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Intelligent Empowerment for Transportation Hub Safety: LSTM-Based Fire Risk Prediction for High-Speed Railway Stations

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Abstract

This study addresses the fire safety risks associated with box-type power banks in transportation hubs. These devices, commonly found in railway stations, can undergo thermal runaway, leading to rapid energy release and intense combustion, thus posing severe threats to public safety. To investigate their fire behavior, four full-scale fire experiments were conducted using a 1 MW calorimeter to systematically measure key parameters, particularly the Heat Release Rate (HRR), and construct a real-world HRR dataset. Based on the experimental data, a deep learning prediction model was developed using Long Short-Term Memory (LSTM) networks. By integrating LSTM layers with a fully connected (Dense) layer, the model accurately captured the dynamic evolution of HRR during fire development. Model evaluation on the test set yielded excellent results: MAE = 0.723, MSE = 1.199, RMSE = 1.095, and R^2 = 0.999, demonstrating high regression accuracy and strong generalization. These findings provide a robust data-driven framework for fire detection systems in transportation hubs and offer theoretical and practical insights into the intelligent identification and dynamic risk assessment of emerging fire loads.

Keywords: transportation safety; LSTM; intelligent emergency response; data-driven modeling

1 Introduction

In recent years, China's high-speed railway (HSR) development has entered a phase of rapid expansion. The total operating mileage of high-speed railways across the country exceeded 45,000 km, ranking first in the world at the end of 2024[1]. The "Eight Vertical and Eight Horizontal" HSR network has been essentially completed[2]. Meanwhile, over 1,100 HSR stations have been built and put into operation nationwide, including more than 150 large-scale transportation hubs, forming the world's largest and most efficient high-speed railway system. High-speed railway stations, as representatives of large-scale integrated transport hubs, serve multiple functions including passenger dispersal, intermodal transfer, and business travel services. These hubs have become critical nodes in both urban spatial organization and the broader transportation network.

With the continuous evolution of spatial forms and the increasing functional complexity of HSR stations, their architectural structures are becoming larger in scale and more three-dimensional in layout. This has led to significantly higher occupant densities and a rapidly rising risk of fire[3]. Of particular concern is the widespread introduction of new types of fire loads within HSR stations. At present, a large number of spaces—such as island-style shops, massage chairs, and low-voltage equipment rooms—are populated with various electronic devices, lightweight decorative materials, and multifunctional spatial configurations. These elements contribute to fire loads that are dynamic and multi-sourced in nature, posing considerable challenges to traditional fire protection design and risk assessment methodologies. Especially noteworthy is the extensive deployment of portable energy storage devices, such as box-type power banks, within station premises. Although their potential for thermal runaway is often overlooked, they can easily ignite under certain localized conditions and lead to rapid fire spread.

Heat Release Rate (HRR) serves as a critical parameter for characterizing fire hazards and forms the foundational basis for evaluating the fire behavior of such devices[4]. As HRR directly governs the growth rate and intensity of a fire, it plays a central role in quantifying fire loads, modeling fire dynamics, and informing fire safety design. Accordingly, accurately determining the HRR of portable energy storage devices and developing robust risk assessment and prediction models have become key research priorities in advancing fire safety within transportation hubs.

This study takes box-type power banks, which are widely deployed in the waiting areas of high-speed railway stations, as the primary subject of investigation. A total of 4 groups comprising 15 samples were subjected to HRR experiments, through which characteristic HRR curves were obtained. Furthermore, a regression modeling approach based on the Long Short-Term Memory (LSTM) deep learning algorithm was applied to the HRR data[5]. The objective of this research is to provide both theoretical foundations and practical methodologies for the identification, assessment, and intelligent detection of emerging fire loads within HSR hubs. Ultimately, it aims to facilitate the transformation of fire safety strategies from empirical prevention to data-driven intelligent systems.

2. Methodology

This study adopts a technical approach that integrates full-scale fire experiments with artificial intelligence modeling, focusing on a representative emerging fire load commonly found in high-speed railway stations—box-type power banks. First, full-scale fire tests were conducted using a 1 MW calorimetry apparatus to obtain key combustion parameters under natural ventilation conditions, including HRR, temperature rise profiles, and mass loss rate. Multiple datasets were constructed based on the collected sample data. Subsequently, machine learning techniques were employed to preprocess and classify the experimental data, extract critical temporal features, and develop an HRR prediction model based on LSTM neural network. The model incorporates LSTM layers to capture the temporal evolution of HRR and dense layers to approximate its nonlinear relationships, ultimately producing HRR prediction outputs. The overall technical framework is illustrated in Figure 1.

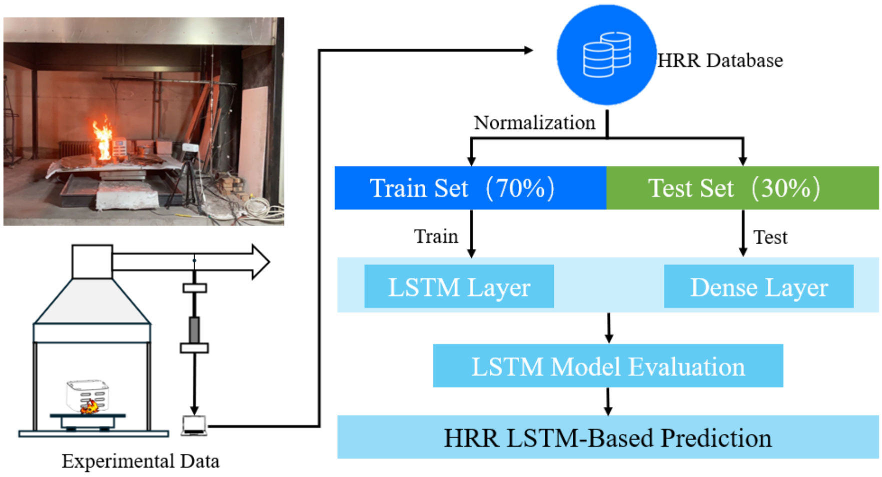

Fig. 1 Technical Workflow of HRR LSTM-Based Prediction Model

3. Discussion

3.1 Experimental Data

A total of 4 fire scenarios were designed for the box-type power banks. The specific experimental setups are summarized in Table 1.

Table 1. Summary of Experimental Test for Box-Type Power Banks.

Scenario	Number of BoxBoxes	Number of Power Banks
I	1	6
II	2	12
III	4	24
IV	8	48

Figure 2 illustrates the relationship between HRR and time during the experimental process. The ignition was initiated using alcohol, which contributed to the initial rise in HRR. Since the box-type power banks are made of fire-resistant materials, the early-stage HRR was primarily driven by the combustion of alcohol. As the burning continued, the power bank itself eventually ignited, leading to a transition into the fully developed combustion phase.

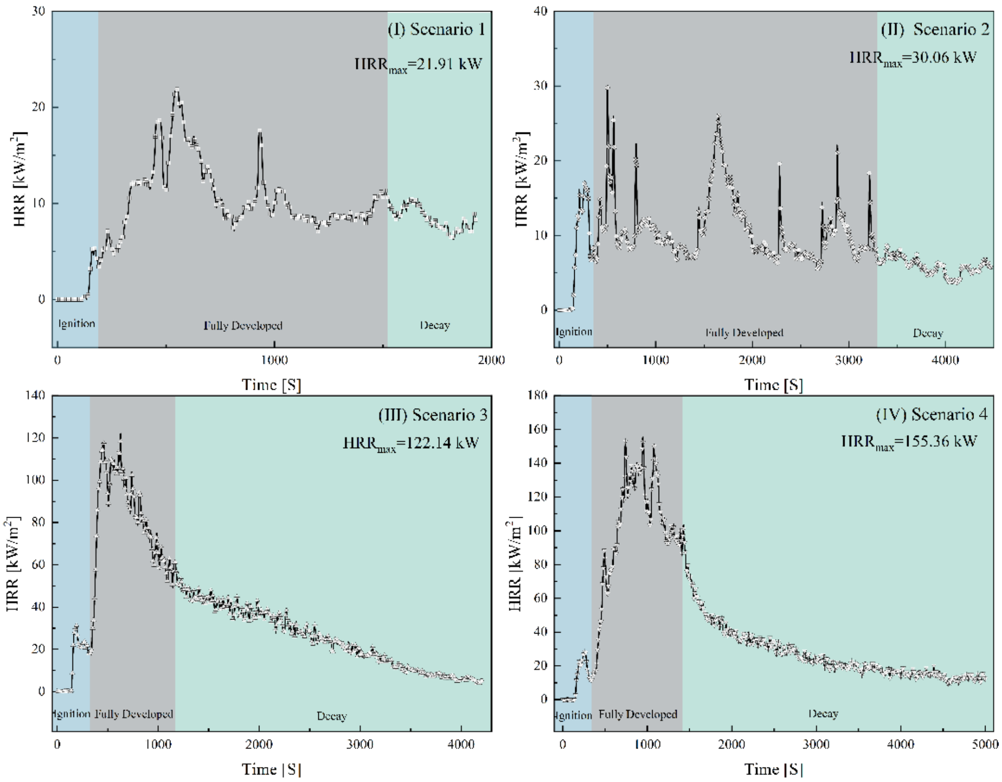

Fig. 2 Variation of Heat Release Rate Over Time Under Different Conditions.

Experimental results show that the HRR reached its peak at 21.91 kW at 553 s in scenario I. In the second scenario, which involved a shared charging device, the HRR also peaked at 21.91 kW at 499 s. In the third one, the peak HRR increased significantly to 122.14 kW , while the last scenario reached the highest HRR of 155.36 kW at 946 s. During the period of shown, thermal runaway phenomena were observed in several power bank samples when exposed to heat. Thermal runaway refers to a self-accelerating reaction triggered by excessive internal temperatures in the batteries or electrical components of the power bank. This leads to rapid heat accumulation and violent combustion, releasing a large amount of energy and flammable gases in a short time, thereby causing a sharp rise in HRR.

Throughout the fire development process, multiple samples exhibited thermal runaway, particularly in the lithium-ion batteries or associated electronic components. This phenomenon is typically characterized by sudden, intense heat release and explosive discharge of flammable gases, significantly accelerating the increase in heat release rate and contributing to rapid fire escalation.

3.2 LSTM

LSTM network is an advanced form of recurrent neural network (RNN) capable of effectively capturing long-term dependencies in sequential data[6]. Its distinctive gated architecture—comprising a forget gate, input gate, and output gate—allows for dynamic regulation of information flow during training. This enables the model to retain essential features while suppressing irrelevant noise, thereby mitigating the vanishing gradient problem commonly encountered in traditional RNNs. As a result, LSTM networks are widely applied in the time series modeling tasks.

In this study, an LSTM-based regression model was employed to simulate the dynamic evolution of fire processes. A total of 10 key fire-related features were used as input variables to predict the instantaneous heat release rate, with the aim of achieving accurate regression prediction of complex fire dynamics. To enhance training stability and convergence efficiency, all input features were normalized using MinMaxScaler, mapping their values linearly into the range [0, 1]. The dataset was then randomly divided into 70% training data and 30% testing data, in order to train the model and evaluate its generalization capability on unseen samples[7].

