses carbon rods and lightweight film to simulate the butterfly wing veins and wing film. The wing film is made of polyethylene terephthalate (PET) film material, which has good stiffness and flight ability. In order to improve flight stability, this project designs three butterfly wing structures for experimental analysis.

In experiment 1, the carbon rods were distributed throughout the wing membrane, in experiment 2, the carbon rods were distributed throughout the wing membrane and longitudinally in the extended wing vein, and in experiment 3, the carbon rods were distributed longitudinally in the extended wing vein. The main object of structural analysis is the distribution of carbon rods on the wing surface. After preliminary modeling with SolidWorks, finite element mesh division is carried out with Ansys. Two kinds of materials were used for the wings, and material cards were established for experimental testing.

Through the experimental analysis, the three design schemes meet the allowable stress value, in which experiment 1 deformation is the largest, experiment 2 deformation is the smallest, and experiment 3 deformation is close to experiment 1, thus we choose design from experiment 2 as the final structural design.

2.3. Material selection of the two wings

Based on bionics research, it is found that the flexibility of butterfly wings in all directions is different, and it is precisely because of this that butterfly wings have good aerodynamic performance to meet flight needs ^[7]. The study found that most of the wings of simulated butterflies are made of thin film materials. To meet the lift requirements of the aircraft, the project studied different thin films. The performance of each material was analyzed and compared, and PET film with a thickness of 0.012 mm was selected to manufacture the two wing films, which have a longer flight distance in the experiment and better performance than other materials. Moreover, the PET film is not easy to deform under surface tension and has certain flexibility, meeting the flight requirements ^[8].

3. Modeling analysis

As the core structure of the entire device, the main torso primarily consists of the carbon main rod, motor bracket, control board fixing bracket, battery connection bracket, and rear wing bracket. Among these components, the controller connection bracket is specially designed, with two such brackets included, along with one battery bracket. These brackets are made of Polylactic acid (PLA+), a material known for its good strength and moderate toughness, providing stable and reliable support and connections for all components.

The rear wing bracket and the wing drive mounting bracket have adjustable characteristics on the axis of the main trunk, which is of great significance. By adjusting the position of these brackets on the axis, the position of the left-wing assembly, the right-wing assembly, the micro-control system, and the power supply system can be accurately adjusted effectively. In the actual operation process, this adjustment function can be flexibly carried out according to many comprehensive factors such as the aerodynamic force of the left-wing assembly and the right-wing assembly, as well as its gravity. When the wing receives large aerodynamic force and its gravity distribution is unbalanced, the relative position of each component can be changed by adjusting the position of the support, to optimize the stress state of the entire device, ensure its stability and balance in the process of flight or movement in the air, so that the device can better adapt to different working environments and task requirements ^[9]. This greatly enhances the flexibility and reliability of the entire system.

4. The selection of other components

4.1. Transmission mechanism

The design of the transmission mechanism largely determines the aerodynamic characteristics of the bionic vehicle ^[10]. Nowadays, the common micro-aerial vehicles are divided into rotorcraft, fixed airfoils, and flapping airfoils. To make the bionic butterfly aircraft of aircraft more like the butterfly flying posture in the natural state, the project is designed and manufactured by the V-type flapping wing aircraft. Through various studies, the micro-flapping wing-type aircraft is based on imitating the biological flight mechanism, using the periodic movement of the two wings to generate the thrust and lift required for flight, and has the advantages of good maneuverability and less energy consumption during flight. The project research proposed CAM rocker design transmission mechanism. In the research, it is found that the CAM rocker mechanism has good bionic characteristics, and the down flutter accounts for 60% of the whole flapping process in the flapping cycle. In a certain range, it can obtain a large lift and thrust force ^[11]. The working principle of the designed flapping mechanism is that the circular CAM drives the guide rod to move up and down under the action of the motor. Thus, the rocker connected with the guide rod is driven to move up and down ^[2].

4.2. Hardware design

The 8-bit AVR microcontroller ATMEGA328P-AU is selected as the main control chip of the small bionic butterfly flying machine. The chip is not only small in size, which can meet the requirements of lightweight design of the aircraft, but also powerful in performance. It can execute powerful instructions in a single clock cycle, and the throughput is close to 1MIPS per megahertz. Such characteristics enable us to optimize the power consumption of the whole machine while ensuring the processing speed^[12]. To meet the trajectory requirements of remote control, the project reserves the pins required for remote control reception in the main control circuit. Through the experimental test of pitching attitude and propulsion efficiency, the bionic butterfly aircraft obtained the most efficient motion mode, that is, flapping wings at a frequency of 1–2 times per second, starting at a position with an angle of 60° from the horizontal plane where the main torso is located, descending to a position with an angle of -10°, and then flapping up and down in this form^[13]. According to the formula calculation, the project can achieve the maximum speed of the bionic butterfly aircraft can reach 1.5 m/s, with a flight time of 3–4 minutes, and with an 80 mAh lithium battery of the power supply system that needs to be charged for 10 minutes.

4.3. Aircraft parts design

To better reduce the weight of the butterfly aircraft, part of the designed parts are made by Fused Deposition Modeling (FDM) 3D printing. Different from the traditional flapping wing flight, this project designed each bracket in the form of a clamping head, which can effectively reduce the weight and simplify the subsequent installation and debugging procedures. Taking the motor bin as an example, after the initial modeling in SolidWorks, the model was imported into Cura to establish support and passed into the printer for printing. Considering that the precision of aircraft parts production is difficult to control, and the impact of high-altitude air flow needs to be considered, the PAL+ material 3D printing technology is optimized in this project, and the printing layer thickness, printing angle, and printing temperature are studied and found that when the thickness of the printing layer is 0.2 mm ~ 0.3 mm, the printing angle is 700, and the printing temperature is 200°C, the mechanical properties of the printed parts are the best^[14]. Under this condition, the motor bin and the connecting rod are manufactured.

5. The production and debugging of the two wings of the bionic butterfly aircraft

5.1. Prototype production

According to the original bionic design scheme, the overall shape layout and partial parameters of the two wings of the aircraft can be obtained. The design of two wings from Computer-Aided Design (CAD) is exported to engineering drawings and printed. The two wings of the bionic butterfly aircraft were made of PET film with a thickness of 0.012 mm and carbon fiber rod. The PET film was placed in the engineering drawing and trimmed to produce the two-wing shape. The bionic butterfly flying machine was electrified for the flapping test, and the flight control was carried out by remote control. After turning on the power, the remote control is turned on and the throttle channel is established to control the flapping frequency of the two wings of the bionic butterfly aircraft. The flapping frequency is controlled by the throttle. When the default throttle is in the end, the two wings are stationary. As the throttle is pushed to the highest point, the flutter frequency of the wings gradually increases. When the throttle reaches the highest point, it can be simply tested that the flutter frequency of the two wings is 7 Hz, which meets the design requirements. The rolling rocker of the remote control can be used to control the deviation of the flutter angle of the two wings of the bionic butterfly aircraft. The default is when the rolling rocker

is in the middle position and the left and right sides of the flutter angle are the same. When the rolling rocker is shifted left or right, the two wings will also complete the corresponding flutter angle change, to promote the aircraft to complete the direction turn operation ^[15].

5.2. The weight and physical display of the bionic butterfly flying machine

The final processed bionic butterfly aircraft has a wing size of 29.5 cm and a weight of 13.8 g. The two direct current (DC) motors weigh 2.5 g, accounting for 18.1% of the total weight of the machine. The two wings weigh 3 g, accounting for 21.7% of the total weight of the whole machine. The main control board weighs 0.9 g, 6.6% of the whole machine, and the receiving bag weighs 0.4 g, 2.9% of the whole machine. 3D printing parts (including all transmission mechanisms and all supports) weighing 3 g accounted for 21.7% of the weight of the whole machine. The battery weighs 4 g, which is the heaviest part of the machine, accounting for 29% of the machine.

5.3. Lift test

Let v be the speed of the butterfly when it swings on the wing, F_p is the thrust received by the wing, and F_f is the resistance received by the wing, according to the inclined plate effect Theoretically, we get:

$$F_q = 2 \sin \cos \theta \rho k V^2$$

$$F_f = 2 C_c \sin^2 \theta \rho k V^2$$

It can be seen from the formula that the thrust is close to the maximum and the resistance is close to zero.

$$\Delta V = V \sin \theta$$

$$v_a = \Delta V \cos \theta = V \sin \theta \cos \theta$$

$$v_c = \Delta V \sin \theta = v \sin^2 \theta$$

$$\xi = \frac{V_a}{V_c}$$

Since different flapping angles correspond to different angles of attack, the angle of attack is a function of the flapping angle, and the total resistance after integration can be written as:

$$F_f = 2 c \rho \int_{r_0}^R k \int_{-\varphi}^{\varphi} V^2 \sin \theta \cos \theta dr d\varphi$$

The total lift force is:

$$F = 2 c \rho \int_{r_0}^R K \int_{-\varphi}^{\varphi} k V^2 \sin^2 \theta dr d\varphi$$

In summary, the lift force can be calculated:

$$F = 2 c \rho \int_{r_0}^R K \int_{-\varphi}^{\varphi} k V^2 \sin^2 \theta dr d\varphi = 4 c \varphi (R^2 - r_0^2) \rho k V^2 \sin^2 \theta$$

6. Conclusion

By simulating the wing structure and movement characteristics of a certain butterfly, that is, designing a reasonable wing shape and combining the structure of the bionic butterfly wing with the material of the imitation butterfly wing film and the flight control system, a movable and complete machine is made on the basis of the bionic butterfly technology, which fully reflects the idea of mechatronics. In recent years, the research of bionic

butterfly flying machine has made rapid development, but due to the limitation of science and technology, most of the transmission mechanism still adopts the cumbersome transmission mechanism to realize the flutter of the two wings, and there is still a long distance from the real bionic butterfly. Therefore, future research will focus on the movement of multiple degrees of freedom, and further explore the impact of wing aerodynamic characteristics and novel design ideas on the bionic butterfly, in order to promote the continuous development of the bionic butterfly field.

Funding

- (1) 2023 Innovation and Entrepreneurship Training Project of Hunan College Students: Tiger Butterfly—Bionic Manufacturing and Morphology Research (Project No. S202313809022)
- (2) Key Project of Education Reform of Hunan Provincial Department of Education: Research on Disciplinary Integration Education Model under Intelligence + Empowerment—A Case Study of Robotics and Logistics Management Majors (Project No. HNJG-20231561)

Disclosure statement

The authors declare no conflict of interest.

References

- [1] Zhang Y, Li S, Wang X, et al., 2024, Butterfly Flying Mechanism and Summarized Research Progress in Imitation of Butterfly Flapping Wing Flight Vehicle. *Journal of Engineering Proceedings*, 2024(9): 582–1593.
- [2] Gao Y, Zhong S, Xiong Z, et al., 2019, Design and Analysis of Bionic Butterfly Robot. *Mechanical and Electrical Engineering Technology*, 53(8): 97–100, 123.
- [3] Chen Q, Wan L, Zhang J, 2018, Bionic Butterfly Mechanism Design Based on High Lift Mechanism of Insects. *Journal of Nanchang Hangkong University (Natural Science Edition)*, 32(3): 14–18, 49.
- [4] Mu Z, 2019, Research on Design, Manufacture and Performance of Biomimetic Functional Surface Based on Typical Butterfly Wing, thesis, Jilin University.
- [5] Ye L, 2019, Imitation of Aircraft Design and Manufacture of Butterfly Research, thesis, Shanghai Jiaotong University.
- [6] Lu Z, Tian G, Li R, et al., 2024, Single and Double Electric Machinery Transmission Direct Comparative Study on the Performance of the System. *Journal of Automobile Engineering*, 2024(2): 310–319.
- [7] Zhang R, He W, Wang X, et al., 2022, Design and Aerodynamic Analysis of Cam-Rocker Type Flapping Mechanism for Flapping Wing Aircraft. *Chinese Journal of Applied Mechanics*, 39(01): 72–78.
- [8] Xiao Y, Cui F, Zhang Y, et al., 2023, Butterfly-Like Flapping-Wing Aircraft: Research Progress, Challenges and Future Development. *Unmanned Systems Technology*, 6(3): 45–58. <https://doi.org/10.19942/j.issn.2096-5915.2023.03.25>
- [9] Sun M, Huang H, 2006, Biomimetic Mechanics of Micro-Aircraft—Aerodynamic Characteristics of Butterfly Flight. *Journal of Beijing University of Aeronautics and Astronautics*, 32(10): 1146–1151.
- [10] Lu Z, Tian G, Li R, et al., 2024, Single and Double Electric Machinery Transmission Direct Comparative Study on the Performance of the System. *Journal of Automobile Engineering*, 2024(2): 310–319.

- [11] Li H, Wang H, Liu X, 2024, The Response Surface Method to Optimize the PLA Material Mechanical Properties of 3D Printing Specimens. *Journal of Plastic Science and Technology*, 52(10): 130–135.
- [12] Mu X, 2022, Bionic Flapping-Wing Flight Robot Autonomous Flight Control System Design, thesis, Beijing University of Science and Technology.
- [13] Huang H, He W, Zou Y, et al., 2020, System Design and Control of Butterfly Flapping Wing Flying Robot Based on Line Drive Steering. *Control Theory and Applications*, 39(7): 1203–1210.
- [14] Cheng H, 2020, Overall Design and Control Simulation Imitation Butterfly Craft, thesis, Nanjing University of Aeronautics and Astronautics
- [15] Zhang J, Chen H, Lu Q, et al., 2018, Mechanical Analysis of Flapping Flight of *Polythymus Hydalia*. *Biological Resources*, 40(1): 57–63.

Publisher's note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Research on Bed Call System Based on AT89C52

Hong Wang*, Lili Wu

Sichuan Vocational and Technical College, Suining 629000, China

*Corresponding author: Hong Wang, wanghongsuse@163.com

Copyright: © 2025 Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY 4.0), permitting distribution and reproduction in any medium, provided the original work is cited.

Abstract: How to realize intelligent and fast bed calls has been a key concern of hospitals. The traditional wired bed call system is not only costly but also less efficient. In this paper, research on bed call systems based on AT89C52 microcontroller is carried out. The nurse-side host (AT89C52) and the bedside slave (AT89C52) communicate over long distances using wireless communication technology. The system transmits signals, including Liquid Crystal Display (LCD), voice announcements, and beeping alarms, to indicate the bed number requiring assistance. This allows the nurse to respond promptly. The system supports real-time updates, where calls and processing occur independently, ensuring efficiency. It is not only cost-effective but also enables a rapid and intelligent call-and-response process.

Keywords: Bed call system; AT89C52; Wireless communication technology; Real-time update; Call and processing

Online publication: February 13, 2025

1. Introduction

With the development of society, the intelligent era is gradually entering people's lives, and fast and convenient treatment services are the common expectation of patients ^[1]. The traditional bed call system consists of digital circuits, and the host and the slave are connected by wires but the wiring is very troublesome ^[2]. It takes up a lot of space, narrow range of use, and is not only slow but also high cost, so the patient cannot get effective treatment quickly ^[3]. Therefore, how to realize fast and intelligent bed calls has become a key concern of hospitals ^[4]. In recent years, China has made remarkable achievements in the field of wireless technology and realized many major technological breakthroughs ^[5].

AT89C51 is a microprocessor control chip, which is of low-voltage, high-performance Complementary Metal-Oxide-Semiconductor (CMOS) 8-bit microprocessor with 4 K bytes of Flash memory, and not only has a very high degree of integration, but also can fully utilize the input/output (I/O) ports of the microcontroller, and its energy consumption is relatively low ^[6,7]. In this paper, an intelligent bedside call system is designed using AT89C52 as a microcontroller chip and wireless communication technology for long-distance signal transmission ^[8]. The slave at the bed end sends a call signal to the host at the nurse end through the GH_xUART serial wireless transmitting module, it generates a voice announcement, a buzzer alarm, and displays the need

for help bed number on the Organic Light-Emitting Diode (OLED) LCD ^[9]. The host side then sends processing instructions to the slave for immediate processing ^[10]. This system enables patients and nurses to realize zero-distance communication, which is more convenient and faster and can improve the quality of hospital services and enhance the social competitiveness of hospitals ^[11].

2. System design ideas

Firstly, the patient of the slave machine at the bed presses the key, and the corresponding call indicator of the patient's bed lights up. Then, the information of the pressed button of the slave machine is transmitted to the host of the nurse station through the wireless serial port, the English character "Bed Call" is displayed on the first line of the host's OLED screen, and the corresponding bed number is displayed on the second line. When there is more than one bed call, the first line of the host's OLED screen displays the "Bed Call," and the second line displays the corresponding bed number. At the same time, the buzzer alarm is issued, the alarm light is on, and the voice broadcasts that the patient needs help. Finally, at the nurse station, the host display coordinates the assignment of nurses to provide service and treatment for the corresponding beds. If there are multiple bed calls, the host processes them sequentially using the processing key KEY0. Each time KEY0 is pressed, the system processes the next call in order, extinguishing the corresponding bed number on the OLED LCD screen and turning off the associated indicator light. When all calls have been processed, the alarm stops, and the Light-Emitting Diode (LED) screen displays "Bed Call" on the first line only. The overall design of the system is illustrated in **Figure 1**.

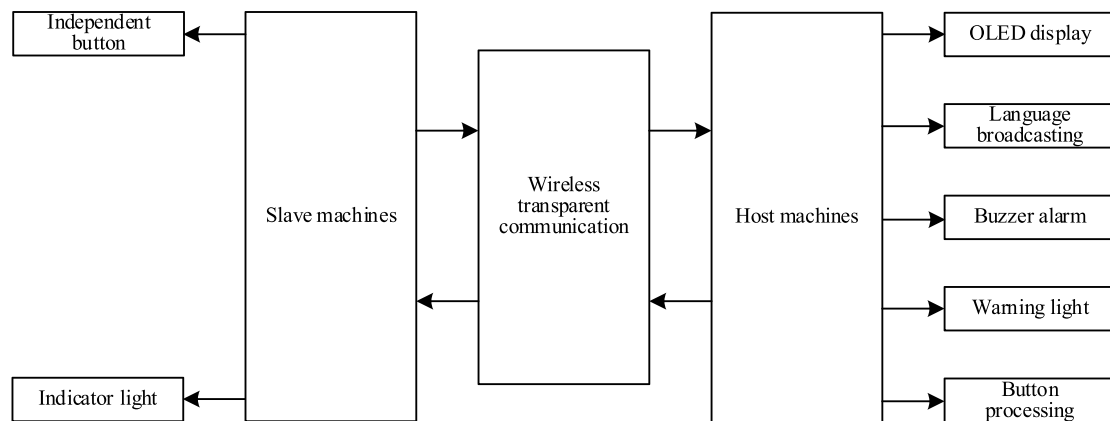


Figure 1. Overall system design

3. System hardware design

The hardware design mainly includes STC89C52 minimum system module, DFPlayer Mini voice broadcasting, OLED0.96 LCD module, GH_xUART serial wireless transmitting module, buzzer module, power supply module, and key module.

The design requires two AT89C52 chips (master and slave), whose minimum systems and their pins (shown in **Figure 2 (a, b)**), 4 K bytes of Flash memory, and 256 bytes of on-chip data memory ^[12]. The minimum system of the AT89C52 microcontroller consists of 32 general-purpose ports, a reset port for external reset circuitry, two crystal ports for external crystal circuitry, a power supply circuit, and a 5 V power supply for its work ^[13].

The design uses a 12 V input voltage, with 5 V as the standard operating voltage for the AT89C52 chip and 3.3

V to 5.5 V as the operating range for other modules. To minimize the use of additional regulator chips and reduce costs, 5 V is standardized as the uniform voltage for the system. To step down 12 V to 5 V, a KIA7805 voltage regulator chip is employed. The schematic diagram is shown in **Figure 2(c)**.

The GH_xUART Serial Wireless Transmission Module is a module that allows simultaneous data transmission and reception, with no interference between the two processes. The module sends data to the target module and automatically switches to the receiving state once the transmission is complete ^[14]. Upon power-up, the LED flashes once to indicate the module has started successfully. During data reception, the LED blinks once, and it also blinks to confirm successful transmission. The minimum interval for sending data is 40 ms. The module features a simple design, is not easily affected by physical factors, and has a compact size with a straightforward circuit design. It operates on a voltage range of 3.3 V to 5.5 V, but can be directly powered by a 5 V supply for simplicity. The pins of the wireless transmission module can be connected directly to the Microcontroller Unit (MCU), as shown in the pin interface diagram in **Figure 2(d)**.

The DFPlayer Mini voice broadcasting module requires minimal peripheral circuitry and can be directly controlled via a serial port. It operates on a 5 V power supply and offers relative independence. However, due to its low audio output, an external audio amplifier is needed for adequate sound amplification. The module requires only a speaker and a power supply to function. Its pin interface is shown in **Figure 2(e)**.

The buzzer module is designed to meet the alarm requirements of the system. When a patient issues a help signal, the host generates an alarm. Through the program, the buzzer can be controlled to alert the nurse. The pin interface for the buzzer module is shown in **Figure 2(f)**.

The Liquid Crystal Display (LCD) module is essential for displaying patient information. At the nurse station, the LCD screen shows the patient's call, enabling more accurate and efficient service. This module is critical for improving service efficiency. The OLED 0.96 display is an organic light-emitting diode with high resolution (128 × 64 pixels) and ultra-low power consumption (0.06 W). The circuit construction is simple, and it can be directly connected to the microcontroller, powered by an external 5 V supply. Its pin interface is shown in **Figure 2(g)**.

Each key on the slave module is equipped with an indicator. When a key is pressed, the call is successful, the LED indicator turns on, and the host's alarm light is activated. When the LED indicator turns off, the host has pressed the processing key, indicating that the patient is being served or treated. The schematic diagram is shown in **Figure 2(h)**.

In this system, the key module consists of eight keys for the slave module and one processing key for the host. The eight keys on the slave represent the eight beds, and the processing key on the host is used to manage the beds, signifying service and treatment. This setup enables human-computer interaction. The schematic diagram for the key module is shown in **Figure 2(i)**.

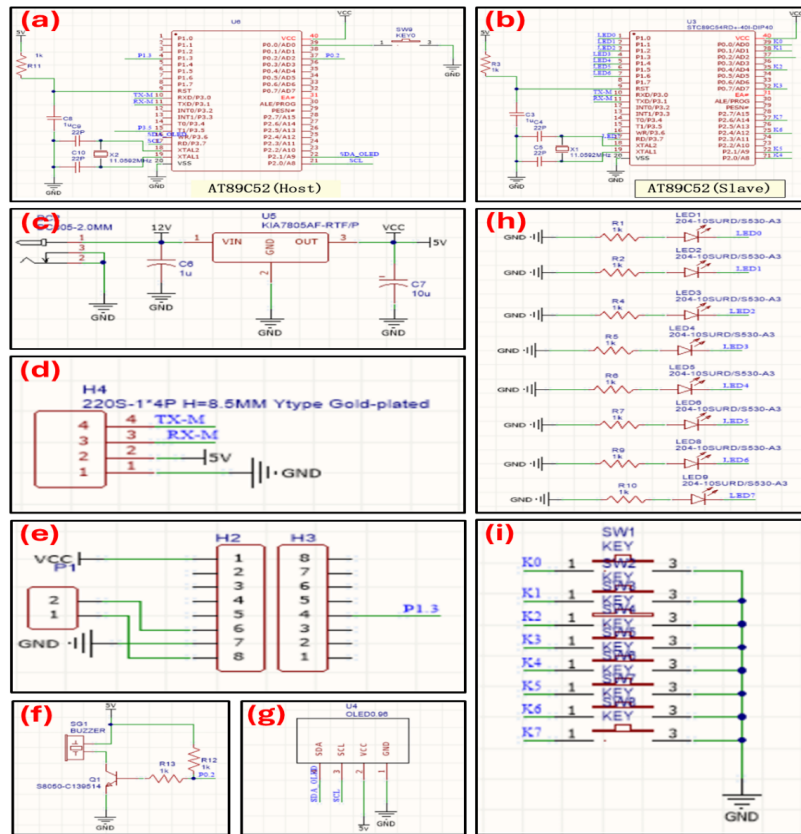


Figure 2. Schematic diagrams of each module: (a,b) master-slave AT89C52 minimum system module, (c) power supply module, (d) GH_xUART serial wireless transmitting module, (e) DFPlayer Mini voice announcing module, (f) buzzer module, (g) OLED liquid crystal display module, (h) LED display light module, (i) key module

4. System software design

4.1. Host program design

First, when the host is powered on, the program begins reading, and the serial port is initialized. The baud rate is set to match the slave, and an initial value is assigned. All interrupts are enabled. The OLED display program is initialized, and continuous updates are performed. The voice module is also initialized, awaiting a response from the slave when a key is pressed.

The host then receives data from the slave through serial communication. If no key is pressed on the slave, the host display functions normally. If a key is pressed on the slave, the OLED screen displays the corresponding bed number of the pressed key, and the buzzer and voice alarm respond immediately^[15].

Finally, the host continuously monitors the KEY0 for processing. When KEY0 is pressed, the host sends data to the slave through the serial port, turning off the corresponding key light and indicating that the treatment and service for the respective bed have been provided^[16]. The design diagram is shown in **Figure 3**.

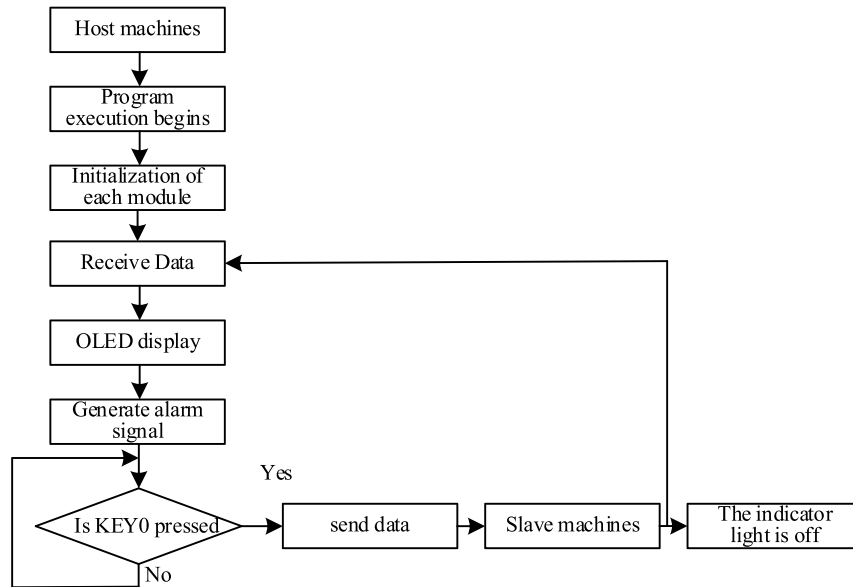


Figure 3. Host program design diagram

4.2. Slave program design

First, when the slave is powered on, the program begins reading, and the serial port is initialized. The baud rate is set to match the host, and an initial value is assigned. All interrupts are enabled. Next, the key status is analyzed. If no keys are pressed, the program continues to check the status of the eight keys. If a key is pressed, the corresponding bed's alarm will be triggered, and the bed's indicator light will turn on, signaling a call. If no key is pressed, the process repeats, continuously checking the status of the eight keys. Finally, the key status is transmitted to the host via serial communication, requesting service or a call. The slave will always wait to receive information from the host. The design diagram is shown in **Figure 4**.