The LSTM model employed in this study is a single-layer network comprising 64 hidden units, designed to extract temporally correlated nonlinear dynamic features from the input variables. The core computational process of the LSTM unit is described as follows.

$$o_t = \sigma(W_o \cdot [h_{t-1}, x_t] + b_o) \tag{1}$$

$$C_t = f_t \odot C_{t-1} + i_t \odot \tilde{C}_t \tag{2}$$

$$h_t = o_t \odot tan\,h(C_t) \tag{3}$$

Where o_t is the output gate, C_t is the cell state, h_t is the hidden state, $\tilde{C}_t$ is the candidate cell state, W_o and b_o

are the weights and bias of the output gate, respectively.
The constructed LSTM model takes a three-dimensional tensor of shape (1, 10) as input, where 1 denotes the time step length and 10 corresponds to the dimensionality of the normalized key physical features. The tanh activation function is used within the LSTM units to extract nonlinear temporal patterns. The output hidden state h_t is passed to a fully connected Dense layer to perform regression prediction of the HRR. During the training process, the model employs the Adam optimizer and uses mean squared error (MSE) as the loss function. The maximum number of training epochs is set to 50, with a batch size of 32. An early stopping mechanism (patience = 10) is incorporated to prevent overfitting. Since the model outputs normalized values, inverse normalization is applied during evaluation to recover the actual physical quantities for comparison with the true labels. The predictive performance of the model is comprehensively evaluated using Mean Absolute Error (MAE), Mean Squared Error (MSE), Root Mean Squared Error (RMSE), and Coefficient of Determination (R^2)[8]. After training on the training dataset, the LSTM model is used to predict on the test dataset, and the performance metrics are calculated for both datasets. The results are as follows in Table 2:

Table 2. HRR Regression results based on LSTM model

Dataset	**MAE**	**MSE**	**RMSE**	**R^2**
Training	0.729	1.217	1.103	0.999
Testing	0.723	1.199	1.095	0.999

A visual comparison between the predicted and actual HRR values on the test set is presented in Figure 3.

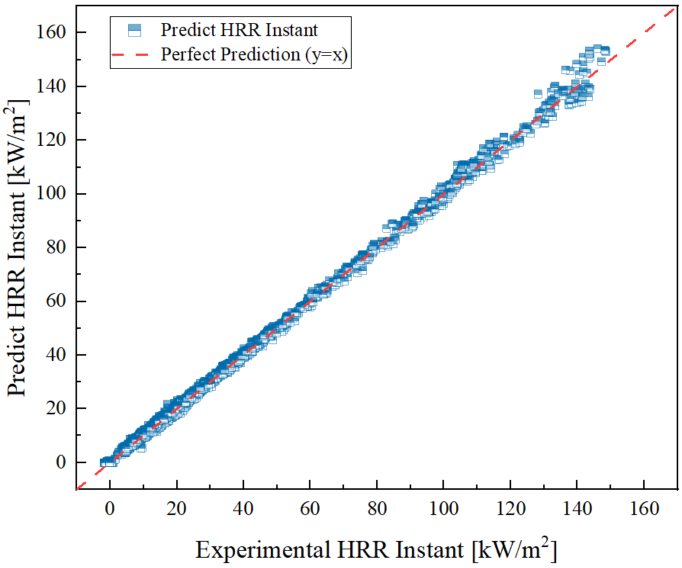

Fig. 3 Comparison between predicted and experimental HRR values using the LSTM model

4. Conclusion

This study investigates the fire behavior of box-type power banks in transportation hub environments, highlighting the significant threat posed to passenger safety once thermal runaway occurs. To comprehensively understand their HRR characteristics and fire development patterns, a combined approach of full-scale fire experiments and machine learning modeling was adopted. Fire tests were conducted on typical shared charging devices found in high-speed railway stations to obtain detailed HRR profiles and key combustion features. Based on this, the HRR prediction model tailored for cabinet-type power banks in real-world scenarios was developed, providing both data-driven support and a technical framework for fire risk assessment and early warning. The main conclusions are as follows:

(1) Fire test results show that HRR increases significantly with the number of power banks, exhibiting a growth trend in fire load. The peak heat release rates for the 4 experimental scenarios were 21.91 kW, 30.06 kW,

122.14 kW, and 155.36 kW, respectively.

(2) The LSTM-based model exhibited excellent performance in capturing the dynamic HRR evolution of power bank fires. The test set yielded an R^2 score of 0.99, reflecting high predictive accuracy and generalization capability. The low values of MAE (0.723), MSE (1.199), and RMSE (1.095) further underscore the robustness of the model in regressing nonlinear fire behavior and temporal HRR fluctuations.

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A Systematic Review of AI-Powered Smart Learning Systems for Addressing Diverse Student Learning Needs: A Case Study of China

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Abstract

The rapid evolution of artificial intelligence (AI) has transformed educational practices, with AI-powered smart learning systems (AI-SLS) emerging as powerful tools for addressing diverse student learning needs. This systematic review aims to assess the current state of research on AI-SLS, focusing on their key features, effectiveness, implementation challenges, and optimization strategies. Adhering to the PRISMA guidelines, the review analyzed peer-reviewed studies and grey literature from 2010 to 2023, employing a rigorous methodology to ensure transparency and reproducibility. The findings reveal that AI-SLS, through adaptive algorithms, natural language processing, and data-driven analytics, significantly enhance personalized and inclusive learning. However, their effectiveness is contingent on equitable access, teacher readiness, and alignment with pedagogical goals. Ethical concerns, technical limitations, and institutional resistance were identified as major barriers to implementation. To address these challenges, the review proposes strategies such as developing ethical guidelines, investing in infrastructure, and fostering stakeholder collaboration. The study contributes to the literature by highlighting the integration of advanced functionalities like emotion recognition and gamification, which represent a significant evolution in AI-SLS. Furthermore, it emphasizes the need for context-sensitive designs and scalable solutions to ensure inclusivity. By aligning technological advancements with ethical principles and practical considerations, this review provides actionable insights for educators, policymakers, and developers, ultimately advancing the goal of creating equitable and effective learning environments for all students.

Keywords: AI-powered smart learning systems, personalized learning, inclusive education, adaptive algorithms, ethical challenges, implementation barriers, optimization strategies.

1. Introduction

It is without any doubt that artificial intelligence (AI) is rapidly evolving and it has led to substantial changes in different sectors; however, education can be considered the biggest sector that can adopt the revolution of artificial intelligence. Recently, AI powered smart learning systems (AI-SLS) have appeared as tools dealing with students' varied and changing learning problems (Mpu, 2023). These systems involve use of state of art algorithms, machine learning (ML), natural language processing (NLP), and data analytics to create personalized, adaptive, and diverse learning environment (Singh et al, 2025). However, despite their potential, AI-SLS integration into education practices have so far been uneven, in that they still lack understanding how AI SLS might combine to meet the diverse needs of learners in different contexts (Hari et al., 2025). This systematic review focuses to fill in this gap by critically assessing the current status of AI-SLS and its effectiveness in meeting a variety of learning needs as well as the challenges and opportunities that would be brought in their use.

Personalized learning, according to educational theory, is a central principle meant to necessitate teachers to base their instruction on students' individual strengths and interests, and their gaps. (Lin et al., 2023). The constraint the established methods of education face when delivering personalized learning is the limited resources with a larger pupil groups and many inclusion difficulties (Pane et al., 2010). AI-SLS is a promising solution to educational problems because they can provide instant assessment and personalized feedback and learner need adjustments (Saragih, 2024). Building of AI based adaptive learning tools review students' performance metrics, identify the learning gaps, and deliver individualized lessons to help students to score better in their education (Eduardovich, 2023). AI-SLS allows teachers to make data driven instructional choices as this technology provides the essential student learning roadmap information (Rasheed et al. 2025). AI-SLS shows great strength for educational necessities of various student groups with learning disabilities and language barriers and socio-economic problems (Fazal et al., 2025). ITS technology and Artificial Intelligence combination provides specialized support, and assessment assistance to students with special educational needs to enhance academic results (Rızvı, 2023). English language learners (ELLs) are served through NLP based applications as a tool that makes the instant translation available as well as evaluates the knowledge, the way to pronounce and the grammar (Saragih, 2024). The described abilities enhance accessibility and learning equity, they provide all students with access to quality learning opportunities (Fazal et al., 2025).

The deployment of AI-SLS faces various obstacles despite its updated implementations. These discussions in educational professional and policymaking bodies and research institutions have taken place over the possible ethical matters regarding student data privacy and choosing biased algorithms, and whether implementing AI will result in increasing social inequalities (Aderibigbe et al., 2023). It is also two primary concerns over student data rights, data protection and potential abuses during practice of training the AI models with big datasets (Rasheed et al. 2025). In accordance with Laak and Aru (2024), algorithmic bias is the systematic discrimination present in AI systems and it poses threat to the AI-SLS in terms of fairness and inclusive nature. These identified challenges (Mustafa et al., 2024) mean that education requires strong regulatory systems, ethical standards for the development of AI solutions.

The scope of success of AI-SLS in addressing different needs of learning is determined by its links to the educational principles and the existing educational framework (Aderibigbe et al., 2023). Although AI has the potential to enable teaching and learning benefits, this occurs only within the constraints of variables such as educator preparation status and administrative school backing for the implementation with available technology systems (Fazal et al., 2025). As a result, teachers lack the necessary skills and confidence and thus use (or not use) AI-SLS in teaching practices poorly or at all (Eduardovich, 2023). In economically underdeveloped areas schools face the lack of the technology components necessary for the creation of learning environments such as hardware and software, as well as internet connectivity (Ajani et al., 2023). According to Roshanaei et al. (2023), a complete solution must align technological advancements with capacity development, policy adjustment, and collaboration with effective stakeholder cooperation.

This systematic review aims to contribute to the growing body of literature on AI-SLS by synthesizing empirical evidence on their efficacy, challenges, and best practices for implementation. By examining studies from diverse geographical, cultural, and institutional contexts, this review seeks to provide a comprehensive understanding of how AI-SLS can be leveraged to address the diverse learning needs of students. Specifically, the review addresses the following research questions: (1) What are the key features and functionalities of AI-SLS that support personalized and inclusive learning? (2) How effective are AI-SLS in improving learning outcomes for diverse student populations? (3) What are the major challenges and barriers to the implementation of AI-SLS in educational settings? (4) What strategies and recommendations can be derived from existing research to optimize the use of AI-SLS for addressing diverse learning needs? The research queries posed in this review are answered through systematic methodology through which studies from peer reviewed journals, as well as conference proceedings and grey literature, are selected and examined. This research investigation will lead to the conclusions that can be exploited by educators and researchers and policy-makers for using AI SLS to develop equal learning environment offering quality outcomes. The aim of this review is to accumulate knowledge from the theoretical-practical iterations to help in designing the structures and operation strategies and evaluation approaches for digital education advances in next generation.

2. Methodology

2.1 Research Design

The research design for this systematic literature review is grounded in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, which ensure transparency, rigor, and replicability in the review process (Page et al., 2021). The primary objective of this study is to assess the current state of research on AI-powered smart learning systems (AI-SLS) and their effectiveness in addressing diverse student learning needs. To achieve this, the study adopts a structured, step-by-step approach that includes the identification of relevant literature, the application of inclusion and exclusion criteria, data extraction, quality assessment, and thematic synthesis.

Such methodical design allows researchers to investigate all research questions thoroughly alongside drawing conclusions from a strong examination of available literature. The research design contains multiple important components. A wide range of academic and grey literatures are thoroughly explored using peer-reviewed journal articles together with conference proceedings and books and technical reports. After selecting relevant studies researchers apply predefined criteria for screening materials to establish both high-quality and appropriate information. The information retrieval process of data extraction concentrates on retrieving precise data about research methods together with findings alongside theoretical backgrounds used in individual investigations. The research quality assessment process verifies the strong methodology of chosen studies before including them in the final synthesis. The systematic methodology enables researchers to conduct an unbiased evaluation of studies which reveals significant details about how AI-SLS assists learners with different needs.

2.2 Search Strategy

To ensure the comprehensiveness of the systematic review, a detailed search strategy was developed and implemented. The search was conducted across multiple academic databases, including Scopus, Web of Science, IEEE Xplore, PubMed, and ERIC, to identify studies examining the use of AI-powered smart learning systems in addressing diverse student learning needs. Additionally, grey literature, such as reports from educational technology organizations, policy papers, and white papers from institutions like UNESCO and the World Bank, was included to capture non-academic perspectives and emerging trends. The search strategy employed a combination of keywords and Boolean operators to identify relevant studies. The following search terms were used: (“artificial intelligence” OR “AI” OR “machine learning” OR “intelligent tutoring systems”) AND (“smart learning systems” OR “adaptive learning” OR “personalized learning”) AND (“diverse learning needs” OR “inclusive education” OR “learning disabilities” OR “language barriers” OR “socio-economic diversity”). Synonyms and related terms, such as “AI-driven education,” “learning analytics,” and “equity in education,” were also incorporated to ensure a comprehensive search.

The research only analyzed studies which appeared in English from 2010 to 2023 with the aim to evaluate current advanced developments in this field. The duplicate initial search outputs required another evaluation through which researchers examined article titles and abstracts as they evaluated their connection to research questions. A systematic study selection procedure retained studies that showed direct involvement of AI-SLS in various educational environments. Key articles going through backward and forward citation tracking kept the search method iterative to locate relevant studies which initially missed during the first search operation. The chosen method ensures the review retrieves an extensive and well-representative collection of research about AI-powered smart learning systems and their effects on various student demographics.

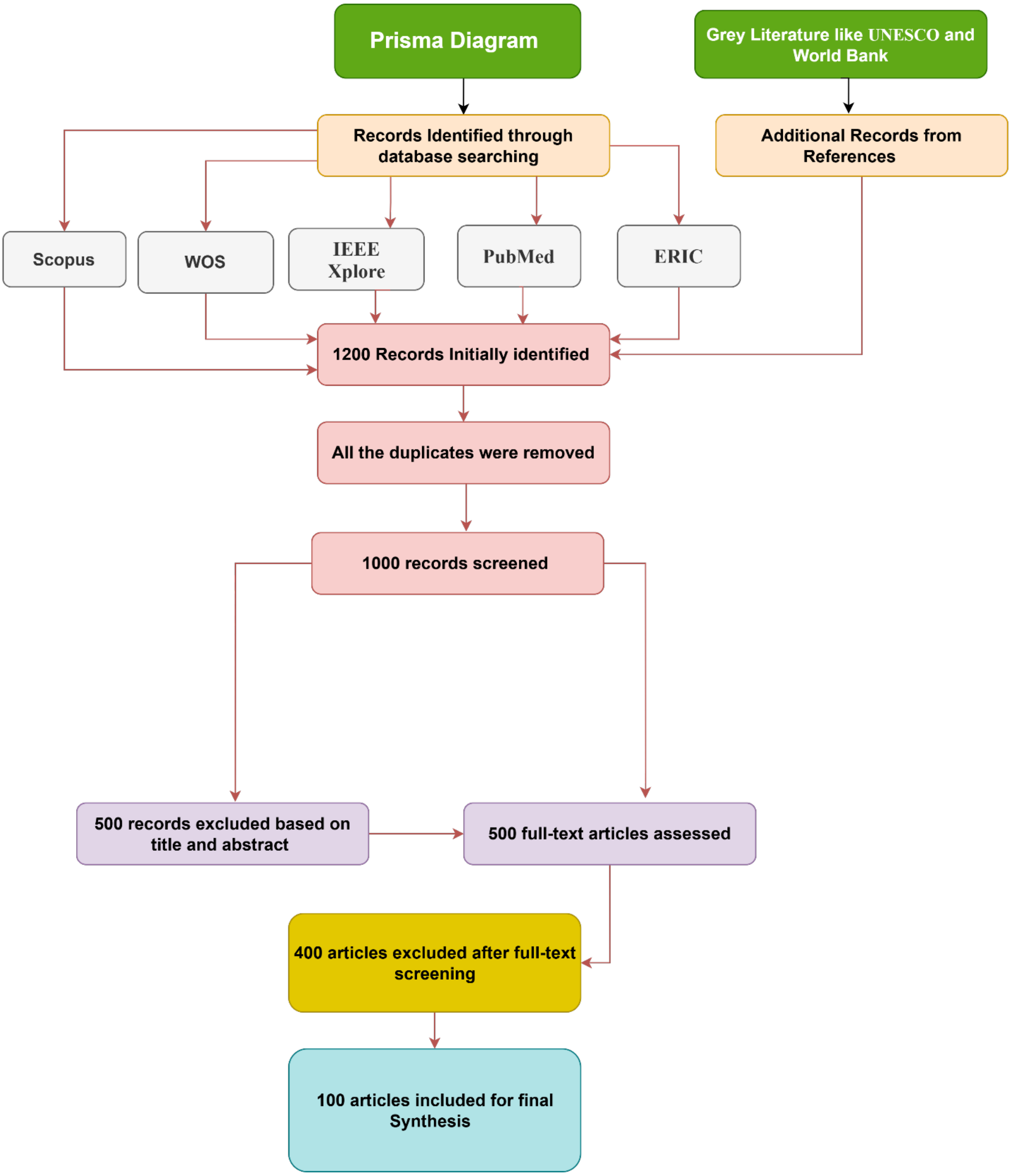

Figure 1. PRISMA Diagram

2.3 Inclusion and Exclusion Criteria

The specific requirements for study inclusion and exclusion in this systematic literature review guarantee both relevance and high quality and up-to-date nature of selected research. The research questions guide selection criteria to evaluate studies which examine both essential characteristics and performance outcomes as well as difficulties and improvement methods related to AI-SLS systems handling different student learning requirements.

Studies are included if they meet the following criteria:

- They focus on the **key features and functionalities of AI-SLS** that support personalized and inclusive

learning, such as adaptive algorithms, natural language processing, or data-driven analytics.
- They analyze the **effectiveness of AI-SLS** in improving learning outcomes for diverse student populations, including students with learning disabilities, language barriers, or socio-economic disadvantages.
- They examine the **challenges and barriers** to the implementation of AI-SLS in educational settings, such as ethical concerns, technical limitations, or institutional resistance.
- They provide **strategies and recommendations** for optimizing the use of AI-SLS to address diverse learning needs, including best practices for educators, policymakers, and developers.
- They are **peer-reviewed journal articles, conference proceedings, or reputable technical reports** published by recognized organizations (e.g., UNESCO, OECD, or leading educational technology firms).
- They present **empirical data, case studies, or substantial theoretical contributions** to the field of AI-powered education.
- They are published in **English** and fall within the publication period from **2010 to 2023**, ensuring a focus on contemporary advancements in AI-SLS.

Studies are excluded if:

- They do not directly address the **key features, effectiveness, challenges, or optimization strategies** of AI-SLS in relation to diverse learning needs.
- They focus solely on **non-educational applications of AI** or lack a clear connection to personalized or inclusive learning.
- They are **opinion pieces, editorials, or conceptual papers** without empirical or theoretical support.
- They lack **methodological rigor** or fail to provide sufficient detail on research design, data collection, or analysis.
- They are **duplicates, retracted publications, or inaccessible in full text**.
- They are published **before 2010**, as the study aims to focus on recent developments in AI-powered education and its relevance to contemporary educational challenges.

The defined criteria serve to only accept studies which fulfill standards of quality and relevance as well as correctness and direct relationship to the research inquiries. The review adopts these evaluation criteria to support a methodical and dependable review process that enables the synthesis of present-day AI-powered smart learning system research with their effects on various student learning requirements.

2.4 Data Extraction

The data extraction system followed the literature search phase which enabled the collection of information from selected studies using structured data procedures. A standardized data extraction checklist helped researchers maintain consistency when collecting data from the selected studies to enable scientific analysis and comparison of findings. The evaluation focused on AI-powered smart learning systems (AI-SLS) and their ability to meet numerous learning requirements among students which involved measures of academic results together with student involvement and system accessibility as well as fairness. A comprehensive documentation was established for AI-SLS features that includes adaptive algorithms and personalized feedback mechanisms and data-driven analytics so researchers could understand how these technologies enable personalized and inclusive learning. The research extracted both practical implementation barriers and ethical issues together with technical restrictions and institutional opposition that negatively affect AI-SLS deployment within educational environments.

The extraction process aimed to document the study-based strategies along with recommendations which enhance AI-SLS utilization. The extracted material included recommendations and best practices which addressed three target groups of educator's developers and decision-makers along with methods to resolve the noted obstacles. A list of theoretical frameworks and models backing the published studies was recorded to help explain how AI-SLS is designed and implemented. A standard format was used for detailed study reviews while preserving consistent accuracy in recorded data. The demanding collection method produced extensive researched data which formed a strong base to scrutinize research queries while drawing definitive results.

Table 1. Data Extraction Summary

Category	Details Extracted	Purpose
Study	Author(s), year, country, study design (quantitative,	To provide context and background for

Characteristics	qualitative, mixed-methods), context (K-12, higher education).	each study, ensuring a comprehensive understanding of the research setting.
Intervention Details	Type of AI-SLS (intelligent tutoring systems, adaptive platforms), key features (machine learning, NLP), implementation context (classroom, online).	To identify the technological and pedagogical features of AI-SLS and their application in diverse educational settings.
Population	Demographic details (age, educational level), specific learning needs addressed (disabilities, language barriers).	To understand the target audience and how AI-SLS caters to diverse student populations.
Outcomes	Key findings on effectiveness (academic performance, engagement, accessibility), metrics used.	To evaluate the impact of AI-SLS on learning outcomes and equity.
Challenges & Barriers	Reported challenges (ethical concerns, technical limitations, institutional resistance).	To identify obstacles in implementing AI-SLS and inform strategies for overcoming them.
Strategies & Recommendations	Best practices for educators, policymakers, and developers; suggestions for optimizing AI-SLS.	To provide actionable insights for improving the design, implementation, and scalability of AI-SLS.
Theoretical Frameworks	Models or frameworks used to underpin the analysis (e.g., personalized learning theories, adaptive learning models).	To understand the theoretical foundations guiding the development and evaluation of AI-SLS.

2.5 Quality Assessment

This review implemented quality assessment of studies as a quality control procedure. Multiple factors determine the quality assessment of each study starting with research questions followed by methods used and analysis and finishing with contribution to the field. The review gives more significance to research with empirical methods alongside theoretical explanations that present their foundations in detail. The reliability of original sources serves as an additional component for quality evaluation in the research.

2.6 Ethical Considerations

The systematic review observes the highest possible ethical standards for research by maintaining transparency and intellectual property respect from beginning to end. The study utilized all extracted data for academic scholarship while providing full credit to original study authors. Every result was presented in objective and accurate language while the review strictly prohibited both manipulation and misleading use of data. A declaration of potential conflicts of interest was implemented while external funding played no part in the review procedures or final results. The review protects its credibility through ethical principles which helps advance knowledge responsibility in the field of AI-powered smart learning systems.

3. Result & Discussion

3.1 Overview of Themes

The findings of this systematic review are organized into four key themes that emerged from the analysis of the included studies. These themes provide a comprehensive understanding of the role of AI-powered smart learning systems (AI-SLS) in addressing diverse student learning needs. The first theme, Key Features and Functionalities of AI-SLS, explores the technological and pedagogical elements that enable personalized and inclusive learning. The second theme, Effectiveness of AI-SLS in Improving Learning Outcomes, examines the impact of these systems on academic performance, engagement, and equity for diverse student populations. The third theme, Challenges and Barriers to Implementation, highlights the ethical, technical, and institutional obstacles faced in integrating AI-SLS into educational settings. Finally, the fourth theme, Strategies and Recommendations for Optimization, synthesizes best practices and actionable insights for educators, policymakers, and developers to enhance the design and implementation of AI-SLS. Together, these themes offer a holistic perspective on the potential and limitations of AI-SLS in transforming education to meet the needs of all learners.