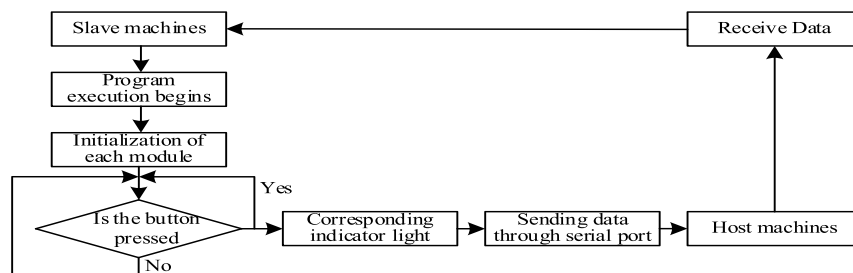


Figure 4. Slave program design diagram

5. System design results

According to the design idea of the bed call system, the specific hardware circuit diagram was constructed and the functional programs were embedded in the master and slave machines to realize the expected design goals.

5.1. No bed call

The master and the slave are powered on at the same time, and the program is downloaded on the master and the slave through the downloader. When there is no bed call from the slave, the OLED of the host only shows “bed

call,” which indicates that there is no bed call, and at the same time, there is no alarm. The physical debugging diagram is shown in **Figure 5**.

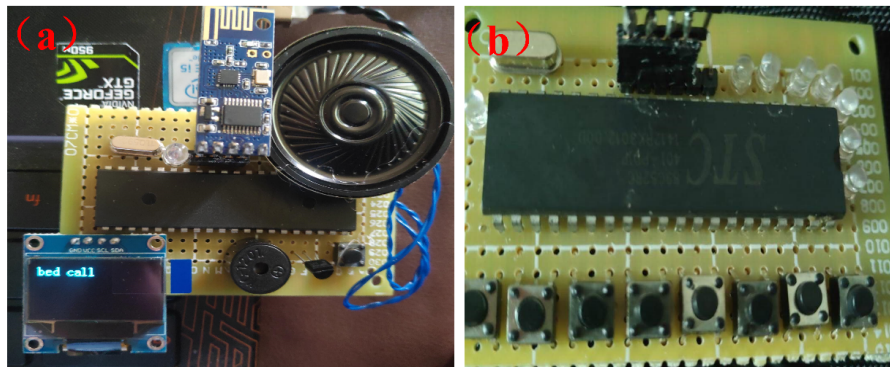


Figure 5. (a) Physical diagram of the master and (b) physical diagram of the slaves

5.2. Only one patient bed calling

When the button for slave No. 4 bed is pressed, it indicates that a patient in bed No. 4 has called for help. The corresponding bed indicator light will turn on, confirming that the alarm has been triggered. Through serial communication, the call for help is sent to the host computer, which will display “Bed Call” on the first line of the OLED screen, and the corresponding bed number on the second line. At the same time, the system triggers an alarm: the buzzer sounds, the alarm light turns on, and a voice prompt announces, “A patient needs help.” The physical debugging diagram is shown in **Figure 6 (a, b)**.

After the nurse presses the processing key KEY0 on the host, the host will send the processed information to the slave via serial communication. The host’s alarm is canceled, and the slave’s indicator light turns off, signaling that the nurse should proceed with service and treatment for the patient. The physical debugging diagram is shown in **Figure 6 (c, d)**.

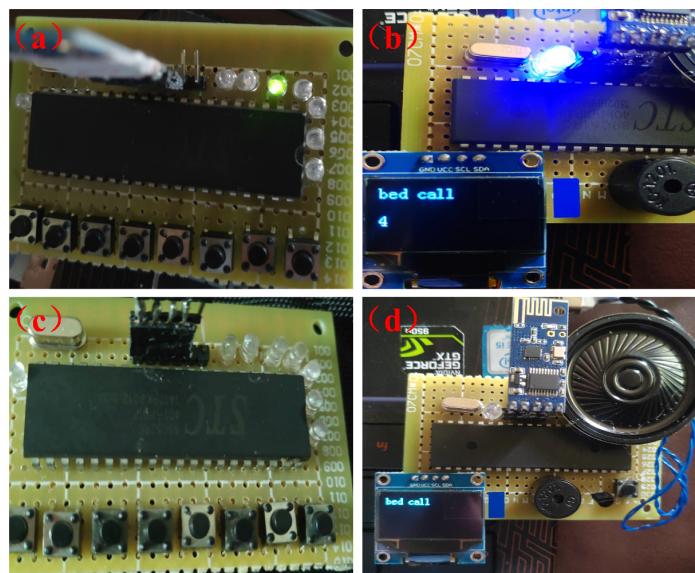


Figure 6. When only one bed is calling: (a) Slave bed No. 4 is calling, (b) the master displays bed No. 4, (c) the slave is extinguished, (d) the master presses the processing key and the bed No. 4 display disappears

5.3. Multiple beds call

When multiple bed calls are made, such as pressing the keys for beds 4, 5, 6, 7, and 3 in sequence, the indicator lights for beds 4, 5, 6, 7, and 3 will turn on. The host receives the signal from the slave and displays “Bed Call” on the first line of the OLED screen, while the corresponding bed numbers (4, 5, 6, 7, and 3) are shown on the second line in the order of key presses. Simultaneously, an alarm is triggered: the buzzer sounds, the alarm light turns on, and the voice prompt announces, “A patient needs help.” The physical debugging diagram is shown in **Figure 7 (a, b)**.

Next, the nurse presses the processing key KEY0 on the host. Each time the key is pressed, the bed calls are processed in order. For example, bed 4 will be processed and treated, its indicator light will turn off, and the OLED screen will continue to display the calls for beds 5, 6, 7, and 3. The physical debugging diagram for this step is shown in **Figure 7 (c, d)**.

The system is updated in real time, allowing the processing and calling functions to operate simultaneously without conflict. Calls can be made while processing and the logic remains intact. If, while processing bed 4, the key for bed 8 is pressed, the bed 8 indicator light will turn on, and the OLED screen will update to display “Bed Call” on the first line, with the bed numbers 5, 6, 7, 3, and 8 on the second line, in the order of the key presses. Simultaneously, the bed 4 indicator light will turn off. The physical debugging diagram is shown in **Figure 7 (c, d)**.

Finally, when the bed 4 call is processed, its indicator light will go off, as shown in the physical debugging diagram in **Figure 7 (e, f)**.

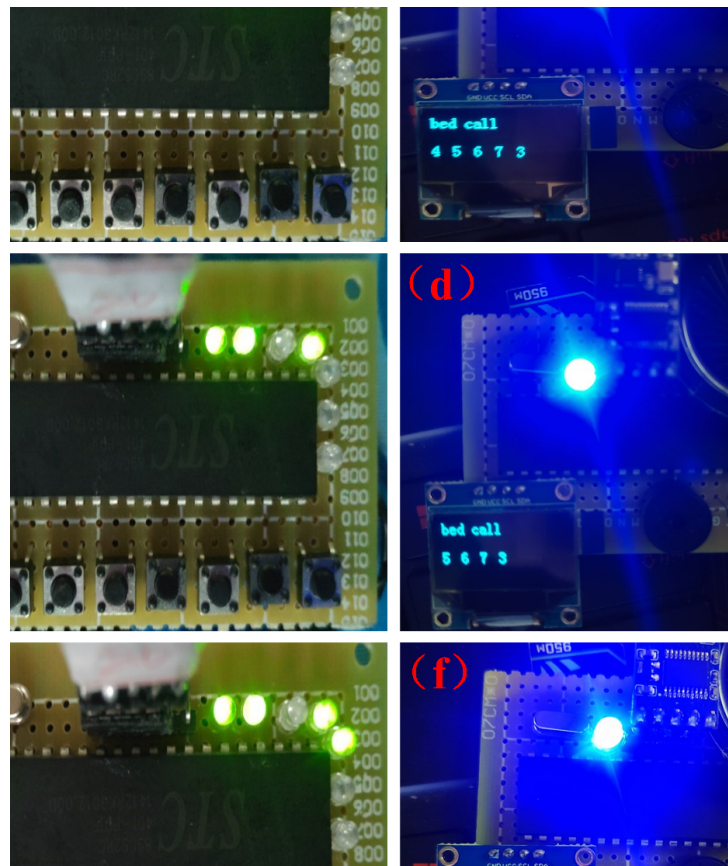


Figure 7. When multiple beds are called: (a) bed numbers 4, 5, 6, 7, and 3 are called sequentially, the indicator light of the corresponding bed is on, (b) the bed number is displayed sequentially on the OLED, (c) the light is extinguished on bed 4, (d) the host computer presses the processing key and the display of bed 4 disappears, (e) while processing is being done, bed 8 is called, and the indicator light is on, and (f) bed 8 is sequentially on the OLED

The alarm will only stop once all processing is complete, and the OLED display will return to showing no bed calls. The alarm cannot be stopped as long as there is an active call. Through debugging, the functionality of this design has been essentially fully realized.

6. Conclusion

In this work, the AT89C52 microcontroller is used as a compact control chip, combined with wireless communication technology to transmit information from the slave side to the host side. The system is equipped with an alarm module that generates real-time alarms and voice announcements during a call. When a patient makes a call, the slave sends a signal to the host, which then receives and processes the signal. If multiple patients make calls, the host will handle them in the order received from the slave. The system updates in real-time, allowing calls and processing to occur simultaneously without interfering with each other, enabling direct communication between patients and nurses. The system is convenient, fast, and low-cost. It is fully functional and can be implemented in hospitals to improve the quality of healthcare services.

Disclosure statement

The authors declare no conflict of interest.

References

- [1] Yan Y, Gu F, Yang S, 2005, Application of Triage Call System in Surgical Outpatient Clinic. Chinese Nursing Journal, 2005(02): 10.
- [2] Diao Y, 2003, Intelligent Alarm Call System Based on Microcontroller. Automation Technology And Application, 2003(04): 61–64.
- [3] Zhang E, Li Z, Liu H, et al., 2024, Design of Wireless Bed Call System Based on Microcontroller. Mechanical Engineering And Automation, 2024(04): 148–150.
- [4] Zhao X, Qi Q, Guo C, et al., 2015, Wireless Call System for Hospital Bed Based on Microcontroller. Science And Technology Communication, 7(21): 174–175.
- [5] Lv X, 2018, A Short-Range Wireless Data Communication for Hospital Bed Call System. Microcontroller And Embedded System Applications, 18(08): 73–75 + 81.
- [6] Meng X, Sun P, Gao H, 2015, Principles and Applications of Microcontroller. People's Posts And Telecommunications Press: 201509.290.
- [7] Wu J, He S, Wan B, 2019, MCS-51 Microcontroller Principles and Applications. Chongqing University Press: 201901.294.
- [8] Hill-Rom Services Inc., 2013, Patent Issued For Hospital Bed With Nurse Call System Interface Unit. Telecommunications Weekly.
- [9] Li S, Yang Y, Zhang J, 2018, Wearable Wireless Calling System in Hospitals Based on Zigbee. International Journal of Performability Engineering, 14(8).
- [10] Wang XZ, Cheng HX, Liu Y, 2013, The Design and Application of Teaching Office Buildings with Electrical Control System Based on RF Wireless Network Technology. Applied Mechanics and Materials, 2617(380–384): 2267–2270.
- [11] Ji M, He FJ, 2014, The Design of Ward Calling System Based on SCM. Applied Mechanics and Materials,

2948(496–500): 1185–1188.

- [12] Zhang XT, Zeng XF, 2007, Principles and Applications of Microcontrollers. Beijing University Of Technology Press, 2007(2).
- [13] Cao TH, Fu WW, 2003, Principles of Microcontroller and Interface Technology. Electronic Industry Press, 2003(8).
- [14] Liu WT, 2005, Microcontroller Application Development Examples. Tsinghua University Press, 2005(5).
- [15] Tan HC, 1991, Programming: C Programming. Tsinghua University Press.
- [16] Zhang P, Hong L, Wang Y, 2024, Research on the Application of Example Teaching Method in the Teaching of “C Language Program Design” Course. Journal Of Anhui Electronic Information Vocational and Technical College, 23(03): 66–70.

Publisher's note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Research on the Theory and Practice of Hydrogen Fuel Cell

Yan Liu*, Lu Yin

Shenyang Polytechnic College, Shenyang 110045, Liaoning, China

*Corresponding author: Yan Liu, lyx1123@163.com

Copyright: © 2025 Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY 4.0), permitting distribution and reproduction in any medium, provided the original work is cited.

Abstract: Hydrogen energy is a renewable and clean resource, that can promote the transformation of energy use terminals to green and low carbon, alleviate the current problems of energy shortage, respond to China's "double carbon" strategy, and further implement the energy-saving and emission reduction targets. The hydrogen fuel cell is an efficient and environmentally friendly distributed power generation device, with the advantages of high energy density, zero-emission, fast charging speed, etc., and has been widely used in the fields of new energy vehicles, electric power equipment, and portable equipment. This paper analyzes the principle and advantages of hydrogen fuel cells, analyzes the key technology system of hydrogen fuel cells and the application of artificial intelligence in hydrogen fuel cells, proposes to strengthen the research on hydrogen production technology, accelerates the technical research and transformation application of key materials and core components, formulate industrial planning scientifically and actively promote hydrogen fuel cell, and promote the transformation of scientific and technological achievements, to promote the development of the hydrogen fuel cell industry.

Keywords: Hydrogen fuel cell; Power generation principle; Technical system; Key technology; Application path

Online publication: February 13, 2025

1. Introduction

Hydrogen fuel cell is an important subversive technology in the field of new energy, leading a new round of global industrial reform, and are of great significance to optimizing China's strategic layout and implementing the goal of "double carbon." Hydrogen fuel cell uses hydrogen as fuel and adds a specific catalyst to convert chemical energy into electric energy through electrochemical reaction. It has the advantages of high energy conversion rate, zero emission and no noise, and has promoted the development of new energy vehicles, marine power and mobile power. In order to further promote the discovery of the hydrogen fuel cell industry. Enterprises should deepen cooperation with scientific research institutes and universities in technology, jointly overcome the difficulties of hydrogen fuel technology, speed up the transformation of scientific and technological achievements, strive for the

government's funding and policy support, and promote the healthy development of the hydrogen fuel cell industry.

2. The principle and advantages of hydrogen fuel cell

2.1. The principle of hydrogen fuel cell

The principle of hydrogen fuel cell power generation is to make hydrogen and oxygen chemical reaction, and then convert chemical energy into electric energy, and use it to drive the power generation device, which is essentially a kind of electrochemical method to convert the chemical energy of hydrogen into electric energy^[1]. The core part of the hydrogen fuel cell is the electrolyte membrane, including a positively charged cation exchange membrane and a negatively charged anion exchange membrane. The hydrogen ion and cation are separated, and then through a specific catalyst to accelerate the chemical reaction of hydrogen and oxygen, the cation creates a chemical reaction to produce electrons and hydrogen ions, and anions generate water and electrons. The electrons return to the anode through the external circuit for continuous reaction, to continuously release electrical energy, to achieve zero emission power supply, reduce the noise in the power generation process, and to meet the power needs of different industries^[2].

Hydrogen fuel cells differ from lithium batteries in several ways. A hydrogen fuel cell consists of two main parts: the reactor and the system components. The reactor is the area where the chemical reaction between oxygen and hydrogen occurs, and it is the core of the entire fuel cell system. It includes the membrane electrode, bipolar plate, collector plate, end plate, sealing rings, and other components. The system components include the air compressor, humidifier, hydrogen circulation pump, and hydrogen bottle, which work together to ensure the smooth operation of the entire hydrogen fuel cell system.

2.2. The advantages of hydrogen fuel cell

2.2.1. Efficient and energy saving

Hydrogen fuel cells differ from traditional fuel engines in that they do not rely on gasoline, oil, or other fossil fuels. Instead, they use cleaner hydrogen as a fuel source. There is no fuel combustion process, leading to lower energy consumption and an electricity conversion rate that can exceed 60%^[4]. The performance of hydrogen fuel cells includes power density and energy efficiency. By optimizing electrode materials and the battery structure, hydrogen fuel cell performance can be enhanced. For example, the use of nanotechnology to manufacture hydrogen fuel cell electrode catalysts improves battery power density, thereby increasing the chemical energy conversion rate. This highlights the high efficiency and energy-saving advantages of hydrogen fuel cells.

2.2.2. Environmental protection and energy saving

Hydrogen fuel cells produce only water and electrons during the power generation process, without emitting carbon dioxide or other harmful gases. This makes them environmentally friendly and energy-efficient, aligning with current energy conservation and emission reduction goals. Additionally, hydrogen, as a raw material for fuel cells, is a renewable resource that can be obtained from solar and wind energy. This helps to meet the energy needs of various industries while addressing the energy crisis and environmental pollution^[5]. Currently, hydrogen fuel cells are widely used in new energy vehicles, supporting the development goals of clean, zero-carbon, safe, and efficient transportation. These fuel cells effectively reduce harmful gases such as carbon dioxide and sulfur dioxide produced by conventional fuel vehicles, as well as various types of dust, contributing to the alleviation of air pollution.

2.2.3. Intelligent management

Hydrogen fuel cell systems can achieve intelligent management and optimize operating conditions by integrating deep learning algorithms. For instance, operational data is collected through a network of sensors and analyzed using machine learning models to predict the optimal working parameters, ensuring the system operates efficiently. Deep learning algorithms can also monitor battery status, provide early warnings of potential failures, reduce maintenance costs, and extend the system's service life.

3. The application of artificial intelligence in hydrogen fuel cells

3.1. Material design and discovery

Deep learning can be used for high-throughput calculations and simulations to accelerate the development of core materials, such as new catalysts, Membrane Electrode Assemblies (MEA), and Gas Diffusion Layers (GDL). By training neural network models, the most promising combinations of new materials can be identified from the vast chemical space, significantly shortening the research and development cycle [7].

3.2. Process optimization

Deep learning or evolutionary algorithms can be applied to explore optimal manufacturing process parameters, such as temperature, pressure, and humidity, to enhance production efficiency and ensure consistent product quality.

3.3. Performance prediction and simulation

A hybrid model combining physical rules and data-driven approaches is constructed to accurately simulate the complex reaction processes within hydrogen fuel cells. This aids in better understanding the battery's working mechanism, guiding experimental design, and providing a theoretical foundation for developing new products.

3.4. Fault detection and diagnosis

Develop an intelligent monitoring system to track the health status of the battery in real-time, quickly identify abnormal patterns, and provide detailed failure cause analysis. This significantly reduces unplanned downtime and enhances the reliability and safety of the system.

4. Hydrogen fuel cell technology development path

4.1. Actively research and develop key materials and components to optimize the functions of hydrogen fuel cells

Although China's hydrogen fuel cell industry started relatively late, the development momentum is very rapid, and the development prospect is bright. Firstly, China actively develops high-pressure gaseous storage technology and low-temperature liquid hydrogen storage technology to ensure the safety of hydrogen storage, control the cost of hydrogen storage, meet the development needs of the hydrogen fuel cell industry, achieve mass production as soon as possible, and further promote the sustainable development of hydrogen fuel cells [8]. Hydrogen fuel cell gas diffusion layers (GDL) have been a significant focus of research and development in recent years. Efforts are being made to develop and optimize materials such as carbon fiber, carbon paper, and carbon cloth for use in GDL production. These advancements aim to meet the requirements of reactors, resistance, and electrical energy

conversion, fostering the integration of the carbon fiber and hydrogen fuel cell industries and promoting high-tech industry development. Domestic production of graphite bipolar plates (BPs) has been achieved, significantly improving durability and reliability. The stack power density has reached 3.8 kW/L, and these systems can operate normally under low temperatures as extreme as -30°C, meeting the operational needs of hydrogen fuel cells. Additionally, research and development efforts should focus on hydrogen fuel cell catalysts and bipolar plate technologies, as well as common technologies that enhance stability and safety. Currently, hydrogen fuel cells are widely used in the field of new energy vehicles. By improving endurance and low-temperature resistance, hydrogen fuel cell technology can be further advanced, driving the sustainable development of the new energy vehicle industry ^[9].

4.2. Accelerating the research and development of core components and promoting the transformation of scientific and technological achievements

Firstly, research and development (R&D) teams need to actively devote themselves to the development of key materials for hydrogen fuel cells, including membrane electrodes, hydrogen circulating pumps, air compressors, and catalysts, to break through the bottleneck of hydrogen fuel cell technology. For example, hydrogen fuel cell research and development enterprises should take the initiative to establish cooperative relations with research institutes and universities to jointly develop hydrogen fuel cell catalysts, new materials, and new technologies for bipolar plates. At the same time, advanced materials such as carbon fiber and graphite will be applied to the research and development of hydrogen fuel cells to solve the problems of uneven porosity and low water vapor transmission efficiency of the gas diffusion layer (GDL), to accelerate the research and development process of the core components of hydrogen fuel cells ^[10].

Secondly, enterprises need to increase investment in scientific research, and actively adopt the latest scientific research results of universities and research institutes, to accelerate the transformation of scientific and technological achievements, enhance the competitiveness and innovation ability of products in the market, and then enhance the economic benefits of hydrogen fuel cells. For example, enterprises can introduce the latest catalyst technology, control the production cost, accelerate the chemical reaction of hydrogen and oxygen, improve the conversion efficiency of chemical energy to electric energy, and enhance the electric storage capacity of hydrogen fuel cells, to improve the overall performance ^[11].

To sum up, the development of the hydrogen fuel cell industry cannot be separated from the close cooperation of the government, enterprises, scientific research institutes, and universities. On the one hand, it is necessary to actively research and develop core components to optimize system performance; On the other hand, it is necessary to overcome the core technical problems, improve the comprehensive performance of hydrogen fuel cells, and gradually enhance the competitiveness and market share of Chinese enterprises in the international market.

At the same time, the key role of artificial intelligence (AI) in accelerating the transformation of laboratory results into actual products is emphasized. For example, using AI platforms to accelerate the testing, validation, and optimization of new materials to bring them to market at a faster pace.

4.3. Formulate industrial plans scientifically to promote the development of hydrogen fuel industry

The government should leverage the goals of “carbon peak” and “carbon neutrality” to optimize the energy industry’s layout, strongly support the development of the hydrogen fuel cell industry, and formulate medium and

long-term development plans. Initiatives such as encouraging the establishment of hydrogen fuel industrial parks across various regions, overcoming technical challenges, and enabling China's hydrogen fuel cells to compete globally should be prioritized.

For example, the education and energy departments could establish a national special project on hydrogen fuel cells, providing research funding to institutes, enterprises, and universities. This would encourage technicians, educators, and students to actively participate in hydrogen fuel cell research and development. Efforts should also focus on strengthening the connection between industries, including hydrogen production and storage, hydrogen fuel cells, new energy vehicles, and electrical equipment, to enhance the hydrogen fuel cell industry chain. These measures aim to drive the high-quality development of the hydrogen fuel cell industry^[12].

In addition, local governments should offer preferential policies to hydrogen fuel cell-related enterprises, including support in areas such as land allocation, taxation, and technical standards. These measures can attract more high-tech hydrogen fuel industries and research institutes to invest in factories, establish research and development centers, and promote the growth of the hydrogen fuel industry chain.

For example, governments should actively provide hydrogen fuel enterprises with loan support, talent acquisition programs, and tax relief. Collaborating with research institutes, industry associations, and experts to develop safety construction standards for hydrogen fuel stations, performance testing standards for hydrogen fuel cells, and other technical regulations will help standardize the hydrogen fuel market. Additionally, strengthening the supervision of related enterprises will ensure large-scale and standardized production of hydrogen fuel cells, promoting the steady and sustainable development of China's hydrogen fuel industry^[13].

4.4. Promoting hydrogen fuel cell technology and the development of new energy industries

Firstly, the application field of hydrogen fuel cells is expanding steadily, which not only promotes the steady development of China's new energy industry but also gradually enhances the competitiveness of China's new energy vehicles and electrical equipment in the global market. Currently, the application of hydrogen fuel cells in the field of new energy vehicles is particularly notable. Their advantages, such as long driving range, high energy density, zero-emission operation, and high safety, have gained significant favor in the automotive industry^[14].

For example, well-known domestic enterprises such as Build Your Dreams (BYD), Great Wall, Huawei, and Xiaomi have adopted hydrogen fuel cells as a power source, significantly enhancing the overall performance of new energy vehicles. Additionally, hydrogen fuel cells are being widely used in the marine industry, where they replace traditional fuel-powered systems, effectively reducing harmful gas emissions and improving the stability of battery systems. The physical properties of key hydrogen fuel cell materials, such as catalysts, electrodes, bipolar plates, collector plates, and end plates, have been significantly improved. Consequently, the thermal, mechanical, and electrochemical stability of these components has been enhanced, making them suitable for meeting the power demands of ships. However, the high cost of basic hydrogen fuel cell technology for ships currently limits its large-scale adoption, necessitating further optimization by researchers^[15].

In addition, researchers can continue to explore and advance hydrogen fuel cell solutions with the assistance of artificial intelligence. The application of this technology is not limited to the automotive sector but extends to various scenarios, including smart homes and industrial automation, aiming to improve user experience and adaptability.

5. Conclusion

In short, hydrogen fuel cells offer significant advantages, including environmental protection, high safety performance, high energy conversion efficiency, and a wide range of applications. These features contribute to advancing China's new energy industries, such as vehicles, ships, and electrical equipment. By utilizing clean hydrogen energy as a replacement for fossil fuels, hydrogen fuel cells can help address the current energy crisis and environmental pollution issues while supporting the transformation and upgrading of China's energy and manufacturing sectors.

Researchers should actively focus on the development of key materials and components, optimize hydrogen fuel cell functionalities, and enhance overall performance. Strengthening collaboration between enterprises, universities, and research institutions is essential to accelerate the development of core components, facilitate the transformation of scientific and technological achievements, and drive the growth of the hydrogen fuel cell industry.

Simultaneously, local governments should develop well-structured industrial plans, provide increased support to hydrogen fuel cell enterprises in areas such as taxation, land allocation, and talent acquisition, and promote the hydrogen fuel industry. Efforts should also focus on advancing hydrogen fuel cell technologies and expanding their applications in new energy vehicles, ships, and other industries. This will foster the growth of the new energy sector and further contribute to the development of China's high-tech and clean energy industries.

Disclosure statement

The authors declare no conflict of interest.

References

- [1] Ji Y, Wu J, Zeng F, 2024, Key Technologies and Development Prospects of Hydrogen Fuel Cell Regional Aircraft. *Aeronautical Science and Technology*, 35(01): 15–24.
- [2] Li H, Tu S, 2023, Development Status, Challenges and Countermeasures of Hydrogen Fuel Cell Technology in China. *Modern Chemical Industry*, 43(11): 5–9.
- [3] Cui P, Wang H, Cui M, et al., 2023, Current Status and Key Technologies of Hydrogen Fuel Cell Bipolar Plate Stamping and Forming Equipment. *Journal of Machine Design*, 40(S1): 130–133.
- [4] Zhang J, Tang P, Yang W, et al., 2023, Research on Metal Bipolar Plate Packaging Technology for Hydrogen Fuel Cell. *Modern Manufacturing Technology and Equipment*, 59(02): 113–116.
- [5] Xu L, Zhang S, Peng G, 2022, Research on Staggered BOOST Equalization Technology of Hydrogen Fuel Cell Power Generation System. *Heilongjiang Electric Power*, 44(01): 63–67.
- [6] Li Z, 2022, Development Status and Prospect of Important Technologies of Hydrogen Fuel Cell Reactor. *New Industrialization*, 12(05): 4–9.
- [7] Cui M, Zhu X, Xue K, et al., 2022, Hydrogen Storage Technology and its Development Status for Hydrogen Fuel Cell Vehicle. *Automotive Practical Technology*, 47(10): 173–178.
- [8] Yang S, 2022, Research on Characteristics of Hydrogen Fuel Cell System and its Safety Detection Technology. *Television Technology*, 46(04): 217–220.
- [9] Hua R, Zhang W, Cheng L, et al., 2022, Review on Design and Forming Technology of Metal Bipolar Plate for Fuel Cell. *Precision Forming Engineering*, 14(03): 25–33.

- [10] Liu Y, Guo H, Ouyang X, 2021, Development Status and Future Prospects of Hydrogen Fuel Cell Technology. Chinese Engineering Science, 23(04): 162–171.
- [11] Xiang H, 2021, Research on Characteristics Simulation and Key Technologies of Hydrogen Fuel Cell for Electric Vehicle, thesis, Chongqing Three Gorges University.
- [12] Wu T, 2021, Research on Policy Tools for the Development of Hydrogen Fuel Cell Vehicle PEMFC Technology in China, thesis, Huazhong University of Science and Technology.
- [13] Wang J, Hu C, 2021, Development Status and Trend Analysis of Hydrogen Fuel Cell Special Vehicle in China. Special Purpose Vehicle, 2021(04): 51–55.
- [14] He Q, 2019, Overview of Hydrogen Fuel Cell Technology Application Status and Development Trend. Southern Agricultural Machinery, 51(11): 211.
- [15] He Q, 2020, Technical Characteristics and Application of Hydrogen Fuel Cell. Hubei Agricultural Mechanization, 2020(09): 48–49.

Publisher's note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Research on Emotion Classification Supported by Multimodal Adversarial Autoencoder

Jing Yu*

The National University of Malaysia, Kuala Lumpur 43600, Malaysia

*Corresponding author: Jing Yu, yujxf18@163.com

Copyright: © 2025 Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY 4.0), permitting distribution and reproduction in any medium, provided the original work is cited.

Abstract: In this paper, the sentiment classification method of multimodal adversarial autoencoder is studied. This paper includes the introduction of the multimodal adversarial autoencoder emotion classification method and the experiment of the emotion classification method based on the encoder. The experimental analysis shows that the encoder has higher precision than other encoders in emotion classification. It is hoped that this analysis can provide some reference for the emotion classification under the current intelligent algorithm mode.

Keywords: Artificial intelligence; Multimode adversarial encoder; Sentiment classification; Evaluation criteria; Modal Settings

Online publication: February 13, 2025

1. Introduction of multi-mode antagonistic autoencoder emotion classification method

1.1. Overall framework

The multimodal antagonistic autoencoder sentiment classification method (MAAE) with a basic application goal of automatically implementing multimodal sentiment data classification. In the framework of the MAAE model, its basic components and functions are implemented as follows.

- (1) Modal feature embedding module: The obtained multi-modal emotion data is input, and the embedded modal features are extracted and dimensionally processed by three parallel Long Short-Term Memory (LSTM) network modules.
- (2) Multi-modal adversarial autoencoder module^[1]: Load the corresponding multi-modal features respectively, and train the antagonism between the encoder and the antagonist to achieve the effective reduction of the heterogeneity of multi-modal features.
- (3) Self-attention prediction network: The self-attention mechanism is used to fuse the important information in the multi-modal characteristics, and then the fully connected network is used to implement emotion classification.

1.2. Task setting

In the application of the MAAE method, researchers can set their task to predict the following emotion types with multi-modal emotion data: (1) Happiness; (2) Sadness; (3) Neutral; (4) Angry; (5) Excitement; (6) Depressed. In this process, the MAAE model can segment the multi-modal data to form M sentence sequences containing three kinds of data including audio mode, visual mode, language mode, and an emotional type label, and extract context-free features from them^[2]. Its representation is as follows: (1) Audio feature sequence: $F_a \in \mathbb{R}^{n \times d}$ (2) Visual feature sequence: $F_v \in \mathbb{R}^{n \times d}$ (3) Linguistic feature sequence: $F_l \in \mathbb{R}^{n \times d}$. represents the sequence length; n and d represents the feature dimension.

1.3. Multi-modal feature embedding

Obtain the multimodal feature sequence with the essence of contextual correlation in the video, and build its context relationship model to understand its relevance. In this case, the typical Bidirectional Long Short-Time Memory (Bi-LSTM) network can be introduced in sequential data processing. The network is composed of two independent LSTM networks, and the time direction of training can be set at the same time. The module is used to embed multi-modal data, and there are two levels of its composition: one is the Bi-LSTM layer whose unit is language, and the other is the Dense (perception layer) in the form of full connection^[1-5]. The former can embed the context feature in the multimodal feature sequence, while the latter can receive the hidden layer state in the former and implement unified processing of the multimodal feature dimensions.

1.4. Multimodal representation learning

Although multimodal features have a unified dimension, the spatial distribution of their features is not consistent. The existing multi-modal sentiment analysis method only focuses on modal dimension alignment and implements sentiment analysis with data fusion methods, such as tensor fusion and attention fusion, etc., and its execution methods are complicated^[6]. Although the above methods have made great progress, due to the heterogeneity among the modes, they will face many obstacles in the subsequent implementation of fusion interaction between different modes. To reduce the heterogeneity of different modes, the most intuitive idea is to map multi-modal data in a common space and learn its invariance. Based on this, in this study, the researchers take the joint representation algorithm as inspiration, and through the organic combination of adversarial network and autoencoder, build a multi-modal adversarial form of autoencoder, and reduce its heterogeneity by multi-modal representation learning^[7].

Firstly, the adversarial network construction is based on generative adversarial network technology. Generative adversarial network technology is a common technique in deep learning, and it is also a typical artificial intelligence generation method. With the help of this technology, the high dimensional distribution of high complexity in multi-dimensional data such as audio, image, and language can be learned. There are usually two neural networks in generative adversarial networks, one is generator G and the other is generator D, which can effectively capture the real distribution of data under the condition of competition^[8-10]. When constructing adversarial networks, it is necessary to build an encoder separately for each unimodal mode, input the multi-modal embedding feature, and make it map in a common subspace of shared form: $m \in \{a, v, l\} G_m x_m$

$$h_m = G_m(x_m; \theta_{G_m}) \quad (1)$$

represents the invariant modal characteristics of the mapping in the common subspace; $h_m \theta_{G_m}$ represents

the unimodal in the encoder. The components here are all fully connected networks, which are very simple in structure and can be used as encoder networks in autoencoders and generator networks in adversarial networks. G_m defines a modal discriminator, multimodal features can be identified by this discriminator. D for modal features of language form, it can be defined by “true;” For other forms of modal features, it can be defined as “false.” When the unknown modal feature task is given, the discriminator can perform modal detection according to the feature as far as possible, and the encoder can generate similar multi-modal features as far as possible, so that they are not detected by the recognizer, to achieve the effective reduction of multi-modal heterogeneity.

Secondly, the autoencoder construction. Autoencoders belong to a specific type of neural network, which can minimize reconstruction loss, try to retain its important information in the original data, and remove redundancy and noise. The overall structure of autoencoder is mainly composed of encoder and decoder two parts. In a typical autoencoder, the main components of encoder and decoder are neural networks. The former is used to make the data form nonlinear mapping, and the latter is used to reconstruct the mapped data. In the reconstruction of invariant modal features in common subspace, the reasonable application of an autoencoder can significantly reduce the risk of information loss in the mapping process^[11]. In specific mapping, for each unimodal mode, a decoder needs to be constructed respectively to carry out feature reconstruction, and its reconstruction loss function is expressed as: $m D_m h_m$

$$\hat{x}_m = D_m(h_m; \theta_{D_m}) \quad (2)$$

represents the reconstruction loss value; \hat{x}_m represents the unimodal mode in the decoder.

1.5. Self-attention prediction network

Self-attention prediction network mainly predicts emotion scores by way of single-peak feature learning in multiple modes. In this network, the self-attention mechanism is the most critical component, and it is also a typical processing technology in deep learning technology. Its main application functions are automatic attention and automatic extraction of important features^[12]. In order to extract more useful information in the multimodal features, researchers can reasonably apply the self-attention mechanism to the reconstructed features, and the algorithm formula is:

$$S_a = \frac{e(h_{mi}^T \cdot h_m)}{\sum_{i=1}^N e(h_m^T \cdot h_{mi})} \quad (3)$$

$$h_m^a = S_a \cdot h_m \quad (4)$$

$$h = \text{concat}(h_a^a; h_v^a; h_l^a) \quad (5)$$

represents the self-attention weight value; S_a represents the modal characteristics of the external input; h_m^T represents the transformation vector; h_m represents the I -th unimodal; h_{mi}^a represents the multimodal feature in the self-attention-directed mode; h represents the multi-modal fusion features obtained by splicing; h_a^a represents the multimodal features of speech sequences guided by self-attention; h_v^a represents the multimodal features of video sequences guided by self-attention; h_l^a represents multimodal features of language sequences guided by self-attention.

2. Multimodal antagonistic autoencoder emotion classification method test

2.1. Test environment

In the above trial of emotion classification method, the selected test environment includes hardware and software, and its basic composition and configuration are as follows:

- (1) Control processing unit (CPU): configuration information is Intel(R)Core(TM)i9-9900K and the frequency is 3.60 GHz.
- (2) Graphics processing unit (GPU): configuration information is NVIDIA GeForce RTX 2080Ti.
- (3) Random access memory (RAM): storage capacity of 64 GB.
- (4) Operating system: configured as 64-bit Windows 10 system.
- (5) Integrated development environment (IDE): configuration information is Pycharm + Anaconda3 + Python3.8.
- (6) Deep learning framework: configuration information is Pytorch 1.8.1.

2.2. Data set

The experiment data is mainly obtained from a script dialogue video shoot, which has five key links, and the dialogue scenes in each link are different. The video was segmented according to several segments by the MAAE model, and each segment needed annotation to refine the emotion category, including six emotions: happiness, sadness, neutrality, anger, excitement, and frustration. The modal feature extraction of the whole video was mainly realized by different algorithms. The statistical features of the audio features, such as Meir frequency cepstral coefficient (MFCC), pitch, voice intensity, and audio, were extracted by the open-source software openSMILE, including mean value and root mean square^[13,14]. The visual features in the visual modal data were extracted with 3D-CNN (software), and the relevant features were learned based on each frame and continuous frame changes. Each sentence in the language mode is split into word form, then embedded into the MAAE model in the form of words, embedded through the Word2Vec language pre-training model, and finally learned the abstract representation of hidden semantics through the convolutional neural network. **Table 1** shows the distribution of emotion category information in this experiment.

Table 1. Distribution of emotion category information in this experiment

Serial Number	Emotions	Pre-test sets	Training Set
1	Happy	114	504
2	Sad	245	839
3	Neutral	384	1,325
4	Anger	170	933
5	Excitement	299	724
6	Frustration	381	1,468

2.3. Evaluation indicators

This experiment is a task to classify multiple emotion categories, so the classification accuracy of the above six emotion categories and the average classification accuracy of all emotion categories will be used as the basic index to evaluate the Interactive Emotion Binary Data Capture Database (IEMOCAP)^[15].

2.4. Model setup

To complete the MAAE model construction in this experiment according to the above method, the drop layer is set in each encoder and decoder of the model, to avoid overfitting. The LeakyReLU function is used as the encoder activation function, the Sigmoid function as the discriminator activation pair function, and the Softmax function as the self-attention prediction network activation function.

2.5. Test results

By comparing the above five traditional artificial intelligence emotion classification models with the MAAE model constructed in this study, it can be seen that the MAAE model has the highest classification accuracy for the three emotions of happiness, sadness, and excitement, and also has a higher classification accuracy for the three emotions of neutrality, anger, and frustration. The average accuracy of overall emotion classification is the highest. **Table 2** shows the results of the multi-modal adversarial autoencoder emotion classification experiment in this study.

Table 2. The results of the multimodal adversarial autoencoder emotion classification test in this study

Serial Number	Emotional classification	Test result					
		CatLATM	cLSTM	TFN	TFN	CMN	MAAE
1	Happy	35.0%	30.6%	29.9%	26.4%	25.0%	40.3%
2	Sad	56.1%	56.7%	55.5%	49.4%	55.9%	73.3%
3	Neutral	47.1%	57.6%	48.8%	56.8%	52.9%	53.5%
4	Anger	55.9%	59.4%	60.6%	61.2%	61.8%	56.3%
5	Excitement	54.7%	52.8%	57.9%	47.2%	55.5%	69.4%
6	Frustration	52.0%	65.9%	63.3%	63.3%	71.1%	55.9%
7	Averages	51.5%	56.3%	54.3%	53.2%	56.6%	58.8%

It can be seen that the multi-modal adversarial autoencoder emotion classification model studied in this research has more advantages in artificial intelligence-based emotion classification, and it can reasonably replace the traditional model to obtain more accurate classification results.

3. Concluding remarks

To sum up, in emotion classification processing based on artificial intelligence, the reasonable construction and application of algorithm models are very important. To deal with the drawbacks of traditional artificial intelligence algorithm models in multiple emotion classification processing, researchers can introduce the current more advanced multi-modal adversarial autoencoder, and complete the corresponding emotion classification model construction on this basis. In this way, the accuracy of emotion classification can be further improved, and a more idealized effect of artificial intelligence emotion classification can be obtained.

Disclosure statement

The author declares no conflict of interest.

References

- [1] Beijing Language and Culture University, 2024, A Method for Identifying Emotion Types and Calculating Emotion Intensity, patent, CN202011426092.1.
- [2] Hunan Mango Sunac Technology Co., LTD., 2024, Emotion Recognition and Video Content Matching System Based on Artificial Intelligence, patent, CN202410905484.8.
- [3] Shantou University, 2024, A Cross-Domain Emotion Classification Method, Device, Equipment and Medium, patent, CN202410770711.0.
- [4] Ye J, Xiang L, Zong C, 2024, Attribute-Level Emotion Classification Method Combining Attribute Modeling and Curriculum Learning. *Journal of Software*, 2024(9): 4377–4389.
- [5] Kunming University of Science and Technology, 2024, A Small Sample Sentiment Analysis Method Based on Adaptive Multi-Modal Prompts, patent, CN202410660214.5.
- [6] State Grid Anhui Electric Power Co., LTD., 2024, Information and Communication Branch. A Method of Input Text Meaning Understanding and Sentiment Analysis Based on Artificial Intelligence, patent, CN202410682831.5.
- [7] Industrial and Commercial Bank of China Co., LTD., 2024, Sparse Emotion Classification Methods, Devices, Equipment, Media and Program Products, patent, CN202410784366.6.
- [8] Wang Y, Zhu G, Duan W, et al., 2024, Emotional Classification Model of Psychological Counseling Texts Based on Interactive Attention Mechanism. *Journal of Computer Applications*, 2024(8): 2393–2399.
- [9] Hunan Mango Sunac Technology Co., LTD., 2024, Artificial Intelligence-based Emotion Recognition and Video Content Matching System, patent, CN202410905484.8.
- [10] Xiamen University of Technology, 2024, Music Emotion Recognition Method, Device, Equipment and Medium Based on Context Feature, patent, CN202410783596.0.
- [11] Tencent Technology (Shenzhen) Co., LTD., 2024, Multi-label Emotion Classification Model Training Methods, Related Devices and media, patent, CN202410210755.8.
- [12] Ping An Technology (Shenzhen) Co., LTD., 2024, Multimodal Emotion Classification Method, Device, Equipment and Storage Media, patent, CN202210834137.1.
- [13] Zhang H, 2024, Application of Artificial Intelligence in Natural Language Processing. *Materials for Information Recording*, 2024(5): 139–141.
- [14] Zhang J, 2024, A Cross-Modal Emotion Analysis Method, Training Method, Device and Equipment, patent, CN202410022411.4.
- [15] Ping An Technology (Shenzhen) Co., LTD., 2024, Emotion Classification Method, Device, Equipment and Media based on Document-Level Emotion Tendency, patent, CN202111158076.3.

Publisher's note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

The Integration of Modern Computer Information Technology and Artificial Intelligence

Caihua Kong*

Yunnan Open University, Kunming 650599, China

*Corresponding author: Caihua Kong, mittykch@163.com

Copyright: © 2025 Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY 4.0), permitting distribution and reproduction in any medium, provided the original work is cited.

Abstract: With the advent of the information age, people's production and life are more closely connected with the Internet. Internet technology not only improves the production efficiency, but also provides great convenience for people's life. At present, people's requirements for computer information technology are gradually increasing. When we look directly at the information transmission and storage capacity, computer information technology cannot meet the market demand. Due to rapid development, the integration of artificial intelligence (AI) can enable the development of computer information technology. In this paper, computer information technology and artificial intelligence integration act as a starting point, and the integration of the development of the two is analyzed for reference.

Keywords: Computer information technology; Artificial intelligence; Integrated development

Online publication: February 14, 2025

1. Introduction

At the dawn of the computer era, due to the immaturity of the technology, its functions were primarily limited to local area networks and stand-alone operations^[1]. Internet technology and computer information technology influence each other, with Internet technology driving the gradual development of computer information technology^[2]. With the advent of the modern information society, the application of Internet technology has established connections between people and things, as well as between things themselves. Artificial intelligence, as one of the most advanced technologies, enables computers to imitate human brain functions. Researchers only need to input predefined instructions, allowing specific operations to be performed within designated processes. This improves production efficiency and ensures that different devices can achieve intelligent operation. This paper explores the integration and development of current computer information technology and artificial intelligence, aiming to provide a theoretical foundation for their advancement.

2. Overview of artificial intelligence

Artificial intelligence, built upon the development of information technology, is a multidisciplinary field that enables computers to imitate human thought processes and behaviors. Its emergence has driven many industries toward intelligent operations, significantly improving efficiency^[3,4].

Mechanical equipment, enhanced by the development of computer information technology and artificial intelligence, can significantly improve work efficiency and largely reduce the need for manual labor, minimizing reliance on extensive human operations. With the application of artificial intelligence, mechanical equipment is endowed with human-like thinking, enabling more intuitive processing methods that align with human production needs. In an increasingly intelligent working environment, many practical problems are easily resolved.

The advancement of artificial intelligence technology represents not just the progress of a single discipline but the integration of multiple interdisciplinary fields, supported by theories and technological achievements from various domains. Contemporary computer information technology serves as a primary application area for artificial intelligence. By integrating the two, many industries can achieve high-quality development and gain substantial technical support.

3. The integration of computer information technology and artificial intelligence significance

3.1. Accurate processing of information

With advancements in computer information technology and the integration of artificial intelligence, data has become a fundamental cornerstone of social development^[5]. For many enterprises, mastering comprehensive data is essential to gaining an advantage in the competitive market. Within the vast amount of information available, much of it is unknown or ambiguous, making accurate identification challenging in a short period. The application of artificial intelligence technology enables the creation of efficient data models and facilitates faster, more accurate information processing.

With the widespread adoption of the Internet, the volume of ambiguous information continues to grow, driving the advancement of artificial intelligence in improving information processing capabilities. In handling ambiguous data, artificial intelligence demonstrates significant advantages through collaborative distributed thinking. By simulating human administrative management structures, it enables hierarchical management of computer networks, where tasks are delegated to responsible parties at different levels. This approach significantly enhances the efficiency of computer network management.

3.2. Improve the ability of computational learning

Computational learning ability is another remarkable feature of artificial intelligence technology. All information within a computer network system holds potential application value. Based on this, managers can deeply analyze the information, harness its value, and apply it to enhance production and daily life. Once the system gains a comprehensive understanding of the underlying data, it can accurately interpret this information, deduce logical patterns, and generate labeled datasets.

In general, the development of computer information technology and the enhancement of artificial intelligence capabilities are mutually reinforcing. Information technology serves as the foundation for continuous breakthroughs in artificial intelligence, enabling it to acquire stronger learning capabilities. Furthermore, improvements in computational learning not only allow artificial intelligence to process vast amounts of data with

greater accuracy but also enable the optimization of algorithms through deep learning and other technologies, thereby enhancing the level of intelligence of the system ^[6-8].

With the continuous advancement of computer information technology, the ability to acquire, process, and analyze information has been greatly enhanced, providing a broader scope for the application of artificial intelligence. In particular, within computer network systems, deep data mining and intelligent processing can effectively support accurate decision-making and personalized services, profoundly impacting various industries and aspects of daily life. By continually improving its computational learning capabilities, artificial intelligence can optimize itself, adapt to evolving needs, and drive ongoing innovation in technology and industry.

3.3. Reduce human resource costs

The application of artificial intelligence operating systems has liberated part of the workforce in traditional production ^[9]. At present, production and daily life cannot eliminate manual labor, but the application of new technologies, controlled by software, can free up human hands and improve production efficiency. Manual operations in the production process are prone to errors, and uncontrollable factors increase the risk. However, the integration of artificial intelligence (AI) can mitigate the impact of human error.

Generally speaking, the resources for artificial intelligence technology are still relatively limited, and many solutions rely on software to address real-world problems. This not only improves computer operation efficiency but also helps businesses save costs, aligning with the needs of social development. Moreover, the widespread application of AI reduces reliance on manual labor, significantly enhancing production efficiency and accuracy. Through automated systems, AI can handle tedious and repetitive tasks, such as data processing, quality inspection, and production line monitoring, reducing errors and safety hazards in manual operations.

As technology continues to advance, AI will become more capable of handling large volumes of data, adjusting production processes in real-time, and optimizing resource allocation, further lowering operating costs for businesses. In the long run, the efficient use of AI will drive industrial upgrades, promote labor structure transformation, and meet society's growing demand for more efficient and intelligent production methods ^[10].

4. The integration path of computer information technology and artificial intelligence

4.1. Improve detection efficiency

Artificial intelligence can enhance the detection of malicious access, hacking, and other harmful behaviors. Currently, the exchange of information on networks is more frequent, and various types of software and security protocols are continuously emerging. However, many criminals exploit these opportunities to commit crimes, modify computer programs, and cause data breaches ^[11]. Artificial intelligence can effectively address this problem.

Firstly, AI-based identity authentication can fully integrate with the computer programming system, storing relevant parameter data in an expert system. If a hacker attempts to invade or tamper with access rights, the expert system will quickly verify and compare the parameters to determine whether the modifications align with normal operational patterns. If there is a significant deviation, the intelligent identification system will promptly issue an alarm, notifying the user that unauthorized modifications have occurred, allowing them to understand the real situation of the computer promptly.

Secondly, when an issue is detected, the AI will automatically generate a fault report, listing the operational

status and any altered parameters. This provides reliable data to assist maintenance engineers, improving the efficiency of their work. Finally, the system's network detection capabilities can be used to identify the root cause of the error, preventing the recurrence of the same issue.

4.2. Improve the protection system

Firstly, artificial intelligence can optimize firewall technology in computer systems^[12]. Currently, most computers use firewalls with the same specifications, which are not tailored to target specific hacker viruses, leading to ineffective protection. Artificial intelligence, with its strong reasoning capabilities, can adjust defense mechanisms in real-time based on the type of virus. It can modify software operation permissions, change Internet Protocol (IP) addresses, and use other techniques to prevent viruses from infiltrating the system's programming area. If a virus is unable to alter the programming instructions, it will not cause harm to the computer, only resulting in a simple coding inflow. This allows technical personnel to manage post-processing with ease.

Secondly, artificial intelligence enhances the security of cloud computing. When network fluctuations occur during uploads, conventional cloud storage systems cannot guarantee stable operation, leading to false positives in relevant data. The advantage of artificial intelligence lies in its high efficiency. It can transmit large volumes of complex information at millisecond speeds, effectively reducing the impact of network fluctuations on information security and improving overall security.

4.3. Strengthen network supervision

On the one hand, AI can promote the development of the entire network management system by enhancing the performance of computer systems, thus optimizing its logic and reasoning. In the complexity of network management, artificial intelligence can accurately retrieve emergency plans from the expert system, break down management processes, and reorganize and combine internal data to ensure an orderly management process. As a highly intelligent machine, AI can independently perform tasks based on the autonomous response of computer hardware and software, eliminating the need for human intervention.

For example, in library management, books need to be classified to help readers easily find the required information. Through the AGENT interface, artificial intelligence can improve the accuracy of message transmission, allowing managers to avoid modifying the operation interface. Instead, it can be segmented through program design, enhancing the convenience of information retrieval^[13].

4.4. Improve the data system

The built-in database of the computer can collect information about commands and system operations issued by the user during use, store and share relevant data, and enhance the connection between the computer, establishing a stable network environment. Artificial intelligence technology can expand the database, improving the system's ability to learn independently. As a result, the relevant data no longer needs to be uploaded by the user, as it can be retrieved directly from the database. Additionally, AI can independently analyze program-related issues. The generation of new modular data enriches the database and expands access to information^[14]. In addition, the highly accurate inference capabilities of artificial intelligence can optimize and classify intelligent algorithms, creating a relatively independent space, which improves the effectiveness and efficiency of problem-solving in computers. Furthermore, the integration of artificial intelligence with databases can enhance the relationships between data, making hidden logic clearer and establishing a new type of semantic network. The role of the semantic network is

to represent the connections between entities in the database, allowing relevant information to remain organized while helping users better understand the data content. This, in turn, improves the rationality and scientific accuracy of data reasoning.

4.5. Strengthen auxiliary management

The computer-aided management system plays an irreplaceable role in the application of artificial intelligence and is one of the most widely used systems ^[15]. It is a type of information system based on cognitive science, allowing for remote control operations. This system is not only free from spatial limitations but also enables the optimization and enhancement of monitoring systems. Through continuous innovation, the auxiliary management system has become widely used in the medical field. Medical personnel can use the system to create electronic medical records and accurately identify images to provide evidence for patients' conditions. Additionally, the system can manage patient health and utilize its analysis function to develop different medications.

However, due to the lack of theoretical support in traditional Computer-Aided Technology (CAT) systems, the data stored in the original database often becomes outdated and unsuitable for modern practical applications. Artificial intelligence technology addresses this issue effectively. Its built-in network management system allows for real-time updates, ensuring that the data in the database evolves with the times and aligns with current developmental needs.

5. Conclusion

To sum up, the integration and development of modern computer information technology and artificial intelligence have led to a clear trend toward the intelligent evolution of computer network systems. Artificial intelligence encompasses many technical theories, such as expert systems and machine learning. These, combined with current computer-aided management and database technologies, have achieved cross-integration, thereby promoting greater diversity in both production and daily life. Overall, when computer network systems handle fuzzy information processing, their processing capacity has significantly improved, and nonlinear problems have been effectively solved—both of which are key achievements of artificial intelligence. AI technology will not stagnate; it will continue to evolve through technological innovation, with its technical capabilities achieving further breakthroughs. In the future, people will become more closely connected with artificial intelligence. With the support of computer information technology, AI will have more room for development and its autonomous operation capabilities will be further enhanced.

Disclosure statement

The author declares no conflict of interest.

References

- [1] Wang B, Li H, Li X, 2021, Practical Strategies of Computer Communication Technology and Electronic Information in the Field of Artificial Intelligence. *Information Recording Materials*, 22(12): 125–126.
- [2] Kang W, 2020, Discussion on Computer Information Technology Security and Protection Strategies in the Era of Artificial Intelligence. *Information Recording Materials*, 23(6): 84–87.