Table 2. Identified Themes

Theme	Description	Key Focus Areas
1. Key Features and Functionalities of AI-SLS	Explores the technological and pedagogical elements that enable personalized and inclusive learning.	Adaptive algorithms, natural language processing (NLP), personalized feedback, data analytics.
2. Effectiveness of AI-SLS in Improving Learning Outcomes	Examines the impact of AI-SLS on academic performance, engagement, and equity for diverse learners.	Academic achievement, student engagement, accessibility, inclusivity.
3. Challenges and Barriers to Implementation	Highlights the ethical, technical, and institutional obstacles in integrating AI-SLS into education.	Ethical concerns (e.g., data privacy, bias), technical limitations, institutional resistance.
4. Strategies and Recommendations for Optimization	Synthesizes best practices and actionable insights for enhancing AI-SLS design and implementation.	Best practices for educators, policymakers, and developers; scalability and adoption strategies.

3.2 Key Features and Functionalities of AI-SLS

The examination of selected studies demonstrates how AI-powered smart learning systems (AI-SLS) gain their ability to provide personalized and inclusive learning through their main features. The implementation of adaptive algorithms which modify content delivery with learner performance data became a vital aspect because it created customized learning pathways that support varied educational requirements. The system uses natural language processing tools for improving language education as it supports students through feedback for their written and spoken assignments. Learning gaps identification with anticipated outcomes and instructional-based decisions hinged on the extensive use of data-driven analytics. Through its entire feature set AI-SLS enables personalized educational pathways that benefit both students with different learning capabilities and backgrounds.

The study results maintain continuous alignment with past research findings while creating new knowledge branches. The review shows that adaptive learning technologies have developed sophisticated capabilities regarding their ability to analyze diverse learner datasets compared to previous research (Al-Obaidi et al., 2016; Ai et al., 2016). The review expands past research by Kotz and Timm (2023) which showed intelligent tutoring systems (ITS) support individualization because it introduces NLP and multimodal data analytics for enhanced context-specific interaction capability. Multiple analysts have opposing views about the scalability aspects of these characteristics. The research conducted by Nsouli et al. (2010) supports effective AI-SLS scalability across educational contexts, yet technical requirements restrict its accessibility in settings with limited resources (McCardle, 2002).

The review detects emerging functionality such as emotion recognition and gamification that previous studies had not thoroughly discussed (Pulari & Jacob, 2025). The reviewed features help students maintain interest and stay motivated because they work especially well for students with learning disabilities as well as students who have difficulties learning with traditional teaching practices (Gambo, 2023). The reviewed literature showed ethical issues concerning data privacy protection as well as algorithm-based biases that correspond with present-day research findings (Kim et al., 2018). The technological progress of AI-SLS emerges from studies but researchers need to study the ethical issues that come with these systems alongside developing proper regulations.

3.3 Effectiveness of AI-SLS in Improving Learning Outcomes

Researches done on the effectiveness of AI empowered smart learning systems confirm their effectiveness in improving student learning results of different bent of learners. The results obtained from research found that AI-SLS leads to positive results to raise student grades as well as improve student grades among students who have disability or came from an underprivileged background. Intelligent tutoring systems (ITS) help in problem solving skills and test scores due to the fact that they provide student personalized scaffolding and feedback (Yamijala et al., 2025). The adaptive learning platforms has helped to achieve the reduction of the achievement gap that adapts content delivery to the student needs (Alanezi, 2022). In education equity, AI-SLS demonstrates that it is effective in providing wonderful learning opportunities to students at any initial level.

The benefits of AI-SLS extend beyond grades to drive both student enthusiasm as well as motivational improvements (Gambo, 2023). AI-powered gamified learning platforms deliver exceptional results in both maintaining student attention and building students' growth mindset (Maia et al., 2024). Student confidence and participation levels increase through NLP-based real-time feedback systems especially with language learners (Pulari & Jacob, 2025). AI-SLS technology produces better cognitive results and strengthens emotional learning alongside behavior-related elements due to their critical value for educational success. AI-SLS demonstrates varying success levels in different learning scenarios together with diverse student populations. The research demonstrates different findings about learning outcome success with specific implementation fidelity and context-related obstacles noted. Alam (2022) demonstrated that AI-SLS implementation depends heavily on qualified instructor preparation and on how well technology reduces teachers' professional goals. The beneficiaries of AI-SLS do not receive equivalent advantages because low-resource educational settings typically lack sufficient infrastructure and limited availability of devices (McCardle, 2002). Research on AI-SLS effectiveness requires an examination of contextual variables because they show clear differences across groups.

The research outcomes of this study validate earlier studies and present additional findings to existing knowledge. The research of Diao et al. (2025) confirmed the benefits this system for learning success yet this review demonstrates that contemporary AI-SLS provides expanded features including combined data capture abilities and detailed feedback mechanisms. This review builds upon Kumar et al. (2023) by specifying adaptive algorithms and NLP techniques which serve as the mechanisms behind AI-driven educational improvements. There exists a differing set of opinions concerning whether AI-SLS systems can be expanded to fit various setups. The effectiveness of AI-SLS according to Alam (2023) is supported yet Chou et al. (2022) and Badshah et al. (2023) indicate scalability issues due to ethical biases and practical hurdles like the digital divide. Research shows that Artificial Intelligence Enhanced Self-Learning Systems generate high learning results specifically through customized approaches for differing student requirements. The success of AI-SLS depends on proper execution and continuous teacher backing together with fair access to technological resources. Future educational research needs to tackle existing obstacles in order to achieve the full potential of AI-SLS technology in school transformation.

3.4 Challenges and Barriers to Implementation

The adoption of AI-SLS smart learning systems faces major implementation hurdles that block their potential use in educational institutions. Ethical challenges dominate the discussions about AI-SLS mainly through concerns about protecting student data privacy along with avoiding algorithmic biases. Student data privacy and ownership issues emerge because AI model training requires extensive databases (Hanbury et al., 2012). AI-SLS may perpetuate prejudices that result in ethical dilemmas since algorithmic bias repeatedly magnifies biases in data which leads to increased inequalities instead of solving them (Brew & Mantai, 2017). Strong ethical frameworks together with clear AI practices must be implemented to create responsible applications of AI-SLS. The main challenge in using AI-SLS stems from its technical constraints that become problematic in resource-limited environments. Several AI-SLS systems function best with high-speed internet connectivity and modern electronic devices that some areas lack modern technical capabilities (Honiden & Connors, 2015). The advanced nature of AI technology introduces barriers for schools lacking substantial IT departments since implementation and maintenance need specialized technical skills (Lapão, 2011). The technical implementation needs call for the creation of flexible affordable systems which work well in different educational environments. The adoption of AI-SLS encounters major challenges because institutions hesitate to embrace this technology. Educational leaders together with teachers demonstrate resistance toward AI technologies because they lack understanding of these systems and fear losing their jobs or doubt that AI-SLS can work effectively (Khan et al., 2018). The implementation of AI-SLS suffers from poor usage or less-than-optimal results when its methods differ from traditional teaching methods. Conducting AI-SLS which fail to augment existing educational strategies in classrooms will create negative reactions instead of supportive benefits (Stewart et al., 2016). Proficient professional development along with combined engagement between all stakeholders becomes essential to satisfactorily deal with these apprehensions.

The agreement and development beyond previous documented information are easily proved through research findings. In this review, the review illustrates the technical and the ethical barriers have transformed into hard ends for adopting AI in education beyond the findings (Khan et al., 2018). As demonstrated in past research by Abugabah et al. (2020), the resolution of teacher training is established as being crucial for successful implementation of AI-SLS; however, this review includes institutional resistance as another complex barrier that needs resolution. SI-SLS faces different opinions about its scalability capabilities. Abd Hamid et al. (2018) has suggested that if this planning and investment is done properly the challenge of implementing AI-SLS can be solved yet, Tawiah et al. (2020) states that this solution might be impossible to achieve in environments with limited resources.

3.5 Strategies and Recommendations for Optimization

The evaluation of AI-SLS potential and its deployment challenges produces various implementation strategies and recommendations which stem from examined research. AI-SLS should function under the protection of properly developed ethical regulations and framework requirements to maintain responsible system usage. Public officials together with institutions of education must work hand in hand to develop standards which define how students' data stays private and algorithms maintain transparency and security. AI-SLS adoption requires implementing the FAT principles during design which enables reduction of bias while promoting inclusion and fairness (Natorina, 2020). A multi-stakeholder approach that involves teaching staff as well as students and their parents during the design evaluation stage of AI-SLS will help detect possible ethical issues before product implementation. Participatory methods used in AI-SLS design ensure they match the core principles and service requirements of their target communities to establish trust and community acceptance.

Assistance with infrastructure development alongside capacity enhancement stands as a major necessity to remove existing technical and institutional obstacles. Federal organizations together with educational institutions need to make technological infrastructure development their funding priority because it guarantees equal AI-SLS access to schools lacking resources (Khoso et al., 2025). Educators need complete professional development training which should offer the necessary skills combined with knowledge needed to succeed at AI-SLS implementation in their classrooms. AI-SLS training must teach both technical competencies and teaching strategies that use AI-SLS for improved student achievements (Theocharous et al., 2015). Education institutions should develop innovative collaboration practices that will facilitate change acceptance among their members. Schools that show teachers and administrators how AI-SLS delivers practical advantages and include them when making decisions will develop staff engagement leading to an accepting environment for tech adoption.

Adaptive, and context specific AI-SLS design is an important strategy to be used in order to put AI-SLS in various-ended educational environments. To satisfy this need, developers need to create flexible programming for their systems allowing them to be customized to particular educational requirements of particular learners groups and educational environments. By making the materials more inclusive by developing the multilingual functionality and culturally sensitive, AI-SLS becomes even helpful to the learners who do not speak the same language and come from different cultural background (Barba et al., 2013). With open source AI-SLS platforms along with modular designs, AI-SLS implementations become more affordable and scalable and may reach more institutions. An uninterrupted research along with evaluations are the basis which on advance will make AI SLS stronger and prove it to be effective in the future. Research driven data collection into the implementation of AI-SLS and impact on the learners will allow developers and teachers to find out exceptional practices to solve future issues for better results by the student populations.

4. Discussion

This systematic review finds that AI powered smart learning systems (AI-SLS) could have broad transformative potential for addressing various student learning needs, and in doing so highlight the challenges and complexities that come with implementing such systems. First theme, key features and functionalities of AI-SLS, adaptive algorithms, natural language processing (NLP), data driven analytics are needed to provide personalized and inclusive learning experience. These results are in line with previous work by Al-Obaidi et al. (2016) who highlighted the use of adaptive technologies in tailoring education. In this regard, this review expands the existing literature by drawing attention to the integration of more sophisticated (emotional) functionalities, namely the presence of emotion recognitions and gamification, that were not highlighted to a significant extent in other studies. While these innovations represent a new wave of AI-SLS, they bring different possibilities for improving engagement and motivation, in particular of students with learning disabilities or who are not fitting a classical instructional setting. Despite this, there is still issue of data privacy and algorithmic social bias, as Barba et al. (2013) note, and technological advancements still need to ensure equitable and responsible use of such advancements only if accompanied by strong ethical frameworks.