- [3] Xu ZS, 2020, Practical Application of Computer Communication Technology and Electronic Information in the Field of Artificial Intelligence. *Digital Technology and Application*, 40(3): 93–95.
- [4] Lu D, Wang Y, 2022, Application of Computer Communication and Electronic Information Technology in the Field of Artificial Intelligence. *Science and Technology Wind*, 2022(21): 50–52.
- [5] Yan H, 2024, Application of Computer Communication Technology and Electronic Information Technology in the field of Artificial Intelligence. *Communication Power Supply Technology*, 41(2): 144–146.
- [6] Sun B, 2019, Application of Computer and Electronic Information Technology in Artificial Intelligence Field. *Journal of Software*, 45(1): 107–109.
- [7] Duan T, Liu H, 2023, Research on Computer Application Software Development Technology of Artificial Intelligence. *Electronic Components and Information Technology*, 2023(1): 102–105.
- [8] Bi Y, 2021, Research on Application of Artificial Intelligence in Contemporary Computer Information Technology. *Exploration Science*, 2021(2): 284–285.
- [9] Gong X, 2023, Application of Computer Communication and Electronic Information Technology in Artificial Intelligence Field. *Applications of Automation*, 64(10): 236–238.
- [10] Li M, 2019, Application of Artificial Intelligence Personalized Learning in Computer Information Technology Teaching. *Information and Computer*, 36(8): 254–256.
- [11] Han D, 2023, Application of Computer Communication and Electronic Information Technology in the Field of Artificial Intelligence. *Computer Enthusiast (Popular Edition) (Electronic Journal)*, 2023(4): 237–238.
- [12] Luo C, 2023, Application of Computer Information Technology in the Development of Artificial Intelligence. *Digital Technology and Applications*, 41(8): 81–83.
- [13] Wang Q, 2024, Application of Computer Information Technology in the Development of Artificial Intelligence. *Information and Computer*, 36(2): 142–144.
- [14] Xu L, 2023, Standardization Application of Artificial Intelligence in Computer Information Technology. *Outdoor Equipment*, 2023(6): 361–363.
- [15] Hao C, 2019, Research on Application of Artificial Intelligence in Computer Information Technology. *Information Recording Materials*, 25(5): 115–117.

Publisher's note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Research on the Application of Small UAVs in Maritime Search and Rescue Activities

Xiuku Dan*, Jing Wei

Foundation Department, Engineering University of PAP, Xi'an 710086, China

*Corresponding author: Xiuku Dan, danxiuku@126.com

Copyright: © 2025 Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY 4.0), permitting distribution and reproduction in any medium, provided the original work is cited.

Abstract: In recent years, with the increasing frequency of global Marine activities, the occurrence probability of Marine accidents and emergencies has also increased. As a new technical means, small unmanned aerial vehicles (UAVs) have shown great application potential in Marine search and rescue activities. In Marine search and rescue activities, small UAVs can quickly arrive at the scene of the accident and carry out efficient information collection and monitoring under its simple and flexible operation. Compared with traditional search and rescue methods, small UAVs can cover a wider area, provide more detailed and accurate on-site information, provide strong support for search and rescue decision-making, and thus improve the quality and efficiency of maritime rescue. In this regard, this paper first describes the application advantages of small UAVs in Marine search and rescue activities and then puts forward effective application paths, to provide some references for relevant researchers.

Keywords: Small unmanned aerial vehicle; Maritime search and rescue; Application path

Online publication: February 14, 2025

1. Introduction

Currently, small UAVs cannot perform tasks independently and autonomously ^[1]. They must work together with a series of control systems and other related equipment to form a complete UAV system ^[1]. The system was designed with the relatively low fuel consumption requirements of small UAVs in mind, so the overall operating cost is also relatively low. This makes small UAVs respond to a variety of sudden disaster events, especially in maritime rescue operations, small UAVs have become an indispensable part, they can respond quickly in harsh environments and provide critical air support and real-time intelligence, greatly improving rescue efficiency and safety.

2. The application advantages of small UAVs in maritime search and rescue activities

2.1. Convenient operation and strong flexibility

Small UAVs have shown great advantages in maritime search and rescue activities because of their small size,

easy operation, and flexibility. For example, they can quickly detect areas and help personnel carry out rescue, especially in large maritime search and rescue missions. With their high mobility, small UAVs can maneuver flexibly in a variety of different environments. The speed and efficiency of search and rescue can be further improved. Additionally, when an emergency occurs, the small UAV can use the search-and-rescue personnel's palm as a springboard, autonomously adjust the route, and change the flight attitude in a certain area, so it has a huge application advantage in the absence of take-off and landing areas. In general, the use of small UAVs in maritime search and rescue can give full play to its advantages of flexibility, improve the efficiency of maritime search and rescue activities, and deal with various emergencies promptly ^[2].

2.2. Strong ability to obtain information

At present, in maritime search and rescue activities, small UAVs organize and analyze relevant information collected through the Beidou navigation satellite system, aerial photography system, navigator, information perception system, positioning system, etc., and collect environmental, meteorological, emergency, and other information in real-time, to facilitate rescuers to make accurate judgments and analysis. For example, for the offshore oil drilling platform explosion accident, rescue workers can use small UAVs to carry out local aerial observation and real-time monitoring, accurately judge the explosion scale and explosion time, real-time monitoring the duration of the fire, and model the fire transmission process. After receiving the early warning signal, the rescue personnel can obtain accurate forward projection and a three-dimensional model of the building according to the on-site photos and mapping information, and according to the observation and analysis of the accident site, determine the various details of the accident site to carry out subsequent rescue missions ^[3].

2.3. Strong safety and reliability

Small drones, due to their compact size, do not require large parking facilities and can perform emergency rescue missions even in harsh environments, offering enhanced safety. For instance, in situations like offshore oil drilling, hazardous chemical storage, fuel transportation sites, offshore ship capsizing, or sea crashes—where traditional search and rescue methods face significant challenges due to the marine environment—small UAVs excel. These drones can safely and reliably conduct rescue operations by leveraging their adaptability to the take-off environment, equipment safety features, and compact design. They can quickly assess the rescue situation, minimizing response time, and mitigating the risks posed to rescue workers by harsh sea conditions, thereby enhancing the overall safety and reliability of rescue missions ^[4].

3. Application path of small UAV in maritime search and rescue activities

3.1. Precise location of trapped people

In search and rescue missions across vast oceans, small drones play a crucial role by effectively locating and assisting trapped individuals. Traditional manual search and rescue methods or the use of ships alone often fail to achieve optimal results, as they may overlook critical areas during operations.

In contrast, small UAVs offer a significant advantage due to their ability to capture a wider range of video images from greater altitudes than ships. At the current stage of technological development, small drones can quickly identify a person's location in the early stages of a search and rescue mission. Once the target is located, helicopters or search and rescue ships can be dispatched for the specific rescue task.

This strategy not only saves valuable time but also reduces the demand for human and material resources,

ultimately improving the success rate of search and rescue missions ^[5]. In addition, small UAVs possess unique advantages, including the ability to achieve vertical take-off and landing, allowing them to complete flight missions even in extreme weather conditions. Beyond their efficient positioning capabilities, small UAVs are equipped with advanced thermal imaging and infrared imaging technology. These tools enable them to accurately detect the body heat signatures of trapped individuals, even at night or in adverse weather conditions, thereby enhancing the accuracy and efficiency of search and rescue operations.

Thermal imaging technology, in particular, is invaluable during nighttime rescue missions, as it can quickly detect heat emitted by the human body. This allows rescue teams to swiftly pinpoint the precise location of trapped individuals, significantly improving the scientific accuracy and overall effectiveness of search and rescue efforts.

3.2. Pay attention to extending the endurance time

The factors affecting the endurance of small UAVs in sea rescue operations are primarily as follows: the weight of the UAV (including its own mass and payload), flight speed, flight state, temperature, wind speed, and power system. The overall weight of a UAV includes components such as the frame, electronic speed controller, motor, blades, head, and flight controller.

In maritime rescue activities, the payload typically consists of cameras, life-saving equipment (such as life rings and manipulators), and other essential tools. The weight of the UAV directly impacts the thrust required to keep it airborne, which in turn affects its power output and limits battery life. Therefore, when utilizing UAVs for maritime search and rescue, rescue workers must prioritize minimizing the weight of the drone wherever possible. This ensures better endurance and efficiency during operations ^[6].

Secondly, the configuration and load selection of each component should be carefully planned. Components or configurations that do not meet the requirements of maritime search and rescue should be eliminated to reduce hardware redundancy ^[7].

Finally, while ensuring the endurance time as much as possible, factors such as the operating sea area should be taken into account. For example, in search and rescue activities conducted in waters with large waves and complex sea conditions, it may be necessary to choose a more durable UAV body and a more stable flight control system to ensure that the UAV can operate reliably in harsh environments.

For missions requiring long-distance flights, it might be necessary to equip the UAV with a larger-capacity battery or implement a more efficient energy management system to extend its flight time. Additionally, during the search and rescue process, the UAV's flight altitude, speed, and heading should be flexibly adjusted based on the specific situation to maximize the efficiency and accuracy of the operation ^[8].

3.3. Playing a vital role in providing warnings

In sea rescue activities, small UAVs must work closely with ground rescue teams by monitoring the rescue situation from above and promptly relaying information to the ground team. Upon receiving instructions, the UAV should immediately proceed to the accident site according to the pre-established plan and continue providing alerts to the ground rescue personnel.

For example, in the event of a marine explosion, small UAVs must quickly cool flammable materials to prevent further explosions. Additionally, they can assist environmental protection agencies in efficiently managing wastewater while supporting the rapid deployment of firefighting resources. This enables rescue forces to promptly reach the scene and ensures seamless coordination between aerial and ground operations. ^[9]

In the event of marine disasters, ground search and rescue teams may struggle to assess the situation at sea on time. Small drones can provide a comprehensive overview of the scene, identify suitable parking locations for rescue vehicles, and offer logistical support for maritime rescue operations.

Additionally, small drones can be equipped with high-decibel sirens or warning lights to fly over the accident site and alert nearby ships and personnel, preventing them from inadvertently entering hazardous areas. By carrying equipment such as loudspeakers, drones can also deliver rescue instructions to trapped individuals, helping them remain calm and wait for assistance.

Therefore, in marine search and rescue missions, fully utilizing the capabilities of small drones can help complete rescue tasks in the shortest possible time, reduce the risks associated with maritime rescue, minimize losses, and highlight the early warning and support functions of small drones ^[10].

3.4. Deliver materials and equipment

Firstly, long-distance transport by small UAVs in maritime rescue. Small unmanned aerial vehicles (UAVs) are highly effective in long-distance transport, especially in complex environments. Thanks to their strong carrying capacity, they can efficiently deliver relief supplies even in challenging conditions. With the ability to take off and land vertically, as well as fly at low altitudes, small UAVs can navigate through complex terrains and avoid obstacles on the ground.

Moreover, when equipped with a high-precision navigation system, small drones can plan their routes in real-time, ensuring that relief supplies reach their destinations accurately and efficiently. The advancement of battery technology has further improved the endurance of small UAVs, making them capable of completing long-distance transport missions. Additionally, the selection of different types of UAVs allows for the transport of varying loads; for example, larger UAVs can carry up to tens of kilograms of material, meeting the demands of rescue operations. By choosing the appropriate UAV model, these devices can adapt to the diverse needs of different rescue scenarios.

Secondly, the delivery of relief materials is a crucial function of small UAVs, particularly in maritime rescue operations. The delivery of basic survival materials, such as food and water, is especially critical in the aftermath of marine disasters. Stranded individuals often lack essential supplies, and the rapid delivery of these materials can make a significant difference in their survival. Small UAVs, with their strong carrying and transportation capacity, can deliver these materials quickly and efficiently to the scene. This ensures that trapped individuals receive the necessary provisions, allowing them to maintain confidence while awaiting rescue. Furthermore, small UAVs can transport urgently needed medical supplies, thereby safeguarding the health and safety of the stranded individuals.

Another important aspect of small UAVs in maritime rescue is their ability to deliver communication equipment. During maritime disasters, communication devices are often damaged or rendered inoperable due to sinking, water entry, or other causes. As a result, it becomes difficult for stranded individuals to communicate with rescue teams. Small UAVs can bridge this communication gap by delivering essential equipment such as satellite phones and mobile base stations. By establishing temporary communication networks, UAVs ensure that effective communication is maintained between the trapped individuals and search-and-rescue personnel, facilitating the smooth progress of rescue operations ^[11].

3.5. Conducting regular maritime safety inspections and information collection

Firstly, designate sea area safety inspections using small UAVs. Small UAVs play a key role in conducting safety inspections in designated sea areas. They take off and land to patrol and search for targets within specific waters,

ensuring the effectiveness of search and rescue operations. The operation process is as follows.

Based on weather conditions, small UAVs are prepared for takeoff, loaded with the designated patrol route, and then vertically lifted off from the launch platform. Once airborne at an altitude of 500 m to 3,000 m, the UAVs patrol the task area at a speed of 100 km/h to perform search and rescue tasks. After completing their mission, they return to base.

During flight, if additional targets are detected, rescue teams can use visual flight plans to connect the small UAV to the target's auxiliary equipment. After observing the target, the ground control operator directs the UAV back to its pre-determined orbit and initiates the return command. If an object of interest is discovered during the return journey, the UAV can deviate from its route, perform navigation or visual navigation, and then return to the original path to complete its return to base ^[12].

Secondly, collect information in specific sea areas. When a small UAV is deployed for mapping, photography, and other information collection tasks in a specific sea area, it will immediately take off for reconnaissance. The UAV targets specific areas or objects, performing remote mapping or capturing photos, videos, and other data. The high-definition image data is transmitted back to the shipping center, providing more detailed information on the target.

For example, small UAVs can remotely identify the appearance and side numbers of targets such as merchant ships and fishing boats, offering valuable decision-making support to users at a distance. In such cases, the UAV's pod locks onto the target and tracks it continuously, monitoring its movement patterns over time. Once the task is completed, the UAV can return to base at any time. It is important to note that information collection can be conducted in a single region or across multiple regions, with several small drones operating simultaneously ^[13].

4. Summary

All in all, small UAVs have gained widespread attention and application in future maritime rescue activities ^[15]. The search and rescue efficiency of small UAVs can be significantly improved by accurately locating trapped individuals, extending flight duration, serving as a special warning system, ensuring efficient material transportation and equipment delivery, and regularly conducting sea safety patrols and information collection. These capabilities can address key technological challenges and enhance the role of UAVs in sea rescue operations.

Therefore, in future maritime rescue missions, it is crucial to recognize the importance of small UAVs in these efforts and proactively adopt effective strategies to utilize them. This will help improve the quality of maritime rescue operations and maximize the preservation of lives and property.

Disclosure statement

The authors declare no conflict of interest.

References

- [1] Do-Hwi L, 2024, "Rescue Whale" Underwater UAV Design, Rescue Emissary in Deep Water. *Industrial Design*, 2024(10): 16.
- [2] Liu R, 2024, Design of Aviation Rescue UAV, Air Guardian of Water Safety. *Industrial Design*, 2024(10): 22.

- [3] Chang X, 2024, Water Rescue UAV Design, AI-Driven Search and Rescue Master. *Industrial Design*, 2024(10): 24.
- [4] Tang D, Han Q, Tian K, et al., 2024, Research on Indoor Target Autonomous Search Scheme of Micro UAV. *Progress in Aeronautical Engineering*, 2024: 1–12.
- [5] Zhou D, 2019, Design of a Surface Intelligent Drowning Rescue UAV Based on Deep Learning. *Science and Technology Innovation and Productivity*, 45(09): 141–144.
- [6] Zhang P, Zhang L, Li F, et al., 2024, Design of Emergency Rescue System Based on Multi-Rotor UAV. *Electronic Technology*, 53(08): 188–189.
- [7] Xu J, Xiang Y, 2023, Research on Key Technologies of UAV Rescue in Water Distress. *Water Safety*, 2023(08): 13–15.
- [8] Wang C, Si K, 2023, Target Detection Algorithm of Small UAV in Low Altitude Airspace. *Journal of Shenyang University of Aeronautics and Astronautics*, 40(02): 54–62.
- [9] Wang S, Luo J, Wang T, et al., 2022, Research on the Application of Warfare Method to Counter Small UAVs at Sea. *Ship Electronic Engineering*, 42(12): 45–47.
- [10] Wang R, 2022, Design of Maritime Search and Rescue Identification System Based on UAV. *Technology & Market*, 29(07): 100–102.
- [11] Zhou Y, Yuan Y, Shen X, et al., 2021, Research on Self-Floating Design of Marine UAV and Search and Rescue Recovery System. *Transportation World*, 2021(Z1): 9–11.
- [12] Gao Y, 2020, Research on UAV Search Planning Method and Application in Maritime Search and Rescue, thesis, National University of Defense Technology.
- [13] Su Z, 2021, Application Status and Development of UAV in Maritime Rescue Operations. *China Equipment Engineering*, 2021(11): 242–243.
- [14] Xu D, 2019, Research on Water Assisted Rescue System Based on UAV. *Technology & Market*, 27(11): 87–88.
- [15] Liu R, 2020, The Application of UAV in Emergency Relief and Talent Training. *Journal of Beijing City University*, 2020(2): 89–91.

Publisher's note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Design of a Small Bionic Butterfly Machine Under the Background of Innovation and Fusion

Yaxuan Wang, Fuming He, Yang Li*

Hunan Applied Technology University, Changde 415000, China

*Corresponding author: Yang Li, liyang5862022@163.com

Copyright: © 2025 Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY 4.0), permitting distribution and reproduction in any medium, provided the original work is cited.

Abstract: With the advancement of modern technology and the continuous development of science, research into flapping wing aircraft is becoming increasingly sophisticated. Addressing issues such as the large wingspan and heavy mass of existing bionic butterfly aircraft, this paper proposes the design of a lightweight lithium battery power supply, a chip integrated into a small circuit board, and a reference to the natural characteristics of butterfly wings. The wings are simulated using 0.125 mm polyethylene terephthalate (PET) film to replicate their movement. The driving structure employs a double motor and a four-bar mechanism to achieve natural and smooth wing vibrations. The control system features a lightweight motor, battery, and a high-performance low-power microcontroller for precise control. Using 3D printing technology, a lightweight design is realized, successfully simulating the structure and movement characteristics of a specific butterfly, demonstrating the principles of mechatronics. Furthermore, the design process incorporates multidisciplinary knowledge, and a workshop combining competitive discipline events with innovation and entrepreneurship has been established. This initiative fosters the deep integration of innovation and entrepreneurship education with professional training, effectively cultivating application-oriented technical talents.

Keywords: Bionic butterfly machine; 3D printing; Mechatronics; Specialized innovation integration

Online publication: February 14, 2025

1. Introduction

In the field of bionic butterfly aircraft research, Western countries have made remarkable achievements. For example, the German Festo's "emotion butterfly" bionic butterfly aircraft can simulate real butterfly flight, with a wingspan of 50 cm, a weight of 32 g, a flapping frequency below 3 Hz, a flight speed of 1–2.5 m/s, and a duration of 3–4 minutes^[1]. In contrast, domestic research started late, but Leng Ye of Shanghai Jiao Tong University also made an attempt to design and manufacture an imitation butterfly flapping wing aircraft with a wingspan of 49.8 cm, weight of 32.2 g, and flapping frequency of about 1 Hz^[2].

Despite these advancements, the design of flapping wing aircraft still faces certain deficiencies, such as large wingspans and heavy mass. These challenges, stemming from issues in control technology, materials, and

structure, have yet to be fully addressed. As a result, the production of small bionic butterfly flapping wing aircraft remains problematic.

The small bionic butterfly designed in this paper utilizes a lightweight lithium battery for power and integrates the chip into a compact circuit board, continuously reducing the overall weight of the machine. Based on bionic butterfly technology, a movable and fully functional machine is created, reflecting the principles of mechatronics^[3]. Furthermore, in the context of professional integration education, our team has established a workshop that combines discipline competition with innovation and entrepreneurship education. This initiative significantly enhances the quality of education and improves the talent development process.

2. Butterfly wing structure design

Butterflies have the super flying ability, which is closely related to their wing geometry, wing vein division, and mass distribution. Through an in-depth study of the bionics of butterfly wings, when the bionic butterfly flaps its wings at a high speed, the upward and downward flapping will be subjected to air resistance. The air resistance does positive work during downward flapping and negative work during reverse flapping^[4]. To improve flight efficiency, we compared the material, performance, and characteristics of the wings of insects, and found that PET film has low cost, high surface density, and strong tension, which is the optimum choice. In the design of the wing structure, the PET film of 0.125 mm thickness is used, which has a longer flight distance in the experiment and better performance than other materials, and the film is not easy to deform under surface tension and has a certain flexibility. Based on the study of the motion morphology of butterflies, Hu *et al.* conducted numerous experiments on two types of butterflies: the monarch butterfly, known for its long-distance flight ability, and the winged papilio butterfly (Bird of Paradise). They concluded that butterflies with different shape characteristics produce distinct flow structures around them^[5].

The leading edge of the monarch butterfly's wing is relatively straight, with a curvature much smaller than that of the Bird of Paradise wing butterfly. In a comparative study of the flow structure during flat flight without power, the front wing surface of the monarch butterfly performed better than that of the Bird of Paradise wing butterfly. Regarding the shape of the rear wing, the monarch butterfly has a smooth edge, similar to the oval wing design seen in fixed-wing aircraft. This wing shape exhibits excellent lift-to-drag characteristics at small to medium angles of attack, and good stall characteristics at large angles of attack. In contrast, the Bird of Paradise wing butterfly has a zigzag rear wing edge, which increases drag under low Reynolds number flying conditions. From an aerodynamic efficiency perspective, the rear wing of the monarch butterfly outperforms that of the Bird of Paradise wing butterfly.

Based on this analysis, the small bionic butterfly designed in this paper features a front wing curvature similar to that of the Bird of Paradise wing butterfly. The rear wing, however, is designed with smooth edges, resembling the oval wing shape found in fixed-wing aircraft, while the wing skeleton mimics the distribution of the monarch butterfly's wings.

3. The butterfly drive structure design

3.1. Drive mechanism design

According to Wang's analysis and summary of typical flapping wing mechanisms, multi-degree-of-freedom compound flapping refers to the coordination of multiple motors to drive the flapping motion of the aircraft via a

connecting rod mechanism. This flapping mechanism enables a higher degree of bionic wing movement ^[6]. Based on this conclusion, the driving mechanism of the small bionic butterfly designed in this paper employs a double motor and four-bar mechanism. The double motor design is superior to a single motor in terms of both power and efficiency, providing maximum lift for butterfly flight ^[7]. The four-bar mechanism can be adjusted by the length, position, and angle of the connecting rods to control the movement and frequency of the butterfly wings. This design allows the wings to produce natural and smooth vibrations, providing a more realistic simulation of the butterfly's flight motion ^[8].

3.2. The main body design

The two wings of the butterfly are connected to the motor via a rocker mechanism. The front wing consists mainly of three carbon rods, which are connected to the external outline. The middle part of the outer profile rod is connected to the four wings from front to back. The rear wing is primarily made of a carbon rod that forms a vortex ring structure. This structure allows the front and rear parts of the outer profile rod to become convex. The butterfly's pitch motion brings the leading-edge vortex closer to the wing surface and center of mass, while the up-and-down vibration of the body enhances the vortex, contributing to increased lift ^[9]. By simulating the average aerodynamic force of the front and rear wings of a dragonfly in each flapping mode, Yao *et al.* obtained the average aerodynamic coefficient of the cycle in different flapping modes of the dragonfly ^[10]. From this, it can be seen that both wings generate maximum lift when they flap simultaneously. Therefore, in the design of the small bionic butterfly machine, carbon fiber sheets are used to secure both the front and rear wings to enable simultaneous flapping.

A carbon rod is extended from the middle of the outer profile rod to connect to the main drive rod. The main drive rod is made of solid carbon fiber with a diameter of 1.5 mm and a length of 250 mm. One end is secured with a connector to hold the main drive rod in place, while the other end is threaded through a hole on the wing root connector and inserted into a specific blind hole on the motor rocker arm in the wing drive assembly to ensure fixation. Additionally, the wing root connector is designed to tightly fit the output end of the motor rocker arm. This configuration allows the main drive rod to transfer the motor's power to the wings, thereby driving the wing assembly to produce the fluttering motion.

Furthermore, the controller and battery are glued directly to the rear of the main rod and fixed securely to reduce the weight of the main rod, achieving a lightweight design. The rear wing bracket and the wing drive mounting bracket are adjustable along the main trunk axis, enabling the adjustment of the positions of the left and right wing assemblies, the micro-control system, and the power supply system.

3.3. 3D printing

In terms of 3D printing material selection, we use polylactic acid (PLA+), which is a new thermoplastic resin, but also a biodegradable plastic, with high strength, elastic modulus, good stretchability, and other advantages ^[11]. At the same time, Yang *et al.* obtained the 3D printing process parameters of the optimal mechanical properties through the PLA tensile specimen, which provided a theoretical basis for the best mechanical properties of the printed parts ^[12]. Based on the research results above, the components of the small bionic butterfly machine designed in this paper are made from PLA+ structural parts. Using SolidWorks modeling software, detailed diagrams of each part were created. In designing the bionic butterfly's drive structure, a comprehensive application of mechanical principles and knowledge from mechanical design courses was employed. Using 3D printing

technology, a set of high-precision, lightweight transmission mechanisms was designed, paired with appropriate driving equipment. Additionally, a mechanical design platform was set up in the workshop, which effectively enhanced students' practical skills in structural assembly and fostered innovative thinking in mechanical design. This initiative stimulates students' creativity and helps better train professional talents in 3D printing.

4. Butterfly control system design

4.1. The choice of motor and battery

The small bionic butterfly machine designed in this paper uses a 3-stage, 300 rpm, 6 mm hollow cup planetary gear motor, which offers several advantages, including lightweight, compact size, sensitive control characteristics, and stable operation. These features help effectively reduce the aircraft's weight. Considering the small wingspan of the bionic butterfly, we selected a lightweight 80 mA lithium battery to ensure sufficient lift. This battery design further reduces the vehicle's weight, thereby improving its flight efficiency. The choice of these motors and batteries contributes to minimizing the overall size of the bionic butterfly, bringing it closer to the real butterfly.

4.2. Main control board design

The aircraft selected uses an 8-bit AVR microcontroller ATMEGA328P-AU as the main control chip^[13]. The chip is not only small in size, which can meet the requirements of lightweight design of the aircraft, but also powerful in performance. It can execute powerful instructions in a single clock cycle, and the throughput is close to 1 MIPS/MHz. It is a microcontroller with high performance and low power consumption, which can ensure the processing speed and reduce the energy consumption of the whole machine. The regulator is AMS1117-5.0, it provides a fixed output voltage, and the output voltage accuracy is high, to ensure the stability and reliability of the power supply. The 16 MHz crystal oscillator provides the reference clock signal for the system. To meet the needs of the remote-control track, the pins required for remote-control reception are reserved when designing the main control circuit.

4.3. Transmission structure design

The flight mode of butterflies differs significantly from that of other insects. During flight, the butterfly's aerodynamic force is primarily directed perpendicular to its body's vertical axis. When the butterfly flaps its wings downward, its body pitch angle decreases, generating a larger aerodynamic force that is directed upward and slightly backward. This aerodynamic force not only provides the vertical lift to support the butterfly's weight but also creates a smaller horizontal force directed backward. In contrast, when the wings flap upward, the body pitch angle increases, generating less aerodynamic force, which is directed forward and slightly downward. This force mainly provides horizontal thrust to overcome the backward horizontal force created by the body during the downstroke. By adjusting the body's pitch angle, the butterfly can control the direction of the aerodynamic force to suit its flight needs^[14]. This unique flight mechanism allows the butterfly to display a high degree of flexibility and control in flight. Based on the above principles, the wing-driven linkage mechanism is derived, in which,

$$l_1 = 3 \text{ mm}, l_2 = 6 \text{ mm}, l_3 = 5.439 \text{ mm}, l_4 = 7.029 \text{ mm}, x_0 = 5.25 \text{ mm}, y_0 = 4.941 \text{ mm},$$

When l_1 and l_2 coincide, $AC_1 = AB_1 + BC_1 = l_1 + l_2 = 9$ mm When the rod l_3 swings to the highest point. In $\triangle AD$, from the law of cosine C_1 :

$$\alpha_1 = \arccos \frac{(l_1 + l_2)^2 - l_3^2 - l_4^2}{2l_3l_4} = \frac{9^2 - 5.439^2 - 7.029^2}{2 \times 5.439 \times 7.029} = 88.493^\circ$$

$$\theta_1 = \arccos \frac{l_3^2 - (l_1 + l_2)^2 - l_4^2}{2(l_1 + l_2)^2l_4} = \frac{5.439^2 - 9^2 - 7.029^2}{2 \times 9 \times 7.029} = 37.165^\circ$$

When l_1 and l_2 coincide, $AC_2 = B_2C_2 - AB_2 = l_2 - l_1 = 3$ mm, the bar l_3 swings to its lowest point. In $\triangle AD$, from the law of cosine C_2 :

$$\alpha_2 = \arccos \frac{(l_1 - l_2)^2 - l_3^2 - l_4^2}{2l_3l_4} = \frac{3^2 - 5.439^2 - 7.029^2}{2 \times 5.439 \times 7.029} = 23.743^\circ$$

Therefore, the swing angle of the bionic butterfly's unilateral wings is:

$$\alpha_1 - \alpha_2 = 88.493^\circ - 23.743^\circ = 64.749^\circ$$

In $\text{Rt}\triangle ADO$:

$$\theta_2 = \arctan \frac{y_0}{x_0} = \arctan \frac{4.941}{5.25} = 43.263^\circ$$

So the angle between the poles of the four-bar mechanism is:

$$\theta = 90^\circ - \theta_1 - \theta_2 = 90^\circ - 37.165^\circ - 43.263^\circ = 9.572^\circ$$

The quick return characteristic is:

$$K = \frac{180^\circ + \theta}{180^\circ - \theta} = \frac{180^\circ + 9.572^\circ}{180^\circ - 9.572^\circ} = 1.112^\circ$$

Based on the above research, we designed a micro-flight control board that highly integrates the remote-control circuit, the voltage regulator circuit, and the motor control circuit. This design demonstrates the concept of integration and intelligence of mechanical and electrical products and integrates the knowledge of single-chip microcomputers, electronic and electrical engineering, Programmable Logic Device (PLD) combined logic circuits, and other related courses. In the design of small bionic butterfly machine, in order to ensure the in-depth practice, we established the mechatronics integration technology workshop, the purpose is to improve the overall quality from the practical level through engineering training tasks and discipline competition training.

5. Conclusion

This paper successfully simulates the structure and movement characteristics of a specific butterfly wing, resulting in a fully functional, movable mechanical bionic butterfly. The butterfly has a wingspan of 29.5 cm, weighs 13.8 g, can reach a top speed of 1.5 m/s, has a flight time of 3–4 minutes, and requires 10 minutes to recharge. During the design process, the team also leveraged relevant knowledge and experience, establishing online and offline learning workshops for students with no prior foundation or those with some experience but no systematic training. These workshops aimed to foster learning through competition and promote the integration of innovation^[15]. However, although this research has successfully designed and manufactured a small bionic butterfly machine, the scope of the study remains relatively limited. The flight speed and endurance of the bionic butterfly still need improvement. We believe that with advancements in science and technology, these challenges can be addressed in the future. We also look forward to optimizing the design, improving material performance, enhancing the intelligence of the flight control system, and achieving more efficient and durable

flight performance.

Funding

- (1) Innovation and Entrepreneurship Training Project for College Students in Hunan Province in 2024: Design of Small Bionic Butterfly Machine Under the Background of Innovation and Integration (Project No. S202413809022)
- (2) 2023 Innovation and Entrepreneurship Training Project of Hunan College Students: Tiger Butterfly—Bionic Manufacturing and Morphology Research (Project No. S202313809022)

Disclosure statement

The authors declare no conflict of interest.

References

- [1] Zhang Y, Li S, Wang X, et al., 2024, Butterfly Flying Mechanism and Summarized Research Progress in Imitation of Butterfly Flapping Wing Flight Vehicle [J]. *Journal of Engineering Science*, 46–48(9): 1582–1593. <https://doi.org/10.13374/j.issn2095-9389.2023.10.11.002>
- [2] Leng Y, Zhang W, Zhou S, et al., 2019, Bionic Butterfly Aircraft Design Analysis. *Journal of Mechanical Design and Research*, 35(4): 32–35 + 42.
- [3] Gao Y, Zhong S, Xiong Z, et al., 2019, Design and Analysis of Bionic Butterfly Robot. *Mechanical and Electrical Engineering Technology*, 53(08): 97–100 + 123.
- [4] Sun W, Feng C, 2016, Imitation Dragonfly Flapping Wing Flight Vehicle Design and Aerodynamic Research. *Journal of Flight Mechanics*, 2016(5): 21–25 + 29.
- [5] Hu Ye, Wang J, Zhang C, et al., 2010, The Influence of Butterfly Wing Surface Shape on the Flow Structure. *Journal of Aerodynamics*, 28(02): 138–142.
- [6] Wang L, 2018, Design and Aerodynamic Analysis of Bionic ornithopter, thesis, Beijing Jiaotong University.
- [7] Lu Z, Tian G, Li R, et al., 2024, Single and Double Electric Machinery Transmission Direct Comparative Study on the Performance of the System. *Journal of Automobile Engineering*, 46–48(02): 310–319.
- [8] Xu B, Zhu W, 2017, Based on Four-Bar Linkage of Flapping Wing Drive Mechanism Design and Motion Simulation. *Journal of Chongqing Institute of Technology (Natural Science)*, 12(5): 63–66.
- [9] Huang S, Shen G, Wei L, et al., 2010, Flow Display Experiment for Hovering Flight of Mechanical Butterfly Model. *Experimental Fluid Mechanics*, 24(02): 59–64.
- [10] Yao D, Shen G, Zhu B, et al., 2011, Experimental Study on Aerodynamic dynamics of a Mechanical Dragonfly Hovering. *Journal of Experimental Fluid Mechanics*, 25(01): 69–75.
- [11] Li H, Wang H, Liu X, 2024, The Response Surface Method to Optimize the PLA Material Mechanical Properties of 3D Printing Specimens. *Journal of Plastic Science and Technology*, 52(10): 130–135.
- [12] Yang L, Meng J, Xue T, 2021, Effect of 3D Printing Process Parameters on Tensile Strength of PLA Specimen. *Plastics Industry*, 49(05): 73–77 + 142.
- [13] Yan H, Xu K, ZhuJia X, 2015, Based on the Four Rotor Aircraft MEGA328P Design. *Value Engineering*, 2015(29): 141–142.

- [14] Sun M, 2015, Aerodynamics of Insect Flight. Chinese Journal of Mechanical Mechanics, 47(02): 384.
- [15] Jin H, Meng L, Liu Z, et al., 2019, Innovation Curriculum Reform and Practice in the Context of Specialization Integration. Journal of Electrical and Electronic Teaching and Learning, 46(03): 208–210.

Publisher's note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Exploration on the Construction of Intelligent Big Data Platform of Ningxia Solar Photovoltaic Industry based on NB-IoT

Huijun Wang¹, Weiying Chong^{2*}

¹Xinhua College of Ningxia University, Yinchuan 750021, Ningxia, China

²School of Management & Marketing, Taylor's University, 47500, Malaysia

**Corresponding author:* Weiying Chong, weiying.chong@taylorsonline.edu.my

Copyright: © 2025 Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY 4.0), permitting distribution and reproduction in any medium, provided the original work is cited.

Abstract: As China's first new energy comprehensive demonstration zone, Ningxia's solar photovoltaic (PV) industry has developed rapidly, but it still faces shortcomings in terms of intelligence and digitalization. This study focuses on the application and construction of an intelligent big data platform based on Narrowband Internet of Things (NB-IoT) technology within Ningxia's solar PV industry. It explores the application trends of digital technology in the energy sector, particularly in the PV industry under the backdrop of energy reform, analyzes the technological development status of the smart energy field both domestically and internationally, and details the research methods and design components of the platform (including the photovoltaic base data platform, outdoor mobile application, remote data system, and back-office management system). The study discusses the opportunities and challenges Ningxia's PV industry faces and proposes a construction pathway. It provides a theoretical foundation and technical support for the digital transformation of Ningxia's PV industry, facilitating industrial upgrading and sustainable development. Although the current research is limited to the proposed design scheme, it establishes a basis for future empirical research and platform development.

Keywords: Ningxia; Solar photovoltaic; NB-IoT; Intelligent big data platform; Digital transformation

Online publication: February 14, 2025

1. Research background

In the context of energy transformation influenced by globalization and environmental pollution, integrating new energy sources and digital technologies is profoundly reshaping the global energy ecosystem. Leveraging clean energy resources such as solar and wind power, combined with technologies like NB-IoT, artificial intelligence, and big data to build intelligent systems, has become a key focus for governments in redefining modern energy management and trading. Globally, the digital transformation of the energy industry is emerging as a significant

trend ^[1]. Many countries and regions are actively promoting the application of digital technologies in the energy sector, such as big data analysis, artificial intelligence, blockchain, and Internet of Things (IoT) technology. These technologies are widely used in the production, transmission, consumption, and management of energy, providing energy enterprises with more efficient and flexible operations. In the photovoltaic industry, digital technologies have been shown to optimize energy management, increase power generation efficiency, and reduce energy waste.

Narrowband Internet of Things (NB-IoT), a low-power wide-area network technology suitable for large-scale device connectivity, is increasingly being used in the energy industry due to its characteristics of low power consumption, wide coverage, and low cost. NB-IoT technology can support remote equipment monitoring, intelligent operation, and data management of solar photovoltaic power stations, greatly improving the operational efficiency of the photovoltaic industry chain ^[2]. Through NB-IoT technology, photovoltaic equipment can transmit operating status data in real-time, and operation and maintenance personnel can remotely diagnose faults and optimize power station operation strategy, to reduce operation and maintenance costs and improve power generation efficiency. In recent years, some areas in China have taken the lead in applying NB-IoT technology, such as the photovoltaic demonstration base in Qinghai and the smart photovoltaic power station in Jiangxi. These successful cases have provided practical experience for Ningxia to explore the construction of a solar photovoltaic intelligent big data platform ^[3].

As an important window for China to open up to the West, Ningxia is one of the core regions of the “Belt and Road” development strategy. The autonomous region is located at an important node of the Silk Road Economic Belt and has a good foundation for cooperation with countries in Central and West Asia. This unique location advantage provides an international market environment for the development of the solar photovoltaic industry. Ningxia is not only the country’s first new energy comprehensive demonstration zone, but also an inland open economy pilot zone, which makes the new energy industry, especially the solar photovoltaic industry, a pillar industry driving regional economic development ^[4]. The 14th Five-Year Plan and the outline of the 2035 vision goals put forward by Ningxia have clarified the policy orientation of developing the digital economy and promoting the high-quality development of the clean energy industry, providing solid policy support for the intelligent and digital transformation of the solar photovoltaic industry.

Although the photovoltaic industry in Ningxia is developing rapidly, there are still shortcomings in terms of intelligent and digital industrial chains. For example, the current inspection and data management methods mainly rely on manual operations, and the storage, processing, and analysis of data lack a unified platform support. There are also big differences in the depth and granularity of industrial digitalization applications, especially the limitations of small and medium-sized photovoltaic enterprises in terms of technology and resources, resulting in the synergies of the overall industry chain are not obvious. In addition, compared with advanced regions in China, Ningxia is still in its infancy in terms of photovoltaic big data platform construction and NB-IoT technology application. Solving these problems is of great significance for enhancing the core competitiveness of Ningxia’s photovoltaic industry and promoting high-quality development of the local economy.

2. Research status at home and abroad

Internationally, technological progress in the field of smart energy has become an important driving force for the global energy transition ^[5]. For example, the United States leads the world in distributed energy management, cloud storage of energy data, and predictive maintenance of big data, and its advanced technologies have been

applied on a large scale in wind energy, photovoltaic, and other fields ^[6]. Germany, relying on its Industry 4.0 strategy and combined with its energy transformation goals, has successfully built several smart photovoltaic power stations and energy data platforms, which optimize energy management efficiency through real-time data collection and analysis, and significantly improve the utilization rate of renewable energy ^[6,7].

Moreover, Japan has established an integrated energy management platform through the deployment of a distributed energy system based on the Internet of Things (IoT), which greatly improves the flexibility of the electricity demand side ^[8,9]. Australia has made breakthroughs in PV data analytics and virtual power plants to provide intelligent energy solutions for PV users at the home and community levels ^[10]. These international practices show that the application of intelligent big data platforms can not only improve energy efficiency but also bring greater resilience and innovation to the energy supply chain.

In China, the photovoltaic industry has developed rapidly in recent years and has initially formed a complete industrial chain integrating research and development, manufacturing, and application ^[3]. For example, the photovoltaic industry demonstration base established in Qinghai has promoted the continuous optimization of photovoltaic power generation efficiency by integrating design, manufacturing, and empirical data ^[11]. The country's first "smart photovoltaic power station" built in Jiangxi has achieved several domestic leadership in intelligent forecasting, operation and maintenance management, and data integration ^[12]. However, on the whole, China's energy digital transformation is still in its initial stage, with unbalanced regional development, inconsistent technical standards, and large differences in the depth, and granularity of digitalization in each link of the industrial chain ^[13].

Specific to the Ningxia region, the solar photovoltaic industry has not yet formed a comprehensive digital system. The existing business is mainly concentrated in the traditional offline data collection and analysis links, the real-time data, integration, and visualization level is low. This status quo limits the further improvement of industry efficiency and also hinders the optimal allocation of upstream and downstream resources in the industrial chain. In this context, exploring and promoting the construction of an intelligent big data platform based on NB-IoT can not only fill the technical gap in Ningxia's solar photovoltaic industry but also provide important technical support and practical experience for the overall upgrade and sustainable development of the industry.

3. Research methods and contents

3.1. Research methods

This study comprehensively uses a variety of methods to systematically carry out research on the construction of an intelligent big data platform for the Ningxia solar photovoltaic industry based on NB-IoT. The specific methods and implementation process are as follows.

3.1.1. Literature research method

Comprehensively collect and analyze local and international literature related to energy digital transformation, photovoltaic industry intelligence, NB-IoT technology applications, etc. By consulting academic journals, industry reports, technical manuals, and such, we will have an in-depth understanding of the research status quo, technology development trend, and successful case experience in this field, to provide a solid theoretical foundation and practical reference basis for the research, and ensure the accuracy of the research direction and the cutting-edge of the research content.

3.1.2. Case analysis method

Select photovoltaic project cases that have successfully applied NB-IoT technology at home and abroad, such as the photovoltaic demonstration base in Qinghai, the smart photovoltaic power station in Jiangxi, and the relevant intelligent energy projects in Germany, Japan, and other countries. The platform architecture, functional modules, data management strategies, and technical application effects in these cases are analyzed in detail, from which experience and lessons are summarized and lessons can be extracted to provide practical reference examples for the design and construction of Ningxia solar photovoltaic intelligent big data platform, avoid repeated trial and error in the research process, and improve research efficiency and quality of results.

3.1.3. Demand analysis method

Carry out field research in local solar photovoltaic enterprises and power station operating units in Ningxia, and extensively collect the functional requirements, business process requirements, and data management requirements of all relevant parties on the intelligent big data platform through questionnaires and interviews. Systematically combing and analyzing the collected data, clarifying the actual needs to be met in the construction of the platform, ensuring that the designed platform can effectively solve the practical problems faced by Ningxia photovoltaic industry in the process of intelligence and digitalization, and improving the practicability and applicability of the platform.

3.1.4. System design method

Based on fully understanding the needs, the use of system design method to carry out the design of a photovoltaic base data platform and photovoltaic backstage management system. Including the overall structure of the platform planning, determining the logical relationship between the functional modules, and the data interaction process. Technology selection, comprehensive consideration of performance, cost, compatibility, and other factors, choosing the most suitable hardware equipment, operating system, database management system, and development tools. Detailed design of the user interface, to improve the convenience and friendliness of user operation as the goal, optimize the interface layout and interactive functions. At the same time, the data management, security, and other aspects of the comprehensive design ensure the efficiency of the platform operation, stability, and security.

3.1.5. Potential impact discussion method

Although the photovoltaic outdoor data mobile application and photovoltaic remote data system are not included in the core scope of the current research, through theoretical analysis and prospective discussion on their possible roles in the future photovoltaic big data demonstration platform, such as preliminary research on the possibility of functional expansion of mobile application and the optimization direction of remote data system security performance, etc. It provides ideas and directions for further expanding the functions of the platform and improving the system architecture in the future so that the research has certain foresight and scalability.

Through the comprehensive application of the above research methods, this study aims to provide comprehensive, scientific, and feasible design schemes and theoretical support for the construction of an intelligent big data platform for the Ningxia solar photovoltaic industry, and promote the digital transformation and sustainable development of Ningxia photovoltaic industry.

3.2. Research content

The design of the PV base data platform aims to realize efficient integration and automatic processing of data. The

platform integrates test data through an automated process, and a remote monitoring computer is responsible for data storage, processing, and display. The process enables automatic identification and recording of device test data, significantly reducing manual intervention and improving the efficiency and accuracy of data management.

In terms of data management, the platform provides an integrated management function that can store, query, print, and analyze test information of measuring equipment for outdoor projects. This not only improves the accessibility and operability of the data but also provides a centralized management solution for the equipment detection information.

The design of the user interface focuses on intuitiveness and ease of use, making it easy for operators to access and manipulate the data. Whether it is real-time monitoring or backtracking of historical data, the user interface provides clear, intuitive views and tools to support complex data analysis efforts.

In terms of data content, the platform includes two parts: general data and project data. The general data integrates the meteorological data acquisition module, including key parameters such as irradiance, temperature, and ultraviolet irradiance, which provides the basis for the analysis of all projects. These common data can be accessed on every project page to ensure the comprehensiveness of the analysis. Simultaneously, project data provides an independent test business data store for each project, supporting both real-time and cumulative storage methods to meet the flexibility of different analysis needs.

The design of the photovoltaic outdoor data mobile application aims to provide a convenient mobile monitoring function for field workers so that they can view the operation status of the photovoltaic base in real-time through mobile devices. This function is essential for quick response and site management. The application's data query and analysis function allows users to query historical data for specific projects and perform basic data analysis, providing on-site decision support for users. The report generation function allows users to generate and view project reports directly on the mobile application, further simplifying the workflow. Additionally, the integrated notification and alarm system can immediately notify relevant personnel when equipment is abnormal or performance deteriorates, improving the response speed and reliability of the system.

The photovoltaic remote data system is characterized by its remote access capability, allowing authorized users to remotely access the photovoltaic base data platform for data monitoring and analysis. This system ensures the real-time synchronization of data and maintains the data consistency between the remote data system and the PV base data platform. To protect the security of data transmission and storage, the system has implemented strict security measures, including data encryption and user authentication. These measures provide a solid guarantee for the security of the data.

The photovoltaic background management system realizes the persistent storage of data through the docking with the database. This system provides the necessary basic data support for the photovoltaic data platform, including user data, event data, project data, etc., to ensure the accuracy and integrity of the data. The integration of the logic judgment module enables the system to make intelligent decision support according to the basic data, such as fault diagnosis, performance prediction, etc., which improves the intelligence level of the system. In terms of data interface, the photovoltaic background management system ensures that the data source of the basic data interface is reliable, including the user (manufacturer) data, event data, and project data obtained from the photovoltaic background management system. Concurrently, the data update mechanism is designed to ensure the timely update and accuracy of the basic data, which provides a solid foundation for the stable operation of the whole photovoltaic big data demonstration platform.

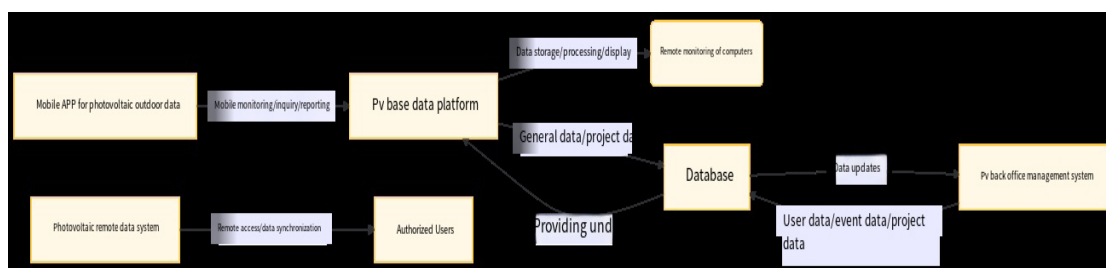


Figure 1. PV big data demonstration platform architecture design diagram

4. Conclusion and prospect

This study proposes a preliminary design scheme of a PV base data platform and PV back-office management system, aiming to provide support for the digital transformation of the solar PV industry in Ningxia. Through the in-depth discussion of the data integration, automatic processing, data management, and user interface design of the PV base data platform, this study presents an efficient, reliable, and user-friendly data management solution. At the same time, the design of the PV background management system emphasizes the importance of data persistence and intelligent decision support, which provides a solid foundation for the stable operation and data analysis of the PV data platform.

The research results show that the proposed design scheme can effectively integrate and process a large amount of data from photovoltaic power stations, and provide a powerful tool for the monitoring, maintenance, and performance optimization of photovoltaic power stations. Moreover, by introducing the concepts of photovoltaic outdoor data mobile applications and photovoltaic remote data systems, this study further expands the potential function and application range of photovoltaic big data demonstration platforms.

Although the current study is limited to the proposal of a design scheme, it lays the foundation for future empirical research and platform development. Future work will focus on the implementation, testing, and optimization of the scheme, as well as further exploration of practical applications of mobile and remote data systems in the PV industry. Overall, this study provides valuable insights into the digital transformation of the photovoltaic industry and provides directions for subsequent technological development and research.

Funding

This paper was supported by the Scientific Research Foundation of Xinhua College, Ningxia University, China; Project name: Preliminary Exploration of Ningxia Solar Photovoltaic Industry Intelligent Big Data Platform Construction Based on NB-IoT (Project No. 23XHXY07).

Disclosure statement

The authors declare no conflict of interest.

References

- [1] Afonassova MA, Panfilova EE, Galichkina MA, et al., 2019, Digitalization in Economy and Innovation: The Effect on

Social and Economic Processes. *Polish Journal of Management Studies*, 19(2): 22–32.

- [2] Winter CJ, Sizmann RL, Vant-Hull LL, 2012, *Solar Power Plants: Fundamentals, Technology, Systems, Economics*. Springer Science & Business Media, Berlin.
- [3] Jiang H, Jin Y, Ye X, et al., 2020, China Photovoltaic Industry 2019 Review and 2020 Outlook. *Solar Energy*, 2020(03): 14–23.
- [4] People's Government of Ningxia Hui Autonomous Region, 2021, Outline of the 14th Five-Year Plan for National Economic and Social Development of Ningxia Hui Autonomous Region and the Long-range Goals to 2035. People's Government of Ningxia Hui Autonomous Region, Yinchuan.
- [5] Asmelash E, Prakash G, Leme R, et al., 2019, Future of Solar Photovoltaic: Deployment, Investment, Technology, Grid Integration and Socio-Economic Aspects (A Global Energy Transformation). International Renewable Energy Agency, Abu Dhabi.
- [6] Guo K, Chen W, Wu K, et al., 2018, New Trends of International Energy Technology Development and its Revelation to Our Country. *The World Science and Technology Research and Development*, 40(03): 227–238. <https://doi.org/10.16507/j.issn.1006-6055.2018.05.005>
- [7] Luo Y, 2022, Data Governance Mechanism and Countermeasure of Promoting Enterprise Digital Transformation. *Business and Management*, 2022: 1–9.
- [8] Zuo Y, Tao F, Nee AY, 2018, An Internet of Things and Cloud-Based Approach for Energy Consumption Evaluation and Analysis for a Product. *Int. Comput. Integr. Manuf.*, 31(4–5): 337–348.
- [9] Rajasekar V, 2015, Indoor Soiling Method and Outdoor Statistical Risk Analysis of Photovoltaic Power Plants, thesis, Arizona State University.
- [10] Luo W, 2019, Analysis of the Long-Term Performance Degradation of Crystalline Silicon Photovoltaic Modules in Tropical Climates. *IEEE Journal of Photovoltaics*, 9(1): 266–271. <https://doi.org/10.1109/JPHOTOV.2018.2877007>
- [11] Kong D, Liao R, 2022, Promulgation of the 14th Five-Year Plan for Energy Science and Technology Innovation—Five Major Routes to Tackle Frontier Technologies. *Oil & Gas & New Energy*, 34(02): 28.
- [12] Han X, Guo J, Pu T, et al., 2022, Theoretical Basis and Development Prospect of Electric Power Artificial Intelligence Technology (I): Hypothesis Analysis and Application Paradigm. *Proceedings of the Csee*, 2022: 1–16. <http://kns.cnki.net/kcms/detail/11.2107.TM.20220713.1101.002.html>
- [13] Wang L, 2020, Current Situation and Prospect of Energy Science and Technology Cooperation Between China and the International Energy Agency. *Coal Quality Technology*, 37(01): 1–7.

Publisher's note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Study on Flue Gas Denitrification Performance and Mechanism Based on Carbon Source of Agricultural Waste

Shufeng Li*

Changchun University of Finance and Economics, Changchun 130122, China

*Corresponding author: Shufeng Li, jshzjingjixuehui@sina.com

Copyright: © 2025 Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY 4.0), permitting distribution and reproduction in any medium, provided the original work is cited.

Abstract: Currently, as environmental pollution becomes increasingly severe, flue gas denitrification has emerged as a significant area of research. With the advancement of modern industry and the improvement of living standards, air pollution has gained growing attention. Sulfur dioxide and nitrogen oxides (NO_x) have become major contributors to air pollution, posing serious harm to the environment. Consequently, flue gas desulfurization and denitrification technologies have become key research focuses in industrial development. This paper explores the selection of agricultural waste carbon sources and their pretreatment methods. It provides an in-depth analysis of the significance of agricultural waste carbon sources in flue gas denitrification, focusing on their performance and mechanisms. The study also discusses the role of agricultural waste carbon sources in flue gas denitrification, aiming to offer new research perspectives for relevant stakeholders.

Keywords: Agricultural waste; Carbon source; Denitrification performance and mechanism of flue gas

Online publication: February 14, 2025

1. Introduction

At the moment, global environmental issues are becoming increasingly prominent, and the prevention and control of various air pollutants have attracted growing attention. Among these pollutants, nitrogen oxides are major contributors, commonly present in the flue gas emissions from industrial production and energy consumption. This widespread presence poses a serious threat to both the ecological environment and human health.