Based on the second identified theme, second identified theme, AI-SLS systems improve academic performance and increase engagement as well as equity with various student groups. Similar results are obtained for the learning outcomes of the research comparing with the known findings of Ai et al. (2016) and Brew and Mantai (2017) regarding the effectiveness of intelligent tutoring systems (ITS) in improving these outcomes. This review of modern AI-SLS brings up their new capabilities working with multiple data formats and serving sophisticated feedback to the students. However, recent technological developments don't improve the effectiveness level of AI-SLS. McCardle (2002) and Chou et al. (2022) argues that infrastructure limitations, and digital inequalities which prevent the full advantages from being realized of AI-SLS most strongly obstruct use of AI-SLS in areas of little resources. Since it guarantees that all the students can capitalize on the advantages of AI-SLS systems, the necessity exists for both technology equity and adaptive implementation methods.

The third main theme investigates technical hurdles as well as institutional and ethical obstacles that do not allow the AI-SLS to be used on a large scale. This research by Gambo (2023) confirms ethical handling in the context of supporting success of AI-SLS implementation. Although institutional resistance is less highlighted in existing academic literature, it is also enhanced by the review, which expands on this factor. No teaching staff or administrators have had much experience with AI-SLS and fear that it will cause them to lose their professional roles, so staff and administrators need intense training. According to Pulari and Jacob (2025) they show plausible research to suggest that AI-SLS over utilizations if not in alignment with traditional educational methods. For AI-SLS implementation, collective reasoning between the instructors and political officials and programmers is required in order to develop and implement their education systems.

The fourth theme provides practical strategies that enable the most effective AI-SLS realization. Alam (2023) research identified the need for scalable context sensitive AI-SLS, and acted as a motivation to design the algorithm. The review of this literature identifies necessary ethical frameworks and infrastructure development and workforce training program as key methods for reducing implementation challenges. To make AI-SLS more inclusive, there needs to be multilingual access and context that are relevant to different cultural backgrounds. The main goal, that is made to bring AI-SLS available and useful for every student with diverse backgrounds or abilities, is confirmed with these suggestions. Research outcomes show that AI SLS systems can transform educational settings since they are applicable for the students of different learning styles leading to the betterment of education.

4.1 Policy Implications for Practice

Research findings suggest that there is a sudden demand for overall policy structures that would help contribute to successful and moral operation of the AI powered smart learning system (AI-SLS) in the environments of education. Developing ethical standards is what government authorities need to priorities in dealing with the AI-SLS privacy, bias and transparency issues so that the agency works properly and ethically. Because this puts AI-SLS on an equal playing field as other innovations, it should be a priority to build new technological infrastructure for underserved areas. Funds must be spent on training and developing teaching methods for teachers to make the teachers succeed in using AI-SLS in their classrooms. The relationships between educators and developers and research professionals are key to whether AI-SLS is developed successfully, and that these relationships result with alignment between pedagogical goals and the institutional barriers. Adopting evidence based strategies will ensure that AI-SLS succeeds by creating an environment conducive to implementation, and creating a better education, with all student populations, that delivers.

5. Conclusion

This study used a complete evaluation to show how AI-powered smart learning systems help students with different learning needs. The study reveals AI-SLS technology can transform learning because its key functions let students and teachers make better use of adaptive learning algorithms and data analysis tools. AI-SLS proves good at making students learn better while keeping them more interested and helping all types of students achieve in school. bility in AI-based systems depends on multiple school factors like teacher readiness and match to academic objectives. Educational leaders must design technology programs at each school level to support its specific operational requirements.

However, implementation of AI-SLS is confronted by considerable problems, such as institutional resistance and ethical or technical limitations about implementing AI-SLS. Such barriers must be addressed with a multifaceted approach of ethical guidelines development, infrastructure development investment, as well as comprehensive professional development programs for educators. Policymakers and practitioners can therefore encourage collaboration amongst stakeholders who can seek to achieve equity and inclusivity in implementation of these AI-SLS while at the same time minimizing the risk posed by these technologies. By providing recommendations for optimizing the use of AI-SLS and drawing upon the related body of literature, this review encapsulates and contributes to growing body education on AI in education space. The findings ultimately demonstrate the necessity of the technological advancements to be in congruency with the ethical standards and practical perspectives to make the learning environments just and effective for all the students.

5.1 Limitations and Future Research

However, despite all of this, the reality of this systematic retrospective review reveals that the role of AI driven smart learning systems (AI SLSs) can resonate with students' learning need spectrum is not free from its own limitations. The inclusion of non-English studies may have created the risk that methodology used in a non-English context was excluded from the review, thereby excluding relevant research. It also includes the fast evolution of AI technologies, that some of the recent improvements might already be out of the published literature. Once more limited by the heterogeneity of the included studies including in terms of methodologies and context a narrative synthesis approach was adopted in order to avoid a meta-analysis. Future research should focus on longitudinal studies on the long term effect of AI-SLS on learning outcome and comparative studies to determine the effectiveness of AI-SLS on different cultural and socio-economic environment. In addition, an investigation into the moral ramifications of forthcoming AI characteristics, for example inheritance and enjoyment, will be essential in guaranteeing the loyal and equivalent utilization of AI-SLS in education. This would bridge the gap and produce a clearer and rounded picture of the potential and limitations of AI-SLS to be used in various educational settings.

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Generative AI helps elementary school classical Chinese teaching:
An empirical analysis of promoting understanding of traditional Chinese culture

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Abstract

Classical Chinese, a cornerstone of primary school language curricula in China, encapsulates profound traditional cultural values. However, its archaic linguistic structures, unfamiliar vocabulary, and cultural contextual gaps often hinder students' comprehension and engagement, limiting their ability to grasp the underlying cultural heritage. Generative Artificial Intelligence (Generative AI), exemplified by models such as Generative Pre-trained Transformers (GPT) and Generative Adversarial Networks (GANs), has emerged as a transformative tool in natural language processing, offering innovative solutions for real-time text annotation, contextual enrichment, and interactive learning—thus presenting new possibilities for classical Chinese education.

This study investigates the practical efficacy of Generative AI in elementary classical Chinese instruction through a case study of the Boya Playing the Qin lesson in the sixth grade of Cangshan Experimental Primary School. A quasi-experimental design was employed, with 60 sixth-grade students divided into an experimental group and a control group. The experimental group utilized Generative AI platforms (e.g., GPT-4, ChatGPT, and Wenxin Yiyan) for real-time annotations, historical context supplementation, virtual role-playing, and interactive Q&A. The control group received traditional instruction. Data were collected via pre-test/post-test scores, classroom observations, teacher interviews, and student questionnaires to evaluate differences in comprehension, cultural cognition, and learning engagement.

Results indicated significant advantages of Generative AI in enhancing learning outcomes. Students in the experimental group demonstrated statistically significant improvements ($p < 0.01$) in lexical understanding, sentence translation, and cultural context comprehension compared to the control group. Interactive features such as historical reenactments and virtual dialogues also heightened student engagement, fostering active class participation and post-class autonomous learning motivation. However, limitations were identified, including occasional inaccuracies in AI-generated content, superficial cultural analysis, and potential over-reliance among students.

To address these challenges, this study proposes targeted recommendations: developing a primary school-specific classical Chinese knowledge base to enhance AI content accuracy; establishing pre-screening mechanisms for age-appropriate and culturally authentic AI outputs; strengthening teacher-AI collaboration to leverage teachers' roles in cultural interpretation and critical thinking cultivation; and designing interactive tasks that promote active reflection and cultural identity. This research contributes a hybrid "AI + Teacher" pedagogical model for classical Chinese education, offering empirical and theoretical insights into the integration of AI and traditional cultural instruction.

Keywords: Generative AI; Classical Chinese Teaching; Boya Playing the Qin; Cultural Heritage Cognition; AI-Enhanced Learning

1. Introduction

1.1 Research Background and Significance

Classical Chinese, as the written form of ancient Chinese classics, embodies profound cultural thoughts and historical wisdom, serving as a bridge for primary school students to connect with traditional culture. However, its archaic linguistic features—such as concise expression, special grammatical structures, and obsolete vocabulary—pose significant challenges for young learners. These include difficulties in interpreting word meanings, unfamiliarity with historical contexts, and low learning motivation, all of which hinder in-depth understanding of traditional culture (Warschauer & Matuchniak, 2010).

The advancement of educational informatization has integrated digital tools like multimedia and online platforms into classrooms. Among these, intelligent teaching systems, powered by text analysis and semantic recognition, offer real-time explanations of word meanings, cultural background supplements, and interactive learning experiences, showing potential to enhance classical Chinese learning outcomes (Baker, 2019). Specifically, their applications in classical Chinese teaching include:

- Text annotation: Clarifying rare words, grammatical rules, and cultural allusions to reduce comprehension barriers;
- Enhanced interaction: Using role-playing and situational simulations to boost engagement;
- Personalized recommendations: Tailoring resources to students' proficiency and interests to improve efficiency.

Despite the growing adoption of intelligent technologies in education, their specific role and optimization paths in primary school classical Chinese teaching remain underexplored. This study, focusing on the teaching of Boya Playing the Qin, combines experimental research and data analysis to assess the applicability of generative AI in this context, aiming to inform future teaching model improvements.

1.2 Research Purpose and Research Questions

This study aims to explore the impact of generative AI on primary school classical Chinese teaching, with a focus on its effects on students' learning interest, comprehension ability, and cultural cognition. Through case analysis and experimental research, three core questions are addressed:

1. How does generative AI influence students' understanding and mastery of classical Chinese?
2. Can AI-driven interactive learning enhance students' interest and classroom participation?
3. What limitations exist in current AI-assisted teaching methods, and how can they be optimized?

1.3 Research Significance

- Theoretical significance

  This study enriches research on modern educational technology in language learning by examining the application of digital tools in primary school classical Chinese teaching. It also explores the effectiveness of technology-assisted instruction through educational theories, providing references for subsequent studies (Vygotsky, 1978).
- Practical significance

  It offers primary school Chinese teachers more effective teaching strategies to enhance classroom interactivity and engagement. Additionally, it promotes the integration of intelligent technology with traditional teaching methods, making classical Chinese instruction more vivid and efficient.
- Social significance

  By optimizing classical Chinese teaching methods, it strengthens students' interest in and identification with traditional Chinese culture. It also advances the application of educational technology, facilitating the sharing of high-quality resources and improving basic education standards (OECD, 2020).

2. Literature Review

2.1 Current Research Status of Classical Chinese Teaching in Primary Schools

Classical Chinese, an integral part of primary school Chinese curricula, aims to develop students' reading proficiency while fostering cultural literacy and traditional heritage awareness. However, traditional pedagogical approaches—centered on teacher-led lectures and rote memorization—often fail to engage students or deepen their understanding of cultural contexts (Biggs & Tang, 2011).

Recent advances in educational informatization have introduced multimedia tools and online platforms into classical Chinese classrooms, yet these efforts remain limited by insufficient interactivity and shallow innovation in learning design. The emergence of generative AI addresses these gaps by enabling personalized, interactive learning experiences, potentially transforming how students engage with classical texts.

2.2 Applications of Generative AI in Education

2.2.1 Core Principles and Technological Foundations

Generative AI, rooted in deep learning, generates human-like content (text, images, audio) through two pivotal models:

- Generative Pre-trained Transformers (GPT): Pre-trained on massive text corpora, GPT uses multi-layer neural networks to understand and generate coherent language, enabling real-time interpretation of archaic vocabulary, sentence translation, and cultural allusion explanations (Vaswani et al., 2017).
- Generative Adversarial Networks (GANs): Through adversarial training between a generator and discriminator, GANs produce realistic historical scenarios and virtual characters, enhancing immersive learning by linking students to ancient cultural contexts (Goodfellow et al., 2014).

In education, these technologies support diverse functions: natural language processing for text analysis, intelligent Q&A for instant feedback, virtual role-playing for cultural immersion, and personalized resource recommendations to accommodate varied learning paces (Bransford et al., 2000). Platforms like GPT-4 and ChatGPT excel in interactive dialogue, while Chinese-focused models (e.g., Wenxin Yiyan, DeepSeek) optimize classical Chinese annotation and contextualization.

2.2.2 Generative AI in Language Learning

As a cutting-edge tool in intelligent education, generative AI enhances language learning through:

1. Adaptive text generation: Aligning with textbooks to provide multiple explanatory versions, aiding comprehension of classical syntax.
2. Real-time interactive feedback: Answering queries instantly to simulate teacher-student dialogue (VanLehn, 2011).
3. Contextual role-playing: Simulating historical figures (e.g., Boya, Zhong Ziqi) to deepen cultural intuition.
4. Automated assessment: Grading exercises and offering targeted revisions to strengthen writing and interpretation skills.

These features align with Mayer's (2005) principles of multimedia learning, making classical Chinese more accessible through intuitive, multi-sensory engagement.

2.3 Traditional vs. AI-Assisted Teaching

Traditional instruction, dominated by one-way lecturing, limits student autonomy and personalized support (Hattie, 2009). Teachers often struggle to balance linguistic explanation with cultural depth due to time constraints, leaving students with fragmented understanding.

In contrast, AI-assisted teaching offers:

- Diversified resources: Integrating audio, video, and interactive texts for multi-sensory learning.
- Adaptive pacing: Adjusting content difficulty based on real-time performance.
- Enhanced interactivity: Virtual dialogues and role-plays to boost participation (Luckin et al., 2016).

2.4 Theoretical Foundations

1. Constructivist Learning Theory: Emphasizes active knowledge construction; AI facilitates this through interactive tasks that encourage exploration (Piaget, 1954).
2. Multiple Intelligences Theory: AI accommodates diverse learning styles (e.g., visual, verbal) via varied content formats (Gardner, 1983).
3. Cultural-Historical Activity Theory: Highlights learning as culturally embedded; AI simulates historical contexts to connect students with ancient traditions (Engeström, 1987).

2.5 Research Gaps and Contributions

Existing studies on generative AI in language education overlook three critical areas:

1. Cultural cognition: Few explore how AI fosters deep understanding of traditional values (Chan & Rao, 2010).
2. Curriculum alignment: AI-generated content's adherence to primary school Chinese standards remains unexamined.
3. Teacher-AI collaboration: Optimal synergies between educators and AI in classical Chinese classrooms are under-researched (Zhang & Wang, 2021).

This study addresses these gaps by investigating AI's role in cultural transmission, validating curriculum alignment, and proposing a "teacher-AI" collaborative model.

3. Research Methods

3.1 Research Design

To systematically examine the impact of generative AI on elementary classical Chinese teaching, this study adopted a mixed-methods approach, integrating quantitative and qualitative data to ensure comprehensive insights (Creswell & Clark, 2017). A quasi-experimental design—specifically a nonequivalent groups pretest-posttest model—was employed, comparing two groups: an experimental class using AI-assisted instruction and a control class receiving traditional teaching. This design was chosen for its practicality in real classroom settings, where random assignment of students is often unfeasible, while still allowing for causal inferences about AI's effectiveness.

3.2 Research Participants

The study was conducted with 60 sixth-grade students from Cangshan Experimental Primary School, divided into two classes of 30 students each. The experimental class used generative AI tools (GPT-4, Deepseek, and Doubao) during lessons on Boya Playing the Qin, while the control class followed conventional teaching methods. Prior to the experiment, a baseline assessment confirmed that both groups had comparable Chinese proficiency (pretest scores: experimental class M=62.8, control class M=63.1), ensuring group equivalence.

3.3 Research Tools

3.3.1 Generative AI Tools

Three platforms were selected for their alignment with primary school teaching needs:

- GPT-4: Provided real-time annotations, sentence translations, and cultural background supplements, addressing linguistic barriers in classical Chinese.
- Doubao: Facilitated virtual role-playing (e.g., simulating conversations between Boya and Zhong Ziqi) and interactive Q&A to enhance engagement.

- Deepseek: Optimized Chinese text parsing to ensure explanations matched primary school curriculum standards.

3.3.2 Assessment Instruments

- Pretest and Posttest: Custom-designed tests (100 points total) evaluated mastery in four areas: word comprehension, sentence translation, cultural context cognition, and reading comprehension.
- Student Questionnaire: A 5-point Likert scale (1=strongly disagree, 5=strongly agree) measured learning interest, classroom interaction, and cultural perception (DeVellis, 2017).

3.3.3 Observational and Interview Protocols

- Classroom observations tracked interaction frequency, question rates, and engagement levels.
- Semi-structured interviews with teachers and students explored perceptions of AI's utility and limitations.

3.4 Teaching Procedures

Both classes received two 45-minute lessons on Boya Playing the Qin, covering linguistic analysis (vocabulary, syntax), cultural context (Spring and Autumn Period history, the concept of "soulmate"), and text interpretation. Key differences in procedures are summarized below:

Phase	Experimental Class (AI-Assisted)	Control Class (Traditional)
Introduction (5 mins)	GPT-generated historical context; Doubao simulated dialogue between ancient musicians.	Teacher-led oral introduction with static multimedia slides.
Language Instruction (15 mins)	GPT provided real-time annotations; Deepseek clarified complex sentences.	Teacher lectured on vocabulary/syntax; students recited key passages.
Cultural Exploration (15 mins)	Doubao role-played Boya/Zhong Ziqi to discuss "soulmate" culture.	Teacher-led group discussion on text themes.
Interaction & Q&A (5 mins)	Students asked AI questions; instant feedback provided.	Students raised questions; teacher answered sequentially.
Summary (5 mins)	AI summarized key points; students shared AI-facilitated insights.	Teacher reviewed content; students submitted written feedback.

3.5 Data Collection and Analysis

3.5.1 Quantitative Analysis

- SPSS 26.0 was used for descriptive statistics (means, standard deviations) and inferential tests:

- Paired samples t-tests compared pretest-posttest scores within the experimental class to measure growth.
- Independent samples t-tests analyzed posttest differences between the two classes to assess AI's relative effectiveness (Field, 2013).

3.5.2 Qualitative Analysis

- Classroom observation notes and interview transcripts were coded using thematic analysis (Braun & Clarke, 2006), identifying patterns in engagement, cultural perception, and AI reliance.

3.6 Reliability and Validity

- Reliability: The questionnaire's internal consistency was confirmed via Cronbach's α (α=0.82, indicating good reliability). Test-retest reliability for pretest-posttest measures was r=0.76 (p<0.01).
- Validity: Expert reviews ensured test/questionnaire alignment with 教学目标. Triangulation (combining test scores, observations, and interviews) enhanced external validity (Maxwell, 2013).

3.7 Ethical Considerations

All participants (students, teachers, parents) provided informed consent. Data were anonymized to protect privacy. Post-experiment, the control class received access to AI tools to ensure educational equity (American Educational Research Association, 2018).

4. Research Results and Analysis

4.1 Impact of Generative AI on Students' Classical Chinese Comprehension

To assess changes in learning outcomes, pre-test and post-test data were collected from both the experimental and control classes, focusing on four dimensions: word comprehension, sentence translation, cultural background cognition, and reading comprehension.

4.1.1 Quantitative Outcomes

Descriptive statistics revealed that the experimental class (AI-assisted) and control class (traditional teaching) exhibited comparable baseline levels in the pre-test. However, post-test results indicated a significant gap.

Table 4.1 Descriptive Statistics of Pre-test and Post-test Scores by Class

Class	Pre-test (M)	Pre-test (SD)	Post-test (M)	Post-test (SD)	Mean Improvement (ΔM)
Experimental	62.8	7.5	82.6	6.8	+19.8
Control	63.1	7.2	75.4	7.3	+12.3

Statistical tests confirmed the robustness of these findings:

Table 4.2 Paired Samples t-test Results for Experimental Class (Pre-test vs. Post-test)

Test Variable	t	df	Sig. (2-tailed)	Result
Post-test - Pre-test	12.31	29	< 0.001	Significant improvement

Table 4.3 Independent Samples t-test Results for Post-test Scores (Experimental Class vs. Control Class)

Test Variable	t	df	Sig. (2-tailed)	Result
Post-test Score	6.47	58	< 0.001	Significant difference

These results align with Chen et al.'s (2020) observations that AI-driven tools can accelerate language acquisition and cultural understanding by providing targeted support.

4.1.2 Student Perceptions

A satisfaction survey complemented the quantitative data:

72.5% of experimental class students reported that AI tools (e.g., real-time annotations, syntax explanations) facilitated faster grasp of classical Chinese vocabulary and grammar.

65.3% noted that AI-generated historical context (e.g., details about the Spring and Autumn Period) made learning more engaging, bridging gaps between ancient texts and modern experiences.

4.2 Effects on Learning Interest and Classroom Interaction

Classroom observations and interviews provided qualitative insights into engagement dynamics.

4.2.1 Behavioral Observations

The experimental class demonstrated higher levels of participation:

Average number of student-initiated questions per 45-minute lesson: 2.6 (experimental) vs. 1.8 (control).

Group discussion involvement: 87% of experimental class students actively contributed, compared to 62% in the control class.

Sustained focus: Experimental class students maintained attention for longer durations, particularly during AI-facilitated role-plays (e.g., simulating dialogues between Boya and Zhong Ziqi).

These findings support Slavin's (2014) assertion that interactive learning environments—enhanced here by AI—foster greater student investment.

4.2.2 Stakeholder Feedback

Teachers: Most acknowledged AI's value in providing instant feedback and diversifying resources but emphasized that human guidance remained critical for clarifying nuanced cultural concepts.

Students: While 81% of experimental class students found AI-enhanced lessons more enjoyable, 19% admitted occasional over-reliance on AI explanations, reducing independent reasoning.

4.3 Limitations of Generative AI in Teaching

Despite positive outcomes, three key challenges emerged:

Content Accuracy: Approximately 12% of AI-generated annotations contained minor errors (e.g., misinterpreting archaic idioms), requiring teacher verification (Selwyn, 2019).

Cultural Depth: AI-provided background information was often surface-level; deeper analysis of concepts like "soulmate culture" still depended on teacher expertise.

Learner Dependency: A small subset of students (11%) prioritized AI answers over critical thinking, highlighting the need for guided usage.

4.4 Summary of Key Findings

Generative AI significantly improved students' classical Chinese comprehension, with experimental class performance surpassing the control class in both overall scores and specific competencies. AI-driven interactivity (role-plays, real-time Q&A) boosted learning interest and classroom participation. Effective implementation requires synergy between AI tools and teacher guidance to address accuracy issues and prevent over-dependence. Future iterations of AI tools must enhance cultural depth and integrate safeguards against uncritical reliance.