While traditional flue gas denitrification technologies can reduce nitrogen oxide emissions to some extent, they are associated with high costs, operational challenges, and the potential for secondary pollution. As a result, the development of efficient, environmentally friendly, and economically viable denitrification technologies has become a critical focus for researchers and industry professionals.

2. The selection and pretreatment of agricultural waste carbon resources

2.1. Analysis of types and characteristics of agricultural waste

At present, there are many types of agricultural waste, including agricultural product processing waste, crop straw, livestock and poultry manure, etc. These wastes contain very rich carbon elements, which have a good potential as a source of flue gas denitrification carbon. In detail, agricultural waste such as peel, core, and shell generally have good organic materials such as sugar, oil, or starch, which can help decompose and release carbon elements. However, different types of agricultural product processing waste have differences in composition and properties, so it is necessary to conduct comprehensive consideration according to the specific crop situation, to ensure the effect of denitrification and economic benefits. Crop straws such as wheat straw, corn straw, etc., are important components of agricultural waste, with large yields, and wide distribution characteristics, at the same time these crop stalks are rich in cellulose and hemicellulose, where after treatment, can produce a lot of carbon elements that can be used as flue gas denitrification reducing agent. The reducing agent generated by combustion is also sufficient for the amount of flue gas denitrification.

Nonetheless, in the selection of materials, it is also necessary to pay attention to the differences between different kinds of straw in carbon content, ash, calorific value, etc., to ensure the effect of denitrification. Similarly, cattle manure, pig manure, other livestock manure, and other materials are also important sources of carbon sources of agricultural waste^[1]. These feces are also rich in carbon, and there are some nutrients such as nitrogen, phosphorus, and potassium, which can be used as organic fertilizers. The same carbon in the manure can also act as a reducing agent to react with the nitrogen oxides in the flue gas to produce harmless nitrogen and water. Even so, it is still necessary to note that the water content of these livestock and poultry feces is still relatively high, and they have certain harmful substances similar to heavy metals, so it is necessary to carry out proper treatment before normal use to minimize the probability of possible environmental pollution.

2.2. Agricultural waste pretreatment technology

The pretreatment technology of agricultural waste is to ensure that the relevant utilization efficiency and denitrification performance can be improved to the maximum extent before the flue gas denitrification. The related pretreatment technology mainly includes crushing, drying, charring, and more. The first step of pre-treatment is to break agricultural waste. Through manual grinding and mechanical crushing methods, agricultural waste can be broken into particles or powders that are easy to handle, and the contact area between the waste and the nitrogen oxides in the flue gas can be expanded, reducing the resistance in the reaction process, to continuously improve the reaction efficiency^[2].

Next, the drying treatment is also another important step in the pretreatment. Most of these waste materials will contain more water, which will affect their efficiency as a carbon source in the flue gas denitrification process. Through natural air drying, mechanical drying, and other methods, the water in the waste can be initially removed, to ensure the stability of the reaction with the nitrogen oxides in the flue gas.

Finally, the agricultural waste for pre-treatment also needs to be carbonized. Through carbonization, the organic matter present in the object can be converted into a stable carbon material. In the process of carbonization, the combustible substances and volatile components of agricultural waste will be consumed, and the final solid residue will be very rich in carbon elements. These residues not only have better reduction performance, but also have a very excellent performance in terms of carbon content, and the ash generated in the process of denitrification can also be reduced, thus greatly improving the overall denitrification effect^[3].

3. The research significance of flue gas denitrification performance and mechanism based on agricultural waste carbon source

3.1. Environmental protection significance

Currently, environmental protection has gradually become a key focus of societal attention, with nitrogen oxides identified as one of the main contributors to air pollution. The harmful effects of nitrogen oxides on the ecological environment threaten the delicate balance of ecosystems. As a result, flue gas denitrification methods utilizing agricultural waste as a carbon source hold significant environmental value for promoting sustainability and environmental development.

Notably, chemical pollutants such as acid rain, fine particulate matter, and photochemical smog are closely linked to nitrogen oxides, highlighting the importance of effective mitigation strategies ^[4]. The use of agricultural waste carbon sources for flue gas denitrification can effectively reduce the emission of nitrogen oxides, reduce the production of pollutants from the source, ensure air quality, and thus contribute to the ecological balance. On the other hand, if large quantities of agricultural waste are not managed and utilized properly, methods such as open burning—though seemingly convenient—can lead to significant air pollution. This process releases large amounts of pollutants into the atmosphere, including nitrogen oxides, particulate matter, and sulfur dioxide, while also resulting in a considerable waste of resources.

To address this issue, the unified collection and conversion of agricultural waste into a carbon source for denitrification offer a practical solution. This approach not only mitigates uncontrolled waste disposal but also enhances the utilization efficiency of agricultural waste. Furthermore, it supports the sustainable and collaborative development of agriculture and environmental protection.

3.2. The significance of resource utilization

As a widely available and abundant biomass resource, agricultural waste represents an opportunity for sustainable development. During agricultural production, common activities and crop processing generate significant amounts of waste, such as rice husks, fruit husks, and straw. However, due to limited understanding and traditional practices, agricultural waste is often discarded or burned. This not only fails to utilize the inherent value of the waste but also causes environmental pollution, particularly through the release of harmful smoke that pollutes the atmosphere and poses health risks.

By utilizing agricultural waste in flue gas denitrification, its unique properties can be harnessed. Through specific processing technologies, these wastes can be transformed into carbon materials with high adsorption capacities. Such processes enhance their catalytic activity, maximize the added value of these resources, and make them integral to flue gas denitrification reactions. This approach reduces reliance on raw materials used in traditional denitrification methods, diversifies industrial raw materials, and significantly improves the efficiency of flue gas denitrification.

Moreover, this utilization strategy enhances resource efficiency and offers a new economic development pathway for the agricultural industry. Farmers would have greater incentives to actively participate in waste collection and initial processing, fostering rural economic development. Ultimately, this model supports the positive cycle of environmental improvement, resource utilization, and economic growth, contributing to the advancement of both rural economies and ecological sustainability ^[5].

3.3. The significance of technological innovation

Using agricultural waste as a carbon source for flue gas denitrification is more innovative than the traditional

denitrification mode. At the technical level, this research direction can further optimize the denitrification system and process parameters, and efficiently integrate the carbon source of agricultural waste with the existing flue gas treatment process, thus effectively reducing the cost and energy consumption in the process of flue gas denitrification. The research on agricultural waste can also provide more data support and reference materials for the subsequent development of a more accurate and intelligent flue gas denitrification control system so that it can adjust the entire process in real time according to the real situation and continuously improve the efficiency and stability of denitrification. In addition, from the perspective of the preparation of raw materials, researchers can develop a unique pretreatment and carbonization process based on agricultural waste, which can be converted into functional carbon materials with specific functional groups and rich pore structures. Materials with these characteristics can perform excellent functions in the adsorption and catalytic reduction of nitrogen oxides. At the same time, it also lays a more solid foundation for subsequent technological innovation.

4. study on the mechanism of agricultural waste carbon source in flue gas denitrification

4.1. Reaction mechanism of carbon source and NO_x

The core of denitrification technology is the reaction mechanism between agricultural waste carbon sources and nitrogen oxides. In the process of flue gas denitrification, the reduction reaction is the main basis of this process, which means that the carbon elements in the carbon source of agricultural waste reduce nitrogen oxides to harmless nitrogen and water. Generally, the main form of carbon in the carbon source of agricultural waste is solid which includes lignin, cellulose, and hemicellulose. When these substances are in contact with the flue gas containing nitrogen oxides, they will adsorb nitrogen oxide molecules, and under the appropriate temperature and catalyst, the carbon elements in the carbon source can also undergo a reduction-oxidation (redox) reaction with nitrogen oxides. In this reaction, the carbon is oxidized to carbon dioxide, and the corresponding nitrogen oxides are reduced to nitrogen and water. For example, NO_x may first be reduced to nitric oxide (NO) and then further react with the carbon in the carbon source to form N₂ and CO₂. Moreover, the process of flue gas denitrification will also be affected by different factors, including the type, nature, and reaction temperature of the carbon source and the type of catalyst, etc., thus in the actual application process, it is necessary to use the basic material and the specific flue gas composition denitrification efficiency as the main reference factors to choose a more suitable agricultural waste carbon source and reaction conditions to achieve the best denitrification effect.

4.2. The mechanism of microbial action

The mechanism of microbial action plays a key role in the flue gas denitrification process using agricultural waste as a carbon source. Agricultural waste contains a variety of organic components, providing an abundant substrate for microbial survival. When these wastes are used as the base material for flue gas denitrification, specific microbial communities can thrive on their surfaces and within their internal spaces. These microorganisms decompose complex organic substances in the agricultural waste through metabolic activities, converting them into intermediates such as small organic acid molecules. These intermediates enhance the adsorption capacity for nitrogen oxides and alter the chemical properties of the waste's surface, thereby actively participating in the denitrification reaction.

Additionally, the metabolic activities of microorganisms can significantly influence their environment by altering local pH, redox potential, and other physicochemical conditions. These environmental changes positively

impact the efficiency of the flue gas denitrification process. Furthermore, microorganisms secrete extracellular polymers during growth, which form biofilms on the surface of the agricultural waste carbon source. These biofilms improve the stability and resistance of the materials to erosion, providing specialized reaction sites for the adsorption and transformation of nitrogen oxides, ultimately enhancing the efficiency and sustainability of the denitrification process.

Certain specialized microbial strains can also directly participate in the reduction of nitrogen oxides. For example, denitrifying bacteria can convert nitrogen oxides into nitrogen gas, ensuring the smooth progression of the reduction process—a critical step in flue gas denitrification. These microorganisms possess unique enzyme systems, such as nitrate reductase and nitrite reductase, which catalyze the stepwise reduction of nitrogen oxides. This enzymatic action effectively removes nitrogen elements and minimizes the NO_x content in flue gas.

4.3. Carbon energy regeneration and recycling

In the denitrification process using agricultural waste carbon sources for flue gas treatment, the regeneration and recycling of the carbon source is a valuable and practical mechanism. After the adsorption and catalytic reduction of nitrogen oxides, the surface active sites and internal structure of the carbon source may change, leading to a gradual decline in overall denitrification performance. However, specific regeneration processes can restore the properties of the carbon source and enable its reuse.

Thermal regeneration is an effective method for restoring the activity of agricultural waste carbon sources. Under appropriate high-temperature conditions, the carbon source can be heated to desorb nitrogen oxides adsorbed on its surface. Additionally, the pore structure and surface functional groups damaged during the reaction can be repaired, restoring the carbon source's adsorption and catalytic activity. This process allows the carbon source to regain its efficient denitrification capacity.

From a carbon cycle perspective, regenerating agricultural waste carbon sources enhances raw material utilization efficiency and reduces costs. This approach decreases the demand for fresh carbon source materials while optimizing resource use in reduction reactions, aligning with the principles of sustainable development.

Furthermore, during continuous recycling, researchers can refine the regeneration process through systematic experimentation on operating conditions. Such efforts can improve the recycling efficiency and extend the number of recycling cycles, unlocking additional value from the carbon source. This iterative optimization supports advancements in recycling technologies and contributes to environmental sustainability.

5. Conclusion

With the development of the economy and continuous advancements in scientific research, the performance and mechanisms of flue gas denitrification are constantly being optimized and refined. Agricultural waste carbon sources, when used as the primary material in flue gas denitrification, promote the regeneration and recycling of carbon sources, offering significant value for environmental protection and sustainable development.

This new research direction not only contributes to technological advancement but also fosters economic growth in related industries. Furthermore, in terms of denitrification performance and mechanisms, agricultural waste carbon sources have demonstrated effective denitrification capabilities.

The reaction mechanism between carbon sources and nitrogen oxides is relatively complex. However, the involvement of microorganisms greatly enhances denitrification efficiency, presenting a novel approach to flue gas

denitrification technology. Additionally, the regeneration and recycling mechanism of the carbon source further enhances the economic feasibility and sustainability of using agricultural waste in flue gas denitrification.

Disclosure statement

The author declares no conflict of interest.

References

- [1] Xu X, 2023, Study on Flue Gas Denitrification Performance and Mechanism Based on Carbon Source of Agricultural Waste, thesis, South China University of Technology.
- [2] Long Y, 2023, Study on Denitrification Efficiency and Metabolic Mechanism of Agricultural Waste Hydrolysate as Carbon Source, thesis, South China university of technology.
- [3] Liu Y, Xuan Q, Hu R, et al., 2022, Based on Agricultural Waste Enhanced Biological Denitrification Effect Research. *Seeds of Science and Technology*, 40(24): 16–19 + 120.
- [4] Zuo Y, Song M, Luo H, et al., 2022, Preparation and Research Progress of Carbon Source Agricultural Waste. *Journal of Applied Chemical*, 2022(9): 2704–2710 + 2714.
- [5] Guo Z, 2022, Study on Carbon Source Extraction From Corn Cob and its Enhanced Nitrogen Removal Effect Based on Physicochemical and Biochemical Methods, thesis, Zhengzhou university.

Publisher's note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Agricultural IoT Security Risk Assessment Method Based on Random Forest

Xinzhe Liu*

College of Information Engineering, North China University of Water Resources and Electric Power, Zhengzhou 450046, China

*Corresponding author: Xinzhe Liu, 11027445851xz@gmail.com

Copyright: © 2025 Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY 4.0), permitting distribution and reproduction in any medium, provided the original work is cited.

Abstract: The agricultural Internet of Things (IoT) system is a critical component of modern smart agriculture, and its security risk assessment methods have garnered increasing attention from the industry. Current agricultural IoT security risk assessment methods primarily rely on expert judgment, introducing subjective factors that reduce the credibility of the assessment results. To address this issue, this study constructed a dataset for agricultural IoT security risk assessment based on real-world security reports. A PCARF algorithm, built on random forest principles, was proposed, incorporating ensemble learning strategies to enhance prediction accuracy. Compared to the second-best model, the proposed model demonstrated a 2.7% increase in accuracy, a 3.4% improvement in recall rate, a 3.1% rise in Area Under the Curve (AUC), and a 7.9% boost in Matthews Correlation Coefficient (MCC). Extensive comparative experiments showed that the proposed model outperforms others in prediction accuracy and robustness.

Keywords: Random forest; PCA; Agricultural Internet of Things; Security risk assessment

Online publication: February 14, 2025

1. Introduction

Rapid population growth brings increasing competition for land, water, and other natural resources^[1]. These issues urgently require reducing the dependence of food systems on the environment^[2]. At the same time, traditional agricultural production methods overuse resources such as water, electricity, fertilizers, and pesticides, resulting in a decrease in land and underground water power year by year^[3]. Therefore, a more advanced agricultural model is needed to meet the growing demand for crop production to guarantee sustainable development.

Smart agriculture is made up of emerging technologies such as blockchain, artificial intelligence, and the Internet of Things (IoT)^[4]. China has issued a series of policy documents to support the development of smart agriculture, including the Opinions of the Chinese Communist Party (CPC) Central Committee and The State Council on Implementing the Strategy of Rural Revitalization, which put forward the development of digital agriculture and promote the trial and demonstration of the Internet of Things^[5]. To meet these needs, the number

of IoT devices used for agricultural purposes is also expected to increase significantly ^[6].

However, there are many security and privacy concerns at each layer of IoT architecture ^[7]. There are many cyber-attacks that attackers can launch, such as distributed denial-of-service (DDoS) attacks that make services unavailable and then inject fake data that can affect food safety, agricultural supply chain efficiency, and agricultural productivity ^[8]. Jawarneh *et al.* have studied the main issues facing agricultural IoT, which they believe include heterogeneous devices and communication, physical device integration, and data privacy concerns, among others ^[9].

Although the standard proposed by some scholars has a good evaluation range, it does not specify its scoring calculation method, there are no unified scoring calculation rules in the industry and academia, and the evaluation method relies heavily on the scoring of experts in the industry ^[10–13]. This will not only lead to the Internet of Things platform security assessment score calculation methods are not uniform but also lead to score evaluation because different companies have different calculation methods and evaluation experts have a large error, reducing the feasibility of the national standard. Therefore, government agencies and related enterprises urgently need an objective and accurate security assessment system to unify the scoring standards of agricultural Internet of Things systems.

The machine learning model has the characteristics of relatively objective evaluation scores, independent of prior expert knowledge in the calculation process, good generalization performance, and low application cost, so it has been widely used in different fields. For example, Wang *et al.* used the assessment model based on Random Forest (RF) to evaluate and forecast flood disaster risk, and the results showed that the model could provide a reference for the study of flood risk management and disaster prevention and reduction in river basins ^[14]. Cen *et al.* proposed a risk assessment method for the operation and maintenance of municipal pipe networks based on machine learning and built a model example based on the data of a pipe network base in a park in Suzhou City to evaluate the leakage risk of the pipe network ^[15].

Inspired by the above work, this study proposed a machine learning-based security risk assessment method for agricultural Internet of Things systems to quantify the risk factors, which can be used for security risk assessment of specific agricultural Internet of Things platforms, and solve problems such as the inconsistency between the subjective assessment of experts and the calculation standards in the traditional assessment methods.

2. Research methods

2.1. Data set construction

The goal of this study is to improve the quality and applicability of the dataset through a series of methods to provide a solid foundation for model development and further analysis. As there is no open-source data set available for agricultural Internet of Things security risk assessment at present, this study screened 200 agricultural Internet of Things security risk assessment reports from a company with information security level assessment qualification and produced agricultural Internet of Things security risk assessment data set according to 87 security risk items stipulated in the national standard.

2.2. Conditional GAN data enhancement scheme

The dataset contains 200 agricultural Internet of Things security risk assessment data, of which 184 items passed the security risk assessment accounted for the majority, while only 16 items failed the assessment. This leads to

an obvious category imbalance in the data set. Therefore, when constructing the prediction model, corresponding strategies should be taken to deal with the imbalance of the data set to ensure the predictive performance and reliability of the model.

Considering that the characteristic variables of the agricultural Internet of Things security risk assessment data set are all sparse high-dimensional attributes, the traditional interpolation data enhancement method cannot effectively generate similar samples when sampling sparse high-dimensional features. In this study, the conditions to be followed when generating synthetic data were regulated by modeling attributive features and introducing condition vectors represented by masks in the training process of Generative Adversarial Network (GAN) models. When dealing with attributive features, the goal of this study is to constrain the generator results $\{\widehat{d}_1, ..., \widehat{d}_{Nd}\}$ to satisfy as much as possible.

$$\mathbb{P}_G(\text{row}|D_{i^*} = k^*) \approx \mathbb{P}(\text{row}|D_{i^*} = k^*) \quad (1)$$

Specifically, for attribute class features in the i row, D_i mask vector is generated m_i , where k represents the mask of the class k ; For each category k , according to the number of times that category appears in the column D_i (the total number of categories is N), calculate the probability function $P(D_i = k) = n/N$, select the category according to the probability function k^* , and update the corresponding element k^* in the mask vector m_i to 1; All the generated attribute class feature masks are spliced to form the final discrete quantity generation result $\{d_{1,i}, ..., d_{Nd,i}\}$. The virtual evaluation unqualified sample generated by the final generator can be expressed as **Equation 2**.

$$\widehat{r}_j = \alpha_{1,j} \oplus \beta_{1,j} \oplus \dots \alpha_{N_c,j} \oplus \beta_{N_c,j} \oplus d_{1,j} \oplus \dots \oplus d_{Nd,j} \quad (2)$$

Where: \widehat{r}_j is the feature of the final generated security risk assessment sample j , c is the dimension of the numerical feature, α_{N_c} is the numerical feature of the generated sample, is the mode quantity of the numerical feature of the generated sample, and $\beta_{i,j} = [0,0,1]$ is the unique thermal code. If the calculated value belongs to the learned pattern, it can be obtained.

In this study, the general GAN normal form is selected as the generator and discriminator, and the cross entropy of the virtual feature \widehat{r}_j and the real feature generated \widehat{r}_j by the generator is taken as the loss function.

2.3. PCARF

In addition, there is some correlation between the data set indicators. Taking physical location selection as an example, physical location selection often affects other characteristic variables such as anti-theft, waterproofing, physical access control, etc. The nonlinear classification capability of the random forest model enables it to be applied to the agricultural Internet of Things security risk assessment scenario with complex high-dimensional sparse features. However, some noise factors that have little impact on classification results may be incorrectly learned by the random forest model. Therefore, Principal Component Analysis (PCA) technology should be used to find appropriate dimensionality reduction embedding space to unify the measurement of various risk factors. To reduce the influence of noise factors on the prediction results.

The standardization method of traditional PCA is a simple linear average, and the difference in degree information between parameters in various dimensions is eliminated while dimensionality is reduced. Therefore, improvements are made in the standardization method, such as log-centric PCA, which is log-centric processing when data is standardized, and balanced PCA, which is weighted normalized mean processing when data is standardized. The nonlinear PCA method proposed in this section is exponential centralized processing when data is standardized.

2.4. Construction of agricultural Internet of Things security risk assessment model based on random forest

To further improve the prediction accuracy, this study uses the ensemble learning method of “Boosting + Stacking” to enhance the prediction effect by combining multiple base learners, forming an ensemble model with better performance by combining homogeneity or heterogeneity. This process creates multiple base learners, integrates, and outputs results by combining modules.

In this study, the extreme gradient lifting algorithm (XGBoost) in Boosting is used for pre-training as one of the base learners in the Stacking algorithm. Then, Principal Component Analysis Based Random Forest (PCARF), statistical learning model Logistic Regression (LR), and XGBoost are selected to be used. The improved BP neural network, four kinds of models that are intrinsically different from each other, are used for model fusion. In terms of the model fusion strategy, RF, LR and XGBoost are used as first-level learners to be responsible for preliminary feature learning and prediction. The improved BP neural network acts as a second-level learner to further synthesize and fine-adjust the output of the first-level learner. Through this hierarchical fusion method, the advantages of different models are integrated to improve the accuracy and generalization ability of the overall prediction.

In terms of the final score of the agricultural Internet of Things security risk assessment, this study takes the probability that the model output-specific case results are qualified as the agricultural Internet of Things security risk assessment score and determines whether the agricultural Internet of Things security risk assessment is qualified according to the existing grade assessment conclusions.

3. Experiment and analysis

3.1. Performance analysis of agricultural Internet of Things security risk assessment model

In this study, the performance of data enhancement methods was evaluated using t-Distributed Stochastic Neighbor Embedding (t-SNE) combined with Kernel Density Estimation (KDE) dimensionality reduction graphs, as shown in **Figure 1**.

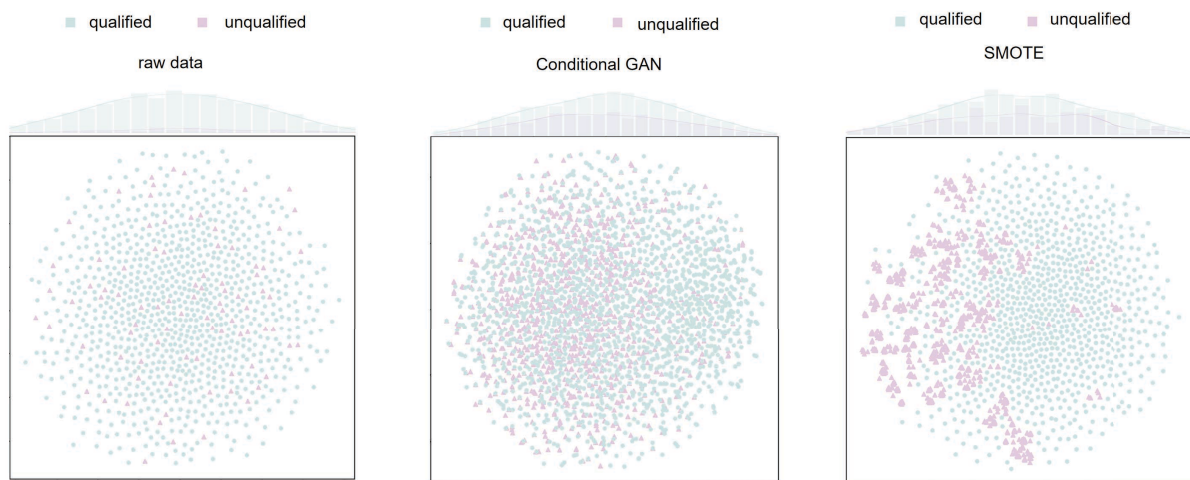


Figure 1. Evaluate unqualified sample data to enhance sample balance results

The Synthetic Minority Over-sampling Technique (SMOTE) method used in this case generated a more uniform sample distribution than the existing interpolation method, which indicates the richness of the generated data. In addition, the closer the distance between the generated sample and the original sample in the t-SNE dimensionality reduction graph, the higher the similarity is. These samples with small differences carry more information, and can better refine the model decision boundary in training and improve the training quality of the model.

The comparative experimental results are shown in **Table 1**. The author compared the accuracy of different models in agricultural Internet of Things security risk assessment when different balanced data participated in model training. The experimental results show that the model used in this study and the conditional GAN achieved the best performance in the test. Compared with the commonly used data-driven model, the recall rate of the agricultural Internet of Things system security risk assessment increased by 3.4%, the AUC increased by 3.1%, and the MCC of the model reached 94.6%. It shows that the model has a good balance in the classification of positive and negative samples.

Table 1. Comparative experimental results

Model name	Enhanced data participation rates	AUC	Recall	MCC
Model for this study	0%	59.7%	56.7%	45.3. %
	40%	79.3%	77.6%	65.5%
	70%	93.7%	91.6%	94.6%
Random Forest (RF)	0%	57.7%	56.6%	44.6%
	40%	75.1%	75.0%	60.7%
	70%	90.6%	88.2%	86.7%
AdaBoost	0%	60.8%	59.1%	50.9%
	40%	74.4%	73.1%	62.8%
	70%	89.2%	88.0%	83.9%
MLPClassifier	0%	55.8%	56.2%	39.2%
	40%	75.9%	78.6%	69.6%
	70%	74.1%	69.8%	62.5%

4. Conclusion

Aiming at the problem of the influence of expert subjective factors in the agricultural Internet of Things security risk assessment, this study uses 200 real agricultural Internet of Things security risk assessment reports as data sources, constructs the agricultural Internet of Things security risk assessment data set, and selects the optimized Conditional Tabular Generative Adversarial Network (CTGAN) algorithm as the data balancing method. The random forest algorithm PCARF optimized based on PCA was used to construct the agricultural Internet of Things security risk assessment model by adopting the integrated model method. The accuracy and reliability of the model were proved through experiments. The prediction results of the data-driven model were used as the reference basis for the agricultural Internet of Things security risk assessment, without relying on expert judgment or other artificial risk grade labels. It is more objective and stable than the traditional method. Overall, this study plays an

important role in promoting the improvement of IoT security risk assessment algorithms and obtaining scientific, reliable, and objective agricultural IoT security risk assessment results.

Disclosure statement

The authors declare no conflict of interest.