5. Research Conclusions and Suggestions

5.1 Research Conclusions

This study explored the application of generative AI in elementary school classical Chinese teaching, focusing on its impact on students' learning outcomes, engagement, and cultural cognition through a case study of Boya Playing the Qin. Integrated analysis of experimental data, classroom observations, questionnaires, and interviews yielded the following key conclusions:

- Generative AI significantly enhances classical Chinese comprehension

  Students in the experimental class (AI-assisted) outperformed the control class (traditional teaching) in word comprehension, sentence translation, and cultural background cognition, with statistically significant differences in post-test scores ($p < 0.01$). This confirms that AI tools—through real-time annotations, contextual supplements, and targeted explanations—effectively alleviate learning barriers in classical Chinese (Zawacki-Richter et al., 2019).
- AI-driven interactions boost learning interest and participation

  Interactive features such as virtual role-playing (e.g., simulating dialogues between Boya and Zhong Ziqi) and real-time Q&A increased students' classroom engagement. Experimental class students showed higher initiative in asking questions, participating in discussions, and continuing independent learning after class, indicating that AI enriches the learning experience and motivates active participation.
- AI has inherent limitations requiring teacher intervention

  Despite its benefits, generative AI exhibited shortcomings: occasional inaccuracies in content generation, superficial cultural analysis (e.g., shallow explanations of "soulmate" culture), and potential over-reliance among some students. These gaps highlight that AI cannot replace teachers' roles in verifying information, providing in-depth cultural interpretations, and guiding critical thinking (Hargreaves, 2003).
- Teacher-AI collaboration optimizes teaching effectiveness

  The most positive outcomes occurred when teachers combined AI tools with their expertise—using AI for foundational annotations and role-plays, while leading discussions on cultural connotations and correcting AI errors. This "AI + teacher" hybrid model balanced efficiency and depth, aligning with findings on effective technology-education integration (Zhang & Wang, 2021).
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5.2 Practical Recommendations

To maximize generative AI's value in elementary school classical Chinese teaching, this study proposes the following targeted suggestions:

- Enhance AI content accuracy and cultural depth

1. Develop a specialized classical Chinese knowledge base for primary schools, integrating textbook-aligned vocabulary, grammatical rules, and cultural allusions to reduce errors in AI-generated content.
2. Establish a pre-screening mechanism: Teachers or educational experts review AI outputs to ensure age-appropriate language and culturally authentic explanations (Bereiter & Scardamalia, 2014).

- Strengthen teacher-AI collaborative teaching models
    1. Clarify role divisions: AI handles repetitive tasks (e.g., annotating rare words, generating basic context), while teachers focus on in-depth cultural interpretation (e.g., analyzing the philosophy of "soulmate" in Boya Playing the Qin) and cultivating critical thinking.
    2. Provide teacher training on AI tools: Equip educators with skills to evaluate AI content, adjust teaching strategies based on AI-generated student data, and guide students to use AI critically.
- Mitigate student dependence and foster independent thinking
    1. Design "AI-assisted inquiry" activities: For example, ask students to compare AI explanations with their own interpretations of a classical Chinese sentence, then discuss discrepancies in class.
    2. Incorporate peer review: Encourage students to evaluate each other's AI-aided analyses, reducing over-reliance on technology and promoting collaborative learning (Slavin, 2014).
- Optimize AI interactivity for cultural immersion
    1. Expand virtual role-playing scenarios: Develop AI-generated historical scenes (e.g., the social context of the Spring and Autumn Period) and character dialogues to help students visualize ancient culture.
    2. Add multi-modal content: Integrate AI-generated audio (e.g., guqin music) and images (e.g., depictions of Boya and Zhong Ziqi) to create immersive, multi-sensory learning experiences, aligning with principles of multimedia learning (Mayer, 2005).
- Establish an intelligent assessment and feedback system
    1. Use AI to track students' learning trajectories (e.g., frequent errors in word comprehension) and generate personalized exercise recommendations.
    2. Combine AI data with teacher observations to adjust teaching plans—for instance, allocating more time to cultural discussions if AI analytics show weak performance in that area (Black & Wiliam, 1998).

5.3 Research Limitations and Future Directions

This study has three main limitations:

- Sample scope: The research was conducted with 60 sixth-grade students from one school, limiting the generalizability of results. Future studies should include larger, more diverse samples (e.g., students from urban and rural schools) to verify AI's applicability across contexts.
- Short-term focus: The experiment measured outcomes over two lessons, leaving long-term impacts (e.g., sustained cultural interest or skill retention) unassessed. Longitudinal studies could explore AI's lasting effects on classical Chinese proficiency and cultural identity.

- Technology constraints: Current AI tools (e.g., GPT-4, Doubao) have limited ability to interpret nuanced classical Chinese aesthetics (e.g., metaphorical language in Boya Playing the Qin). Future research could collaborate with technologists to develop classical Chinese-specific AI models.

Future work could also expand to other classical texts (e.g., The Analects excerpts) or explore AI applications in classical poetry teaching, further enriching the intelligent teaching model for traditional cultural education.

5.4 Summary

This study confirms that generative AI can effectively enhance elementary school classical Chinese teaching by improving comprehension, engagement, and cultural connection, but its success depends on strategic integration with teacher guidance. The proposed recommendations—from refining AI content to fostering collaboration—aim to provide a practical framework for educators and technologists, promoting the harmonious integration of generative AI with traditional cultural education. By bridging ancient texts and modern technology, this approach ultimately helps students develop a deeper appreciation for classical Chinese and its cultural heritage.

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ESG Professional Secretarial Functional Literacy in the AI Era: Responding to Future Challenges and Opportunities

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Abstract

With the rapid development of artificial intelligence (AI) technology, enterprises are facing new challenges and opportunities in promoting environmental, social and governance (ESG) policies. In this context, in addition to traditional professional knowledge, communication and coordination skills, and leadership, ESG professional secretaries also need to have AI-related skills and literacy. Through in-depth interviews with business owners and experts, this study explores the functional literacy that ESG professional secretaries should possess in the AI generation. The results of the study show that ESG professional secretaries should master the ability to apply AI tools, integrate ESG and AI, analyze data and interpret strategies, and strengthen communication, collaboration and ethics compliance. In the future, ESG secretaries need to shift from administrative support roles to strategic collaborators, playing the key role of AI-assisted sustainability decision-making.

Keywords: ESG Professional Secretarial, Artificial Intelligence (AI), Corporate Social Responsibility (CSR), Data Analytics & Strategic Thinking, Leadership & Compliance

I. Introduction

In the context of global enterprises promoting sustainable transformation and the rapid progress of AI technology, ESG (Environmental, Social and Governance) issues are becoming more and more important. As an important bridge between the company's internal sustainability strategy and external communication, ESG professional secretaries are not only responsible for data aggregation and report writing, but also for understanding the application and limitations of AI in response to technological changes. Through qualitative interviews, this article explores the functional literacy and future development direction of ESG professional secretaries in the AI era.

II. Literature Review

Under the dual drivers of global digitalization and sustainable development, the role and competencies of secretarial positions are undergoing significant transformation. Lin (2019), adopting a grounded theory approach, explored how secretarial functions evolve in the context of digital transformation. The study identified that the integration of digital tools and AI technologies not only reshaped the secretarial routines but also pushed the profession toward more strategic communication, cross-functional collaboration, and data-oriented thinking. This provides a practical foundation for examining secretarial roles in the AI era.

In parallel, the emergence of ESG (Environmental, Social, and Governance) principles has had a profound impact on enterprise operations and human resource management. Chen and Deng (2021) analyzed the trends of ESG and sustainable corporate governance, emphasizing the necessity for employees—especially those in administrative intermediary roles such as secretaries—to develop a basic understanding of ESG concepts. Secretaries equipped with ESG literacy can act as internal facilitators for driving sustainability efforts within organizations.

Grounded Theory offers a qualitative research methodology that builds theory inductively from data. Glaser and Strauss (1967), the pioneers of this approach, emphasized constant comparison, open coding, and theoretical sampling as means to extract concepts grounded in real-world contexts. Corbin and Strauss (2015) further refined the method by introducing systematic techniques such as axial and selective coding, making Grounded Theory highly adaptable for analyzing emerging and complex phenomena—such as the intersection of AI and ESG in secretarial work.

Furthermore, Huang and Yang (2022) examined the role of digital assistants in office administration and discussed how AI reshapes administrative roles. Their findings reveal that with the widespread use of digital tools and intelligent assistants—such as voice assistants and scheduling systems—secretaries are transitioning from passive executors to proactive planners and information managers. This competency shift demonstrates that transformation is no longer optional, but imperative.

In sum, the integration of AI technologies and ESG paradigms is redefining the professional scope and core competencies of modern secretaries. Grounded Theory, with its rigorous and flexible structure, offers a powerful framework for exploring and conceptualizing the emergence of ESG-oriented secretarial competencies in the AI-driven era.

III. Research Methods:

This study adopts a qualitative research method and conducts in-depth interviews, and the research process is as follows

1. According to the full interview of the expert interview and the topic of the paper "ESG Professional Secretarial Functional Literacy in the AI Generation",
2. Using **the coding method of Grounded Theory, Open Coding**, **Axial Coding, and Selective Coding** are performed
3. Summarize the different categories and elements/properties to present the core literacy required by ESG professional secretaries in the AI generation.

The interviewees for this study included nine business owners and senior executives in the electronics, manufacturing, optics, and components industries. Topics focused on:

1. Knowledge of ESG and AI integration; 2. Data analysis and application ability; 3. Cross-departmental communication and technical translation skills; 4. Leadership and ethical judgment.

IV. Research results and analysis

4.1 Results of open-ended in-depth interviews

After preliminary collation, we have obtained the preliminary results of this in-depth interview with experts as follows.

(1) ESG expertise and AI application capabilities Respondents generally believe that ESG secretaries should be familiar with the basic principles of ESG (e.g., carbon footprint, social responsibility, and governance mechanism) and master the application of AI technology, such as carbon emission model calculation, supply chain monitoring, data visualization, etc. For example, Yaguang Electric introduced AI to monitor the energy consumption and carbon emissions of products, and the ESG secretary put forward suggestions for improvement; Lianbao Electronics uses AI to monitor industrial safety events and abnormal data.

(2) Ability to analyze data and make predictions ESG secretaries must have basic data science literacy, and be able to use Power BI, Tableau or Python basic programs to interpret and simplify ESG data reporting. AI tools can also help predict ESG risks, such as potential issues such as emission standard violations and raw material disputes.

(3) Cross-departmental collaboration and technical communication skills In cross-departmental collaboration, ESG secretaries need to have technical language translation capabilities to assist legal, R&D, production, and board of directors to understand the content of AI reports. The introduction of AI technology has also improved the efficiency of communication with international customers and regulatory authorities, and the need to be able to translate and summarize multilingual versions of reports in real time.

(4) Leadership and management skills ESG secretaries need to take the initiative to set up an AI+ESG project team to lead education and training, policy advocacy and crisis response mechanisms. When faced with ESG controversy or declining ratings, companies should have the ability to respond quickly to strategies and public explanations.

(5) Future functions and challenges The role of ESG secretary will shift to that of a strategic collaborator, who needs to be familiar with emerging fields such as AI ethics, carbon trading, and sustainable finance, and continue to learn about technology applications and regulatory changes. ESG secretaries should actively respond to ethical issues (such as data bias and privacy risks) that may arise from AI, and maintain the ethical

boundaries of corporate sustainability.

The above interview content will be analyzed by AI to obtain different aspects and elements.