References

- [1] Karlov AA, 2017, Cybersecurity of Internet of Things—Risks and Opportunities. Proceedings of the XXVI International Symposium on Nuclear Electronics & Computing (NEC'2017), 2017: 182–187.
- [2] Stafford JV, 2019, Precision Agriculture '19. The Netherlands: Academic, Wageningen.
- [3] Ahmed N, De D, Hussain I, 2018, Internet of Things (IoT) for Smart Precision Agriculture and Farming in Rural Areas. *IEEE Internet of Things Journal*, 5(6): 4890–4899.
- [4] Ferrag MA, Shu L, Friha O, et al., 2021, Cyber Security Intrusion Detection for Agriculture 4.0: Machine Learning-Based Solutions, Datasets, and Future Directions. *IEEE/CAA Journal of Automatica Sinica*, 9(3): 407–436.
- [5] Zhao C, 2019, Research on the Development Status and Strategic Goals of Smart Agriculture. *Smart Agriculture*, 1(01): 1–7.
- [6] Malavade VN, Akulwar PK, 2016, Role of IoT in agriculture. *IOSR J. Comput. Eng.*, 2016: 56–57.
- [7] Tewari A, Gupta B, 2020, Security, Privacy and Trust of Different Layers in Internet-of-Things (IoTs) Framework. *Future Gener. Comput. Syst.*, 108: 909–920.
- [8] Zhu WJ, Deng ML, Zhou QL, 2018, An Intrusion Detection Algorithm for Wireless Networks based on ASDL. *IEEE/CAA J. Autom. Sinica*, 5(1): 92–107.
- [9] Kuthadi VM, Selvaraj R, Rao YV, et al., 2023, Towards Security and Privacy Concerns in the Internet of Things in the Agriculture Sector. *Turkish Journal of Physiotherapy and Rehabilitation*, 32(3).
- [10] General Office, Standing Committee of the National People's Congress, 2016, Cybersecurity Law of the People's Republic of China. China Democracy and Legal Press, Beijing, 2016.11.
- [11] National Standard of the People's Republic of China, 2022, GB/T 20984-2022 Information Security Technology—Risk Assessment Method for Information Security.
- [12] National Standard of the People's Republic of China, 2019, GB/T 22239—2019 Information Security Technology — Baseline for Classified Protection of Cybersecurity.
- [13] National Standard of the People's Republic of China, 2019, GB/T 28448—2019 Information Security Technology — Evaluation Requirement for Classified Protection of Cybersecurity.
- [14] Wang Z, Lai C, Chen X, et al., 2015, Flood Hazard Risk Assessment Model Based on Random Forest. *Journal of Hydrology*, 527: 1130–1141.
- [15] Cen H, Huang D, Liu Q, et al., 2023, Application, Research on Risk Assessment of Municipal Pipeline Network Based on Random Forest Machine Learning Algorithm. *Water*, 15(10): 1964.

Publisher's note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Research and Application of EMUs Braking System Control Logic Based on MBSE

Wen-yu Wang^{1*}, Yong-qiang Wang², Yue Lin³

¹College of Automation Engineering, Guangxi Vocational College of Water Resources and Electric Power, Nanning 530000, China

²College of Energy, Power and Environmental Engineering, Guangxi Electrical Polytechnic Institute, Nanning 530000, China

³College of Railway Locomotive and Rolling Stock, Liuzhou Railway Vocational Technical College, Liuzhou 545000, China

**Corresponding author:* Wen-yu Wang, wwy1066_6@126.com

Copyright: © 2025 Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY 4.0), permitting distribution and reproduction in any medium, provided the original work is cited.

Abstract: As Model-Based Systems Engineering (MBSE) was applied to the Electric Multiple Unit (EMU) braking system control logic, a preliminary exploration was conducted for bullet train braking system control logic research using an MBSE practice framework. The framework mainly includes the requirement analysis phase, functional analysis phase, and design phase. Systems Modeling Language (SysML) was used as the modeling language, and Cameo Systems Modeler (CSM) was employed as the modeling tool. By integrating the EMU braking system control logic and utilizing a top-down design approach, the implementation of MBSE in the bullet train braking system was analyzed and studied. The results show that, according to the MBSE practice framework, a unified description of the requirement analysis, functional analysis, and design synthesis of the EMU braking system control logic can be achieved. Additionally, the correlation and traceability between models can be established.

Keywords: MBSE; Braking system; Control logic; SysML

Online publication: February 18, 2025

1. Introduction

In Traditional Systems Engineering (TSE), a series of documents written in natural language are used to express user requirements, design schemes, analysis reports, and physical models made of real objects. However, TSE documentation has obvious shortcomings. As the system size increases, it becomes challenging to maintain consistency in engineering design. If the latest glossary and vocabulary are not used, it may lead to misunderstandings and inconsistencies^[1].

The International Council on Systems Engineering (INCOSE) formally defined Model-Based Systems Engineering (MBSE) in 2007^[4,5]. MBSE addresses the limitations of Traditional Systems Engineering (TSE) in

managing complex systems, enhances work efficiency, and reduces costs.

An Electric Multiple Unit (EMU) is a typical complex industrial system, consisting of multiple subsystems with intricate interrelationships. It involves various disciplines, making its design highly complex. Currently, the domestic development of EMUs primarily follows Traditional Systems Engineering (TSE), which poses challenges for the inheritance and reuse of certain subsystem models, as well as for the maintenance and management of development experience, knowledge, and the EMU life cycle.

Based on the principles of Model-Based Systems Engineering (MBSE) and the control logic of the EMU braking system, this paper explores the implementation of MBSE in the braking control logic of EMUs from the perspective of forward design. This research enables a unified description of requirement analysis, functional analysis, and design synthesis for the control logic of the EMU braking system while ensuring correlation and traceability between various models.

2. Practical basis of EMU braking system based on MBSE

2.1. Modeling language

Since the Object Management Group (OMG) endorsed Unified Modeling Language (UML) as a standardized modeling language, UML has been widely adopted in industry, science, and technology. To meet the needs of systems engineering, the International Council on Systems Engineering (INCISE) and OMG extended and reused UML 2.0, developing a new system modeling language known as Systems Modeling Language (SysML) ^[3].

SysML defines requirements on the semantic model, structure model, behavior model, and parameter model, to visualize the important aspect of system design and the convenient communication modelers. SysML offers the following advantages over UML 2.0.

Firstly, SysML represents systems engineering semantics better than UML, this approach can reduce software offset in UML, and two new requirements diagrams and parameter diagrams are added.

Secondly, SysML is smaller and easier to learn than UML. SysML gets rid of a lot of unreasonable structure, so the diagram types and overall structure of the whole language are smaller ^[5]. To sum up, this paper adopts SysML modeling language.

2.2. Modeling tools

Mainstream Model-Based Systems Engineering (MBSE) modeling tools include IBM Rational Rhapsody, Capella, MagicDraw, and M-Design, among others. With the rapid development of various industries worldwide driving MBSE adoption, No Magic's MBSE products have experienced significant growth. Their products are known for powerful capabilities, good usability, and cost-effective implementation.

The core team at No Magic has been deeply involved in the research and development of Systems Modeling Language (SysML) standards, ensuring that their products naturally conform to these standards. Additionally, No Magic was among the early adopters in realizing SysML-based product implementations.

Based on a summary analysis and insights from foreign rail transit enterprises, this paper adopts the Cameo Systems Modeler (CSM) as the MBSE modeling tool.

2.3. Practical framework

With the gradual development of Model-Based Systems Engineering (MBSE), several MBSE methods have emerged, including the Object-Oriented Systems Engineering Method (OOSEM), the Harmony-SE method, the

Vitech MBSE method, and the Object-Process Methodology (OPM) defined by Dori. This study summarizes these classic methods and formulates an MBSE research framework for the bullet train braking system control logic. The practical implementation is shown in **Figure 1**.

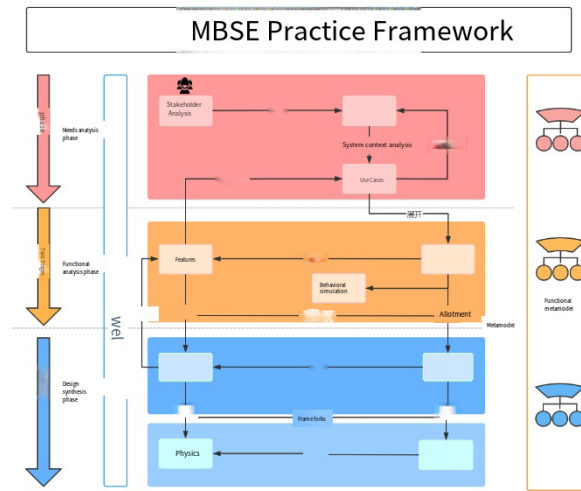


Figure 1. MBSE practice framework

- (1) Requirements analysis stage: Identify stakeholder requirements through investigation, discussion, and literature review. Analyze these requirements and use Cameo Systems Modeler (CSM) to create models. This stage generates use case diagrams and a traceability matrix that links use cases to user requirements.
- (2) Function analysis stage: Based on the output from the requirements analysis stage, determine the necessary functions to meet system requirements. Use CSM to model and decompose functions for further design.
- (3) Integrated design (architecture) stage: Integrate the functional analysis model elements into the system architecture. Decompose functions and assign them to corresponding physical components using CSM. The traceability matrix is used to ensure completeness and verify traceability between use cases.

3. Requirements analysis phase

3.1. Stakeholder analysis

According to ISO/IEC/IEEE 29148:2018, stakeholders include but are not limited to, end-users, developers, trainers, maintainers, customers, operators, and regulators. To identify stakeholders, various methods were used, including customer interviews, market research, stakeholder analysis, elaboration, clustering, and comprehensive assessment. The identified stakeholders are as follows:

- (1) All individuals on the train, including passengers and train staff.
- (2) Railway operators, including depots, passenger depots, electric depots, and locomotive depots.
- (3) EMU braking system suppliers, such as Beijing Zhongheng, Nanjing Haitai, Qishuyan, and Tianyi Shangjia.
- (4) Related systems, including the Traction Control Unit (TCU), Train Control and Monitoring System (TCMS), and train operation control system.

- (5) Constraints and restrictions, including laws and regulations, industry standards, and environmental conditions such as haze, salt fog, acid rain, coastal humidity, highland sand, snow, and rain.

3.2. Requirements

Requirements analysis is a step-by-step process that involves itemizing requirements. Throughout the entire product lifecycle, requirement traceability must be ensured across various stages. This allows for the timely identification of new requirements, modification of unreasonable demands, and overall design improvement.

Requirement entries are listed according to itemized specifications and exist across multiple layers. Each requirement entry can be edited, modified, associated with other requirements, and status-tracked. The basic elements of a requirement entry include: requirement ID (number), title, and description.

According to ISO/IEC/IEEE 29148:2018, requirement descriptions should be written in natural language. Each statement must include a subject and a verb, describe the subject system, and define the measures or constraints to be considered. The itemized requirements for the braking system are presented in **Table 1**.

Table 1. User requirements

Number ID	Title	Description
R1000	Braking	Applying common braking, including UB emergency brake, EB emergency braking, parking brake, keep the brake, clean all user requirements.
R2000	Air supply	Including the main air compressor control and other user requirements.
R3000	Sanding	Include all user requirements for sanding.
R4000	Skid resistance	Includes non-rotating shaft detection, wheel sliding protection and other user requirements.
R5000	Testing	Includes all user requirements for both a menu-guided brake test and an automatically performed brake test.
R6000	Diagnostics and troubleshooting	Includes all user needs for fault management and diagnosis.
R7000	Assistance	Includes all user needs for emergency traction mode and rescue return.

3.3. Use cases

Use cases focus on specific actions and capture the behavior of the system's stakeholders in relation to the system. They document different scenarios in which stakeholders interact with the system to achieve their goals. Each use case describes the user's perspective when interacting with the system, helping to define the system's intended functionality. Based on the needs of different user groups, requirements are further elaborated into use cases.

3.4. Traceability relationship between use cases and requirements

To meet the requirements of use cases and ensure a more concise model view, the Satisfy traceability matrix is used to describe the traceability relationship between use cases and requirement groups. By utilizing the Satisfy traceability matrix, missed requirements can be identified, and requirements change management can be effectively facilitated.

4. Functional analysis phase

4.1. Functional analysis process

The Functional Breakdown Structure (FBS) of railway trains is defined in EN15380-4 Part 4, which provides guidelines for systematically organizing the functional components of a railway vehicle. Developing a functional breakdown structure requires adherence to key principles that establish a hierarchical framework for defining system functions.

At the highest level, the functional domain or service of the vehicle represents the primary function, which serves as the foundation for all subsequent functions. Supporting this primary function are secondary functions, which contribute directly to its execution. Further decomposition results in Level 3 functions, which support Level 2 functions and consist of multiple Level 4 functions, typically corresponding to specific tasks. At the most detailed level, Level 5 functions encompass activities required to perform Level 4 functions, ensuring a comprehensive and systematic breakdown of the system's functionality.

To enhance the functional decomposition process, existing methodologies have been analyzed alongside the provisions outlined in EN15380-4, particularly those concerning railway vehicle function groups. Based on this analysis, a functional breakdown table for the EMU braking system has been developed. This table offers a structured representation of the braking system's functions, improving clarity in system design and ensuring traceability across different levels of functionality. The details of this breakdown are presented in **Table 2**, which illustrates the hierarchical relationships among the various functions within the braking system.

Table 2. Classification of function groups of EMU braking system

Number ID	Description	Number ID	Description
GCB	Equipped braking system	GCF	Handle braking based on train configuration, braking mode, and braking demand
GCC	Get brake demand	GCG	Apply and relieve the braking force
GCD	Prioritize braking needs and choose a braking mode	GCH	Provides roller skid protection
GCE	Distribution force	GDB	Managing sanding

4.2. Functional use case traceability relationship

In order to realize the bidirectional iterative relationship between use cases and functions, the refine traceability matrix is used to describe the traceability relationship between use cases and functions. **Figure 2** shows the traceability matrix diagram between use cases and functions of the braking system.

5. Design synthesis phase

5.1. Architecture modeling

During the demand analysis and functional analysis phases, the braking system is systematically decomposed into several subsystems based on its overall functionality. The determination of these subsystems follows key principles, including identifying the system's role, characteristics, limitations, important data sets, and their sources ^[10]. Additionally, subsystems are classified according to common functionalities, shared data, and resource requirements. Specific rules governing subsystems are established to ensure logical division, and the identified subsystem features are integrated to form interfaces. Based on this decomposition, the logical

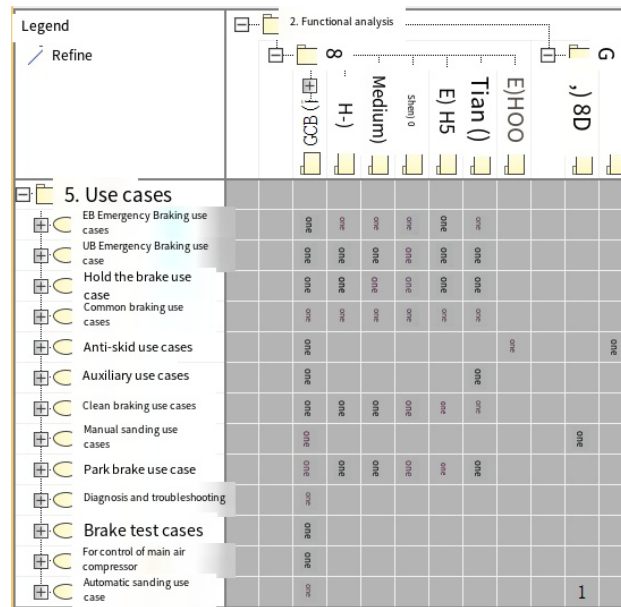


Figure 2. Cases traceability matrix to function

architecture of the braking system is constructed.

The braking system is divided into several subsystems, including driver braking instruction equipment, straight-through air braking system, wind supply system, foundation braking device, air spring for the risk control system, Brake Pipe (BP) rescue conversion device, and auxiliary equipment. The driver braking instruction equipment is responsible for executing brake commands, while the straight-through air braking system controls air brake functions. The wind supply system ensures adequate airflow for braking operations, and the foundation braking device executes braking commands at the mechanical level. Additionally, the BP rescue conversion device and other auxiliary subsystems support braking operations and contribute to the overall safety and efficiency of the system ^[11].

5.2. Physical modeling

Based on the analysis of braking system requirements, functions, and logical architecture, the system functions were ultimately assigned to physical components. The braking command transmission relies on the driver's braking command device, which is integrated into the physical architecture. This system primarily includes the brake handle, UB emergency brake button, parking brake application button, parking brake release button, keep brake application button, clean brake button, a double-needle pressure gauge (for displaying the pressure of the main air duct and brake cylinder), and a single-needle pressure gauge (for displaying the pressure of the train tube of the rescue device) ^[12]. These components are strategically placed in the driver's cab for ease of operation.

In different types of train cars, additional braking components are arranged according to specific requirements. These include the Brake Control Unit (BCU), pneumatic suspension device, parking brake device, wheel anti-skid device, tread cleaner, brake discs, brake calipers, air cylinders, and sanding devices. Each of these elements plays a critical role in ensuring the safe and efficient operation of the EMU braking system under various conditions.

5.3. Architecture function traceability

After the architecture modeling is completed, the correlation and correspondence between the braking system functions and the components of the architecture are established, and the reasonable allocation of functions is realized. The Allocate traceability matrix is used to verify the traceability of functions and architecture^[13,14].

6. Conclusion

This paper conducts an in-depth study on the control logic of the bullet train braking system, drawing upon classic Model-Based Systems Engineering (MBSE) methodologies. By exploring the application of the MBSE framework in the control logic of the bullet train braking system, this research systematically examines the requirement analysis, functional analysis, and design stages through comprehensive modeling and analysis. The study ensures traceability between models and validation of system functions, contributing to a structured and efficient design process^[15].

Building on the MBSE practice framework for the EMU braking system control logic, this paper further explores the construction of requirement metamodels, function metamodels, architecture metamodels, and physical component metamodels tailored to the professional characteristics of EMU braking systems. This structured approach lays a strong foundation for model integration across subsystems, ensuring consistency and coherence throughout the system development lifecycle.

Disclosure statement

The authors declare no conflict of interest.

References

- [1] Wang K, Yuan J, Chen H, et al., 2012, Research and Practice of Model-Based Systems Engineering Method Abroad. *Chinese Astronautics*, 2012(11): 52–57.
- [2] Bao P, 2008, SysModeler: Research and Implementation of a SysML Modeling Tool, thesis, Inner Mongolia University.
- [3] Jiang C, Wang W, Li Q, 2006, SysML: A New Kind of System Modeling Language. *Journal of System Simulation*, 2006(6): 1483–1487 + 1492.
- [4] Weilkiens T, 2011, *Systems Engineering with SysML/UML: Modeling, Analysis, Design*. Morgan Kaufmann, San Francisco.
- [5] Yao WW, 2017, On the Basis of MBSE Carrier-Based Unmanned Aerial Vehicle (UAV) Flight Control System Architecture Research, thesis, Nanjing University of Aeronautics and Astronautics.
- [6] Yang J, Deng X, Yang M, 2019, MBSE Application in Design of Model Library. *China Aviation Institute*, 2019 (4th) China Aerospace Science and Technology Conference Proceedings. China Aviation Publishing Media Co., LTD., 2019: 960–965.
- [7] Lu F, Zhan G, 2015, MBSE Method Deals with the Application Study. *Computer Programming Skills and Maintenance*, 2015(24): 37–38.
- [8] Lu F, 2014, Research on Interaction Method and Application of Equipment System Model Based on MBSE, thesis, National University of Defense Technology.

- [9] Drijti, 2014, SysML Essence. China Machine Press, Beijing.
- [10] Zhu J, Yang J, Wan L, et al., 2022, Preliminary Application of MBSE in Nuclear Power Design. Nuclear Power Engineering, 2022(43): 1–6.
- [11] Han X, 2015, Overview of Brake System Principle of South Hong Kong Island Metro. Equipment Machinery, 2015(02): 14–18.
- [12] Tang C, Fang J, Xie L, et al., 2015, Application of MBSE in Landing Gear System Design of Civil Aircraft. Civil Aircraft Design and Research, 2015(03): 56–60.
- [13] Zhu J, Yang J, Wan L, et al., 2022, Preliminary Application of MBSE in Nuclear Power Design. Nuclear Power Engineering, 2022(43): 1–6.
- [14] Han X, 2015, Overview of Brake System Principle of South Hong Kong Island MTR Vehicle. Equipment Machinery, 2015(02): 14–18.
- [15] Zhang Y, Yang L, Wang P, et al., 2014, Exploration of the Application of Model based Systems Engineering Method in Manned Space Mission. Spacecraft Engineering, 23(05): 121–128.

Publisher's note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Challenges and Solutions in the Practice of “From Coal to Gas” Transformation in the Foshan Ceramic Industry

Jiayi Liu, Wanyi Chen*

Guangdong University of Foreign Studies South China Business College, Guangzhou 510080, China

*Corresponding author: Wanyi Chen, 13106701318@163.com

Copyright: © 2025 Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY 4.0), permitting distribution and reproduction in any medium, provided the original work is cited.

Abstract: This paper focuses on the practice of building ceramics industry in Foshan City in the clean energy transition from coal to gas, and discusses the challenges and solutions in the transition process. As an important base of China’s building ceramics industry, Foshan City’s energy transformation is of great importance to regional energy security and environmental protection. This paper summarizes the practical background and effect of Foshan’s energy transformation and points out the challenges in the process of natural gas supply stability, technological renewal, and market competition. By comparing the experience of coal to gas at home and abroad, the paper summarizes the enlightenment of policy promotion, technological innovation, and upstream and downstream cooperation in the industrial chain. Based on this, the paper puts forward policy suggestions on strengthening policy support and supervision, promoting technological innovation, and research and development. Finally, it emphasizes the importance of promoting energy transformation to Foshan’s sustainable development and puts forward practical solutions.

Keywords: Building ceramic industry; Coal to gas; Clean energy; Energy transition; Foshan

Online publication: February 18, 2025

1. Introduction

1.1. Research background

With the increasingly severe problem of global climate change, energy transformation has become the focus of global attention. As one of the world’s largest energy consumers, the optimization and transformation of China’s energy structure is of great significance to global energy security and environmental protection. Foshan City, one of the most economically developed cities in China, is also the agglomeration area of the building ceramic industry, and its energy transformation practice has important demonstration significance for the energy transformation of the country and even the world^[1,2].

The report of the 20th National Congress of the Communist Party of China points out that achieving

peak carbon neutrality is a broad and profound economic and social systemic change. We should base on China's energy and resource endowments, adhere to the principle of building before breaking down, and carry out the carbon peaking action step by step in a planned way. We will improve the regulation of total energy consumption and intensity, with a focus on controlling fossil energy consumption, and gradually shift to a system of dual control over total carbon emissions and intensity. In recent years, Foshan City has actively responded to national environmental protection policies and vigorously promoted energy transformation, especially in the building ceramics industry, where the transition from coal to natural gas has become an important trend. However, there are also many challenges and problems in this transition process. This paper aims to deeply explore the practice of Foshan's energy transformation, analyze the challenges faced, draw on the experience of energy transformation at home and abroad, and put forward policy suggestions to promote Foshan's energy transformation.

1.2. Significance of the research purpose

This paper aims to explore the practice of energy transition from coal to natural gas in Foshan City, analyze the main challenges encountered in the process, and put forward corresponding solutions based on domestic and foreign experience. Through the study of Foshan's energy structure optimization, the key factors in the transition are revealed, which can provide decision-making reference for local governments and enterprises and promote regional clean energy applications. As a center of building ceramics industry, Foshan's energy transformation not only plays an important role in local environmental protection but also provides a demonstration of significance for other high-pollution industries. This study will also explore the role of energy transition in promoting sustainable development from the perspectives of technological innovation, industrial upgrading, and the application of market mechanisms, and provide experience for national energy security and environmental governance ^[3,4].

2. The practice of energy transformation in Foshan

Foshan's energy consumption structure is dominated by coal, and the proportion of clean energy such as natural gas is relatively low. In recent years, as the government attaches great importance to environmental protection and energy structure adjustment, Foshan has gradually increased the use of clean energy such as natural gas, and the proportion of coal consumption has gradually decreased, while the proportion of natural gas consumption has gradually increased. In 2020, the city's total energy consumption is about 30.3 million tons of standard coal, with an average annual growth rate of 0.5% in the 13th Five-Year Plan period, and the growth rate is 2.6 percentage points lower than that in the 12th Five-Year Plan period. In the "13th Five-Year Plan," the city's energy consumption per unit of Gross Domestic Product (GDP) decreased by 24.34%, exceeding the provincially-mandated energy conservation targets by 5 percentage points, and the energy efficiency level has been significantly improved ^[5,6].

Foshan's energy transformation practice can be divided into three stages, each stage has its own characteristics of goals and practical effects, and gradually promotes the clean energy transformation of the entire building ceramic industry.

2.1. Start-up stage (2010–2015)

In the initial stage from 2010 to 2015, Foshan's main goal is to explore the application of natural gas in the building ceramics industry. Through policy guidance, some enterprises were encouraged to take the lead in clean energy transformation. At this stage, some large enterprises responded positively and took the lead in completing the initial transformation from coal to natural gas, forming a good demonstration effect. These enterprises have not only reduced pollutant emissions, but also reduced production costs to a certain extent, and promoted more enterprises to participate in the clean energy transformation.

2.2. Expansion phase (2016–2020)

In the expansion phase from 2016 to 2020, Foshan's clean energy transformation has entered the stage of large-scale promotion. Foshan has vigorously promoted the wide application of natural gas in the building ceramics industry, and more enterprises have completed the transition from coal to natural gas. At the same time, the continuous progress of technology has further improved the efficiency of natural gas use. Through advanced combustion technology, enterprises have achieved improved energy efficiency and reduced production costs and environmental pollution. In addition, the Foshan government has actively promoted the cooperation between enterprises and scientific research institutions to further promote the research and development, and application of clean energy technologies.

2.3. Deepening stage (2021–present)

The deepening phase from 2021 to the present marks the completion of Foshan's clean energy transformation. The vast majority of building ceramics enterprises have realized the transformation of natural gas, and the clean energy in the industry has been realized. At the same time, the government has actively improved the natural gas supply system and ensured the stable supply of natural gas sources by establishing long-term cooperation with upstream suppliers. In addition, Foshan has established a strict supervision system to regularly inspect and evaluate the effect of the renovation to ensure that the policy is effectively implemented. The whole transformation process has provided a strong guarantee for Foshan's environmental protection and economic development ^[7,8].

3. Challenges faced by Foshan's energy transformation

Although Foshan has made remarkable progress in energy transformation, it still faces many challenges at multiple levels, including policy, technology, market, and industrial chain.

3.1. Insufficient policy support

Although the Foshan Municipal government has introduced a series of relevant policies, the implementation needs to be strengthened. Small and medium-sized enterprises lack sustained and stable policy support during the transformation process, and some enterprises are slow to respond to policies due to poor communication or poor implementation. In addition, the short-term nature of some policies has made enterprises lack long-term confidence, especially subsidies and preferential tax policies have not been sustained for a long time, reducing enterprises' enthusiasm for transformation.

3.2. Technical bottlenecks

In the process of “from coal to gas,” Foshan City faces challenges in natural gas supply and combustion technology. Natural gas supply may be in short supply during peak winter, affecting production. At the same time, some enterprises are immature in natural gas combustion technology, with low energy utilization rate and poor control of pollutant emissions. The lack of sufficient research and development funds has also restricted the progress of enterprises in optimizing technology, leading to slow transition.

3.3. Cost pressure

The price of natural gas is higher than that of coal, and it is highly volatile, especially when the international market is unstable, and it is difficult for enterprises to predict the price trend. Large enterprises can afford it to some extent financially, but small and medium-sized enterprises are under greater pressure. Equipment renewal and technology introduction require a lot of capital, while clean energy has a long initial payback cycle, increasing the financial risk of transition.

3.4. Lack of industrial chain synergy

The energy transformation of Foshan ceramic industry requires the cooperation of the entire industrial chain. The number of upstream natural gas suppliers is limited, and the uncertainty of supply has affected production. Downstream customers have been less receptive to clean energy, seeing its high cost and inconvenience as a constraint on market promotion. At the same time, the lack of effective communication among all parties in the industrial chain has led to insufficient synergy and affected the progress of transformation.

3.5. Talent shortage

The clean energy transition relies on talents with professional knowledge, but Foshan’s talent reserve in this field is insufficient, and many enterprises lack talents to master the technology, which hinders the introduction and application of technology. Talent mobility is large, outstanding talents are difficult to retain, and enterprises lack a corresponding mechanism in skill training, which further slows down the transformation process.

4. Experience and inspiration of energy transition at home and abroad

The successful experience of energy transition at home and abroad has provided valuable reference for Foshan City.

4.1. International experience

4.1.1. Germany

Germany relies on policy support and market mechanisms to promote the development of renewable energy. The government guides enterprises to transform through long-term policies and financial subsidies and introduces market mechanisms to encourage technological innovation. Foshan can learn from its experience in combining policy continuity with market incentives to ensure that companies actively participate in the transformation.

4.1.2. United States of America (U.S.A.)

The U.S.A. has promoted clean energy use through technological innovation and policy incentives. The

government has set up a special fund to encourage enterprises to cooperate with universities to research and develop new technologies and has promoted the development of clean energy through policies such as carbon tax and financial incentives. Foshan should increase investment in research and development of natural gas combustion technology and combine incentive policies to promote technological progress.

4.2. Local experience

4.2.1. Beijing

Beijing has achieved clean energy transformation of coal-fired boilers through policy support and financial subsidies and implemented strict regulatory measures. Foshan can learn from Beijing's subsidy policy and regulatory system to ensure that enterprises complete the natural gas retrofit.

4.2.2. Shanghai

Shanghai emphasizes the combination of technology research and development and market guidance, promotes technological progress through policies, and encourages enterprises to participate in the energy transition. Foshan can draw on Shanghai's experience to encourage companies to invest in technological innovation and improve energy efficiency.

4.3. Inspiration

Domestic and international experience shows that the combination of policy support and market mechanisms is the key to promoting energy transition. At the same time, technological innovation is the core driving force of the transformation, and Foshan should increase its technological research and development efforts. In addition, industrial chain collaboration and upstream and downstream cooperation are crucial to securing energy supply and improving the efficiency of the transformation ^[9–11].

5. Policy suggestions and solutions for promoting energy transformation of the Foshan ceramic industry

In order to effectively respond to the above challenges and promote the “coal to gas” energy transformation of Foshan ceramic industry, the government and enterprises should start from many aspects such as policy, technology, market and talent, and formulate a systematic solution path.

5.1. Strengthen policy support and supervision

The government should further improve the policy support system for the clean energy transition to ensure the continuity and long-term nature of the policies. First of all, the government should formulate special support policies for small and medium-sized enterprises, providing financial subsidies, low-interest loans, and tax incentives to help enterprises ease the financial pressure in the early stages of the transition. Simultaneously, policies should have a long-term plan and clearly define the transformation goals at different stages, so that enterprises have a clear direction in the transformation process. In addition, the government should strengthen supervision over the implementation of policies by enterprises, ensure that clean energy transformation projects are promoted as planned, and carry out regular inspections and evaluations to help enterprises solve difficulties encountered during the implementation of policies ^[12,13].

5.2. Promote technological innovation and research and development

Technology is at the heart of driving the energy transition. The Foshan municipal government should set up a special research and development fund to support cooperation between enterprises and scientific research institutions, and promote the research and development and promotion of natural gas combustion technology and clean energy application technology. A clean energy solution suitable for Foshan's ceramic industry can be developed by introducing advanced foreign technologies while combining with the actual needs of local enterprises. The government can also provide technical consulting and training services to enterprises to help them quickly master new technologies. Moreover, enterprises are encouraged to adopt intelligent equipment and digital management means to improve the efficiency of natural gas use, optimize energy management and reduce production costs through technologies such as the Internet of Things and big data.

5.3. Ensure the stability of the natural gas supply chain

To ensure the stability of natural gas supply for enterprises, the government should strengthen cooperation with domestic and foreign natural gas suppliers, expand natural gas import channels, and build more natural gas storage facilities to improve storage capacity. At the same time, the government should speed up the construction of natural gas transmission networks to ensure that natural gas can be supplied to enterprises in a timely and stable manner. On this basis, an early warning mechanism for natural gas supply can also be established to deal with possible supply shortages in advance. Furthermore, the government should encourage enterprises to sign long-term contracts with natural gas suppliers to stabilize the supply of natural gas sources and reduce supply risks.

5.4. Promote coordinated development of upstream and downstream industrial chains

Energy transformation is not only a matter within enterprises, but also requires collaboration between the upstream and downstream industrial chains. The government should actively encourage all parties in the industrial chain to strengthen cooperation, and promote communication and collaboration between upstream gas suppliers and downstream customers through policy guidance and market incentives. For example, it can improve the acceptance of clean energy by downstream customers by reducing the cost of clean energy use and encouraging enterprises to share experience in clean energy application. Additionally, the government can build a communication platform by holding activities such as industrial chain cooperation forums or exhibitions to promote in-depth cooperation between upstream and downstream enterprises in the use of clean energy, forming synergies and promoting the smooth implementation of energy transformation ^[14–16].

5.5. Strengthen talent training and introduction

Talent is an important driving force for energy transition. The Foshan municipal government should formulate a talent introduction and training plan for the clean energy industry, cooperate with universities and scientific research institutions, set up relevant courses and majors, and cultivate compound talents with clean energy technology and management capabilities. Concurrently, the government should also introduce policies to attract high-level clean energy technology experts and management talents to Foshan for development. For small and medium-sized enterprises, training subsidies provided by the government can be used to upgrade the skills of internal talents to ensure that enterprises have a sufficient talent reserve during the energy transition process.

6. Conclusion

The “from coal to gas” energy transformation of Foshan building ceramics industry has provided a model for other high-pollution industries in the country. By analyzing the challenges in policy, technology, market and industry chain, this paper puts forward a targeted solution path. Promoting the energy transition requires not only policy and financial support, but also technological innovation and upstream and downstream collaboration. Foshan should combine domestic and foreign experience to strengthen policy support, technology research and development and talent introduction to ensure the sustainability of the transformation results. In the future, Foshan should continue to deepen the promotion of clean energy and make greater contributions to regional environmental protection and industrial upgrading.

Disclosure statement

The authors declare no conflict of interest.

References

- [1] Xi J, 2020, Speech at the General Debate of the 75th Session of the United Nations General Assembly. State Council Bulletin of the People’s Republic of China, 2020(28).
- [2] Xi J, 2022, Hold High the Great Banner of Socialism with Chinese Characteristics and Strive in Unity to Build a Modern Socialist Country in All Respects—Report to the 20th National Congress of the Communist Party of China. Party Building, 2022(11): 6–30.
- [3] Foshan Government Office, 2022, Foshan Energy Development “14th Five-Year Plan”. Government Document, 2022: 160
- [4] Liu M, 2024, Foshan: Green Finance Supporting Industry to Go Green. Environment, 2024(08): 41–43.
- [5] Tang X, Liao C, Li Y, et al., 2023, Analysis on the Benefit of Clean Energy Transformation to Reduce Pollution and Carbon in Building Ceramic Industry—A Case Study of Guangdong Province. Environmental Ecology, 5(11): 95–100.
- [6] Wen T, 2022, Suggestions on Building a Natural Gas Trading Market in Guangdong. Southern Energy Construction, 9(S2): 11–17.
- [7] You G, 2022, Natural gas will be the main application energy in Jianwei ceramic industry. Building Materials Technology and Application, 2022(03): 72.
- [8] Qu P, 2022, Guangdong: Natural Gas Consumption Increased by 65.5% in the 14th Five-Year Plan. China Energy News, published April 25, 2022(013).
- [9] He X, 2022, Mona Lisa: Fifteen Years of Technological Precipitation, Foshan’s “Green Intelligent Manufacturing” Leader. China Architectural Decoration, 2022(02): 6–9.
- [10] Zheng X, Zhao Q, 2020, Sample of “Coal to Gas” in Ceramic Industry. Environment, 2020(08): 60–62.
- [11] Liu K, Huang B, Li J, et al., 2019, Observation and Thinking of Coal to Gas in Construction Pottery Industry. Foshan Ceramics, 29(10): 1–4.
- [12] Tan J, 2019, Dilemma and Strategy of High-Quality Development of Ceramic Industry Under “Coal to Gas”—Taking Qingyuan as an Example. Guangdong Economy, 2019(04): 44–49.
- [13] Zhang Q, 2018, Suggestions on Improving the Utilization Level of Natural Gas in Guangdong Province. Equipment Management and Maintenance, 2018(23): 163–164.

- [14] Guo X, 2018, Natural Gas Utilization Status and Related Problems in Guangdong. *Electric Power and Energy*, 39(02): 235–238.
- [15] Li J, 2011, Research on Natural Gas Development Strategy of Foshan City. *City Gas*, 2011(04): 31–33.
- [16] Xie B, 2009, Analysis of Energy Utilization in Ceramic Enterprises. *Foshan Ceramics*, 19(11): 1–7.

Publisher's note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

The Evolution of Traffic Lights: A Comprehensive Analysis of Traffic Management Systems in Shanghai

Zhichen Eden Guo*

Dulwich College (Singapore), 658966, Singapore

*Corresponding author: Zhichen Eden Guo, eden.guo30@stu.dulwich.org

Copyright: © 2025 Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY 4.0), permitting distribution and reproduction in any medium, provided the original work is cited.

Abstract: This paper comprehensively analyzes the evolution of traffic light systems in Shanghai, highlighting the technological advancements and their impact on traffic management and safety. Starting from the historical context of the first traffic light in London in 1868 to the modern automated systems, the study explores the complexity and adaptability of traffic lights in Shanghai. Through field surveys and interviews with traffic engineers, the paper debunks common misconceptions about traffic light operation, revealing a sophisticated network that responds to real-time traffic dynamics using software like the Sydney Coordinated Adaptive Traffic System (SCATS) 6. The study also discusses the importance of pedestrian safety, suggesting future enhancements such as Global Positioning System (GPS) based emergency systems and accommodations for color-blind individuals. The paper further delves into the potential of Artificial Intelligence (AI) and Vehicle-to-Infrastructure (V2I) technology in revolutionizing traffic light systems, emphasizing their role in improving traffic flow and safety. The findings underscore Shanghai's progressive approach to traffic management, showcasing the city's commitment to optimizing traffic control solutions for the benefit of both vehicles and pedestrians.

Keywords: Traffic management; Traffic light; Traffic network; Smart city; V2I (vehicle-to-infrastructure)

Online publication: February 18, 2025

1. Introduction

Traffic lights are indispensable tools that govern traffic flow and ensure the safety of pedestrians and motorists. The functionality of traffic lights goes beyond simple control signals: they embody a sophisticated network that coordinates vehicular and pedestrian movements by using a combination of red and green signals.

This study on traffic lights originated from a frustration with long wait times. However, through a multifaceted approach—including field surveys and interviews with esteemed traffic engineers from the Shanghai Traffic Management Authority—the complexity of traffic light systems and their significant development over the past 150 years became evident. This article aims to unravel the intricacies of traffic light

systems in China, providing insights into their current operation, common public misconceptions, and future advancements.

2. The interesting history of traffic lights

To understand how traffic lights work and the journey behind them, we first need to look at the history of traffic lights, and their background information. The first traffic light was invented in December 1868 in London, England, by a railway engineer named J.P. Knight. This early traffic signal was installed outside the House of Parliament and was intended to control the flow of horse-drawn carriages and pedestrians. The traffic lights at that time were manually operated with gas-lit signals. It featured two semaphore arms and a gas light. The arms were used during the day and the gas light was used at night. During the day, the semaphore arms would be raised or lowered to signal “Stop” and “Go.” At night, the gas light would show red to signal “Stop” and green to signal “Caution” (not exactly “Go”). The system was manually operated by a police officer. The signals helped to regulate the flow of horse-drawn carriages, reducing congestion at busy intersections. This was particularly important in bustling areas like the vicinity of the House of Parliament in London. Also, it improved the safety of the horse-drawn carriages as the signals can reduce collisions and maintain a safe distance between the carriages.



Figure 1. The first traffic light invention in London, England (Source: Knight, J.P. (1868) ^[1])

Unfortunately, this early traffic light had a significant drawback. On January 2, 1869, just a few weeks after it was installed, the gas light exploded, injuring the policeman operating it. This incident halted further development of traffic lights until the early 20th century.

The modern electric traffic light was later invented in 1912 by Lester Wire, a policeman in Salt Lake City, Utah, United States of America (USA), and the first electric traffic light was installed in Cleveland, Ohio, in 1914. This version used red and green lights and was manually operated from a nearby booth ^[2].



Figure 2. One of the first traffic cops in Detroit ^[3]

3. The misconception of modern traffic light systems

A common frustration among students is the prolonged waiting time at traffic lights. Since controlling traffic signals to reduce wait times is not feasible, identifying patterns in their operation can provide valuable insights. Additionally, such research may contribute to improving pedestrian safety, particularly for students.

This study investigates the timing and patterns of traffic lights in Shanghai, beginning with the development of a structured methodology to determine optimal observation periods. The selected time for analysis was 3:30 PM, coinciding with the end of the school day when many students rushed home, anticipating the light to turn green.

Initial data collection focused on establishing a baseline for the hypothesis. Observations revealed that green lights lasted approximately 20 seconds, whereas red lights lasted about 90 seconds—4.5 times longer. To determine the traffic light status at 3:30 PM, it was necessary to calculate the total cycle time and assess how many complete cycles occurred within the timeframe from an assumed starting point of 3:00 PM to 3:30 PM.

4. Steps and formula

4.1. Determine the total cycle time

- (1) Green light duration: $G = 20$ seconds
- (2) Red light duration: $R = 90$ seconds
- (3) Total cycle time (T): $T = G + R = 20 + 90 = 110$ seconds

4.2. Calculate the total time in seconds from a starting point

- (1) Starting point: 3:00 PM
- (2) Observation time: 3:30 PM
- (3) Total time from 3:00 PM to 3:30 PM (t): $t = 30 \text{ minutes} \times 60 \text{ seconds/minute} = 1,800$ seconds

4.3. Determine the number of full cycles passed by 3:30 PM

(1) Number of full cycles (N): $N = t/T = 1,800/110 = 16$ cycles

4.4. Calculate the time elapsed into the current cycle

(1) Time elapsed in full cycles (E): $E = N \times T = 16 \times 110 = 1,760$ seconds

(2) Time into the current cycle (C): $C = t - E = 1,800 - 1,760 = 40$ seconds

4.5. Determine the status of the traffic light

(1) If $C \leq R$: the light is red

(2) If $C > R$: The light is green

Based on the above steps, the light will be red at 3:30 PM because 40 seconds is less than the duration of the red light (90 seconds).

4.6. Simpler formula

(1) Calculate the elapsed time into the current cycle: $C = t \times T$

(2) Determine the light status:

(i) If $C \leq R$: the light is red

(ii) If $C > R$: The light is green

Since 40 seconds is less than the duration of the red light (90 seconds), the light will be red at 3:30 PM. This hypothesis was tested through observations conducted at different times of the day over three days: Thursday, Friday, and Saturday. These days were selected based on expected pedestrian traffic patterns—higher volumes on Thursdays and Fridays and lower volumes on Saturdays. However, the results were unexpected. While the hypothesis was validated for Thursday and Friday, it did not hold true for Saturday.

4.7. Explanation of results

To analyze and understand the unexpected results, interviews were conducted with engineers from the Shanghai Municipal Traffic Management Bureau. Their insights provided a deeper understanding of the complexity of Shanghai's traffic light system, which, contrary to popular belief, is not purely time-based.

A key limitation of the initial survey was its reliance on timing as the sole variable. In reality, multiple factors influence traffic light operation. The system is controlled by advanced automated mechanisms that dynamically adjust signal timings in response to real-time traffic conditions. Software such as SCATS 6 enables engineers to fine-tune these timings to optimize traffic flow and safety.

This explains the observed discrepancies in the survey results: on Thursdays and Fridays, the traffic lights operate under high-traffic conditions, while on Saturdays, with significantly lower pedestrian flow, the intervals between green lights become longer.

Shanghai has already abandoned the time-based system since 1982. It is a perfect symbol of China's technological advancement. Notably, pedestrian safety emerges as a paramount concern in traffic light design. Suggestions for future enhancements, such as the integration of GPS-based emergency systems (to detect abnormal driving behavior) and accommodations for color-blind individuals, underscore the commitment to optimizing traffic light safety.

As pedestrian safety is improving, a problem slowly emerges as sometimes, pedestrians do not want to wait that long, causing some people to complain to the Shanghai Municipal Traffic Management Bureau. This

issue can be improved by integrating solutions from other countries. One solution to this issue is by looking at Singapore's interesting policy dedicated to senior citizens. How this works is that people with a specific card (Senior Citizen Public Transport Concession Card) can tap the traffic light, therefore extending the time for crossing to an extra 20 seconds. What Shanghai can do is add more variation of cards, maintaining safety, and making the experience of pedestrians better.

5. Comparison of old and new traffic light systems

The evolution of traffic lights from the early gas-lit manually operated signals to the sophisticated, automated systems we see today highlights the significant advancements in traffic management technology.

5.1. Old traffic light systems

- (1) Manual operation: Early traffic lights required a human operator, often a police officer, to manually change the signals.
- (2) Gas light: The initial systems used gas lamps, which were prone to accidents, such as the explosion of the first traffic light in London.
- (3) Simple timers: Later, electric traffic lights used simple timers to change signals at fixed intervals, without considering real-time traffic conditions.
- (4) Limited adaptability: These systems could not adapt to varying traffic conditions and relied on fixed schedules, leading to inefficiencies during non-peak hours.

5.2. New traffic light systems

- (1) Automated control: Modern systems are automated and use advanced algorithms to control signal timings.
- (2) Real-time traffic data: They incorporate real-time traffic data through sensors and cameras to adjust signal timings dynamically.
- (3) Software integration: Advanced software like the Sydney Coordinated Adaptive Traffic System (SCATS) is used to optimize traffic flow based on current conditions ^[4].
- (4) Pedestrian safety features: Modern systems include features like extended crossing times for senior citizens, detection of abnormal driving behaviors, and accommodations for color-blind individuals.
- (5) Integration with AI and V2I: The future of traffic lights includes AI integration for better traffic management and Vehicle-to-Infrastructure (V2I) technology, allowing vehicles to communicate with traffic signals for enhanced safety and efficiency.

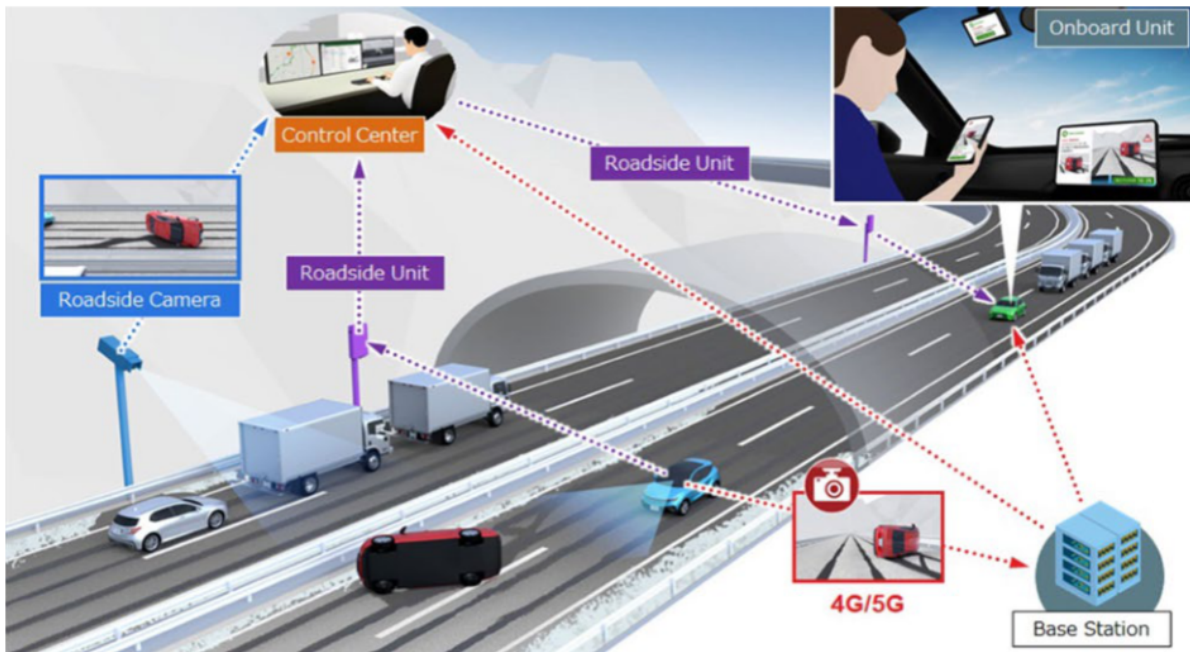


Figure 3. Conceptual image

Information in the forward direction undetectable by the onboard unit of an autonomous vehicle following another vehicle is transmitted to the rearward vehicle by V2I ^[5].

6. The future: a traffic light system without lights

Artificial Intelligence (AI) has already been integrated into traffic light systems. Although it may seem like a distant development for some, similar technologies have already been implemented and are expected to expand globally.

The primary advantage of AI in traffic management is its ability to optimize signal timing and coordination more efficiently and logically. As AI continuously learns and improves, it can analyze and recognize traffic flow patterns, adapting to changing conditions in real-time. Moreover, AI can assess overall traffic conditions, providing valuable insights to law enforcement for identifying the causes of traffic incidents and enhancing road safety for both vehicles and pedestrians.

Besides AI technology, a more revolutionary change is also on the horizon: Vehicle-to-Infrastructure (V2I) technology. Vehicles can communicate with traffic lights and other infrastructure. The goal of V2I is to improve traffic management, enhance road safety, and support the development of autonomous and connected vehicles. V2I relies on several key components and technologies to facilitate communication:

- (1) Onboard Units (OBUs): These are installed in vehicles and are responsible for sending and receiving data. OBUs can communicate with other vehicles (V2V) and infrastructure (V2I).
- (2) Roadside Units (RSUs): These are installed along the roadway and in traffic infrastructure (traffic lights, road signs). RSUs collect data from vehicles and send relevant information back to them.
- (3) Communication protocols: V2I communication uses dedicated short-range communications (DSRC) or cellular networks (C-V2X). DSRC operates in the 5.9 GHz band and is specifically designed for

automotive use, providing low latency and high reliability.

- (4) Sensors and cameras: These are integrated into the infrastructure to gather data on traffic conditions, weather, road hazards, and more.
- (5) Central management systems: These systems aggregate data from multiple sources, analyze it, and make decisions to optimize traffic flow and safety.

This futuristic technology can provide crucial data for the efficient operation of the transportation system. More importantly, it can create better safety for vehicles, pedestrians, and bikes.

7. Conclusion

Through a nuanced exploration of traffic light operations in Shanghai, a holistic perspective emerges, revealing the intricate interplay between technology, safety, and efficiency. The adaptive nature of these systems, coupled with an unwavering focus on pedestrian welfare, underscores a progressive approach to traffic management. This study serves as a small beacon illuminating the ongoing advancements in traffic light systems and the enduring quest for optimized traffic control solutions in Shanghai, also helping individuals who are interested in this topic understand the importance of traffic lights in our everyday lives.

Disclosure statement

The author declares no conflict of interest.

References

- [1] Knight JP, 1868, The First Traffic Light Invention In London, England. Illustrated Times, published January 16, 1869.
- [2] Clark L, 2019, Traffic Signals: A Brief History. Washington State Magazine, published Fall 2019.
- [3] Schreiber R, 2015, The Ferndale Crow's Nest When It Was Operational. How Detroit Invented Traffic Cops, Traffic Lights, No Parking Zones & Towing Your Car. Published April 28, 2015.
- [4] IEEE Vehicular Technology Society, 1980, Vehicular Technology. Volume Vt-29 Number 2, published May 1980, ISSN 0018-9545.
- [5] Mitsubishi Heavy Industries, Ltd., Mitsubishi Heavy Industries Machinery Systems, Ltd. Mitsubishi Heavy Industries Engineering, Ltd., 2022, MHI Group To Participate In Vehicle-To-Infrastructure (V2I) Demonstration Test Program To Support Autonomous Highway Driving -- Groupwide Technologies To Help Achieve Autonomous Driving Society. Mitsubishi Heavy Industries News. Published October 5, 2022.
- [6] Stephens D, Schroeder J, Klein R, 2015, Vehicle-To-Infrastructure (V2I), Safety Applications, Performance Requirements, Vol. 7, Stop Sign Gap Assist (SSGA). Repository & Open Science Access Portal, published August 1, 2015.

Publisher's note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Integrated Services Platform of International Scientific Cooperation

Innoscience Research (Malaysia), which is global market oriented, was founded in 2016. Innoscience Research focuses on services based on scientific research. By cooperating with universities and scientific institutes all over the world, it performs medical researches to benefit human beings and promotes the interdisciplinary and international exchanges among researchers.

Innoscience Research covers biology, chemistry, physics and many other disciplines. It mainly focuses on the improvement of human health. It aims to promote the cooperation, exploration and exchange among researchers from different countries. By establishing platforms, Innoscience integrates the demands from different fields to realize the combination of clinical research and basic research and to accelerate and deepen the international scientific cooperation.

Cooperation Mode



Clinical Workers



In-service Doctors



Foreign Researchers



Hospital



University



Scientific institutions

OUR JOURNALS



The *Journal of Architectural Research and Development* is an international peer-reviewed and open access journal which is devoted to establish a bridge between theory and practice in the fields of architectural and design research, urban planning and built environment research.

Topics covered but not limited to:

- Architectural design
- Architectural technology, including new technologies and energy saving technologies
- Architectural practice
- Urban planning
- Impacts of architecture on environment

Journal of Clinical and Nursing Research (JCNR) is an international, peer reviewed and open access journal that seeks to promote the development and exchange of knowledge which is directly relevant to all clinical and nursing research and practice. Articles which explore the meaning, prevention, treatment, outcome and impact of a high standard clinical and nursing practice and discipline are encouraged to be submitted as original article, review, case report, short communication and letters.

Topics covered by not limited to:

- Development of clinical and nursing research, evaluation, evidence-based practice and scientific enquiry
- Patients and family experiences of health care
- Clinical and nursing research to enhance patient safety and reduce harm to patients
- Ethics
- Clinical and Nursing history
- Medicine



Journal of Electronic Research and Application is an international, peer-reviewed and open access journal which publishes original articles, reviews, short communications, case studies and letters in the field of electronic research and application.

Topics covered but not limited to:

- Automation
- Circuit Analysis and Application
- Electric and Electronic Measurement Systems
- Electrical Engineering
- Electronic Materials
- Electronics and Communications Engineering
- Power Systems and Power Electronics
- Signal Processing
- Telecommunications Engineering
- Wireless and Mobile Communication