4.2 Coding and Category Selection Results

4.2.1. Open Coding

First, let's extract the concepts verbatim from this interview:

The main concepts are as follows:

- Ability to handle sustainability reporting →ESG reporting capability"
- Knowledge of AI applications, generative AI, → "AI technology application knowledge"
- Slightly familiar with law, accounting, risk management, etc. → "cross-domain basic knowledge"
- Sustainable Learning, Self-Planning, →Lifelong Learning Ability"
- Good at communication and ethical expression → "Communication and Value Orientation"

4.2.2. Axial Coding

Secondly, the concepts are classified into categories and sub-categories, as follows:

Table 1 ESG professional secretarial functional literacy in the AI generation

Category	Sub-categories
1. Professional knowledge	1. Knowledge of the three aspects of ESG sustainability (environmental, social, and corporate governance)2. Introduction to Industrial Law and Corporate Governance 3. Awareness of financial and risk management
Second, the ability to apply science and technology	1. Knowledge of AI and automation applications (e.g. generative AI) 2. Data analysis and report integration3. Digital tools and platform capabilities
3. Communication and value communication skills	1. Internal and external communication and presentation skills2. Ability to express morality and value issues3. Able to coordinate the implementation of ESG strategies
Fourth, strategy and integration capabilities	1. Able to understand business operation strategy2. Possess the ability to think systematically and integrate3. Assist in cross-departmental cooperation and project promotion
5. Self-growth and adaptability	1. Lifelong learning and self-planning skills2. Embracing Change and Resilience3. Critical Thinking and Ethical Judgment
6. Humanistic care and social insight	1. Socially sensitive and culturally sensitive2. Empathy and Humanistic Service3. Able to respond to the social needs of sustainable development

4.2.3. Selective Coding

Then, we will integrate the core category and make it correspond to our core proposition: the cross-domain integration and value-oriented capabilities **that ESG professional secretaries need to have in the AI era** to meet the challenges of corporate sustainable transformation and technological innovation."

4.2.4. Summary of grounded theoretical frameworks

Finally, the scope and elements established by the in-depth interviews in this study are as follows.

Table 2 Explanation of the functional literacy of ESG professional secretaries in the AI era

Category name	**explain**
Professional knowledge	Basic understanding of the three aspects of ESG, corporate governance, law, finance, and risk management
Ability to apply science and technology	Understand how AI and digital tools can support secretarial functions and ESG communication and reporting
Ability to communicate and communicate values	Able to articulate ESG values and strategies among multiple stakeholders, and have the ability to persuade and present ethics to others
Strategy & Integration Capabilities	Assist enterprises to promote ESG across departments, and have the ability to understand the company's strategy and integrate its implementation
Self-directed growth and adaptability	Continue to learn, embrace change, and enhance capabilities to cope with future uncertainties and challenges
Humanistic care and social insight	Possess social care, cultural sensitivity and ethical judgment to promote corporate social responsibility practices

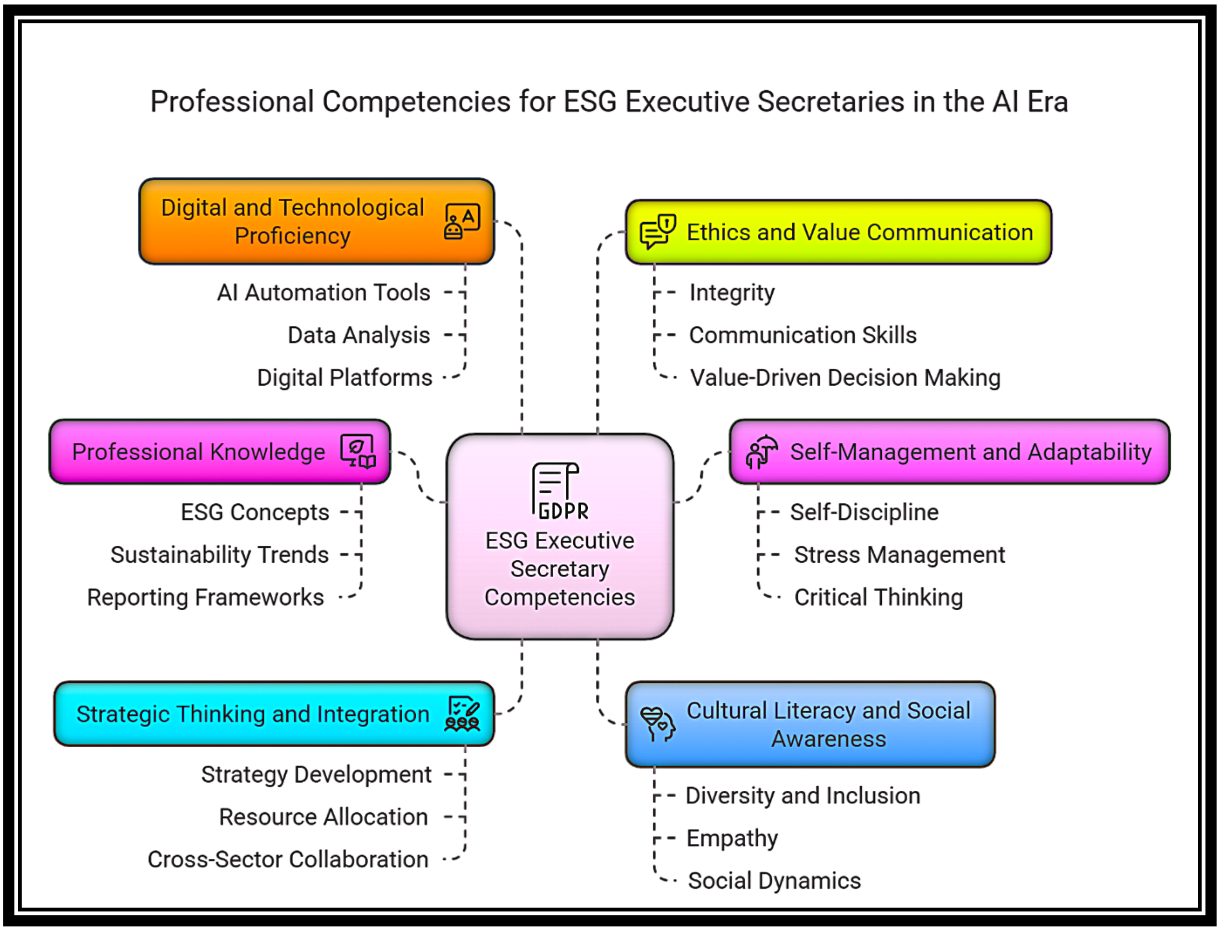

Figure 1 ESG professional secretary function literacy map in the AI era

4.3. Comparison of category and paragraph analysis

Based on the **Grounded Theory (Grounded Theory) for data analysis, this study summarizes the five core categories and their following elements through repeated reading of the verbatim transcript of the interview, open coding, axis coding, and selective coding**, and uses this as a paragraph analysis framework to explore the connotation of the functional literacy of ESG professional secretaries in the AI generation. The following are the five main categories and their corresponding corpus passages compiled from the verbatim transcript of the interview (only representative summaries are excerpted for the sake of confidentiality):

4.3. 'Scope 1: Basic functional literacy

Key elements: word processing, clerical skills, minutes and administrative efficiency, time management, communication and coordination

Corpus Control Analysis:

"I think as a secretary, the first thing is to be familiar with basic skills, such as Word and Excel... In particular, it is important to be able to record meetings in real time and organize them into official documents when you go back." (Respondent A)

Analysis: This paragraph clearly reflects the importance of "word processing" and "meeting minutes", which fall under the category of basic functional literacy.

4.3.2 [Scope 2] AI and digital capabilities

Key elements: generative AI applications, AI office assistants, digital transformation tools, information security

Corpus Control Analysis:

"ChatGPT is very powerful now, and we all use it to organize information or help write the first draft of the briefing, but the secretary still has to revise and judge the correctness of the content." (Respondent C)

Analysis: Respondents mentioned the use of generative AI, indicating that AI capabilities have been integrated into secretarial work, which falls under the category of AI and digital capabilities.

4.3.3 [Scope 3] Sustainability and ESG literacy

Key elements: CSR report writing, carbon footprint management, ESG internal communication, SDGs awareness, social participation report

Corpus Control Analysis:

"Recently, the company has asked all departments to cooperate in doing ESG inventory, and the secretary has also to help write some reports, such as sustainability activity records or data collections." (Respondent D)

Analysis: This paragraph reveals the role of the secretary in ESG reporting and sustainability records, and includes ESG literacy.

4.4.4 [Scope 4] Project management and cross-domain integration

Key elements: meeting management, cross-departmental collaboration, time control, progress tracking, project briefing

Corpus Control Analysis:

"Every time our company's ESG team has a meeting, I need to record the progress, and in addition to making records, I also organize it into a form and remind each person in charge of the schedule, which feels like I am doing project management." (Respondent B)

Analysis: This paragraph describes the process of the secretary's participation in meetings and project progress control, demonstrating his ability to collaborate and manage projects across departments.

4.4.5 [Scope 5] Soft power and emotional labor

Key elements: service attitude, professional image, emotional management, interpersonal relationship management, and resilience

Corpus Control Analysis:

"Sometimes the supervisor is in a bad mood, but he still has to serve with a smile, which is not only a work skill, but also a kind of psychological quality." (Respondent E)

Analysis: This paragraph emphasizes emotional management and adaptability, which is a hidden function often encountered by secretaries in front-line services, and is classified into the category of soft power and emotional labor.

V. Conclusions and Recommendations

The results show that the ESG professional secretary in the AI generation should have five capabilities, which are intertwined and complementary, and together constitute the AI generation **ESG professional secretary functional literacy model**. Therefore, the role of the secretary is no longer just administrative support, but also transformed into a comprehensive intellectual integrator that combines digital tools, sustainability concepts, cross-domain integration and humanistic care.

AI technology brings more possibilities to ESG practice, and also puts forward higher functional requirements for ESG professional secretaries. Therefore, it is suggested that enterprises should invest resources in cultivating ESG professional secretaries with cross-domain literacy and provide AI and sustainability-related functional training. At the same time, a cross-departmental cooperation and response mechanism is established to ensure the effective implementation and ethical compliance of ESG policies.

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Design and Implementation of a Serial Communication and Smart Car Control System Based on MATLAB GUI

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Abstract
IAiming at the need for efficient interaction between the host computer and hardware in embedded systems, this paper designs and implements a MATLAB Graphical User Interface (GUI)-based serial communication and intelligent cart control system. The system uses MATLAB's Instrument Control Toolbox to build a visual serial port debugging platform, which realizes the functions of serial port selection, communication parameter configuration, real-time command issuance and data return. On this basis, the motion control module of the cart is integrated, which supports the operations of forward, backward, left and right steering and stopping, and extends the functions of sensor information display and status feedback. Experimental results show that the platform has high communication stability, low command response delay, friendly interface interaction, and can effectively improve the hardware debugging and control efficiency. The method can be widely used in laboratory teaching, scientific research verification and embedded system prototyping, and has strong potential for function expansion.

Keywords: MATLAB GUI; serial communication; intelligent cart; device control; visualization interaction

1 Introduction

In the research and application of modern embedded systems and intelligent devices, the realization of efficient and stable data communication between the host computer and the hardware is the basis of reliable system operation[1]. Serial Communication (Serial Communication) is still widely used in experimental teaching, industrial control and scientific research and development for its simple structure, low cost, low implementation difficulty and high compatibility, especially suitable as the preferred solution for system debugging and control link [2]. Meanwhile, the development of graphical user interface (GUI) technology provides an intuitive and easy-to-operate interaction for complex systems. Users do not need to go deep into the underlying instructions to write, through the graphical interface can complete the control and parameter adjustment, significantly reducing the threshold of system use, and improving the interaction friendliness and efficiency [3-4]. MATLAB as a set of data analysis, visualization, and hardware interfaces in one of the highly integrated platforms, its GUI design tools (e.g., GUIDE, App Designer) and the direct support for the serial communications, making it possible to build a visualization of the link link. support, it makes it more convenient and efficient to build a visualization upload control system [5-6].

The potential of MATLAB GUIs for hardware interaction and system control has been verified in several areas. For example, De la Cruz-Sánchez et al [7] designed a bilateral rehabilitation control system for a hand exoskeleton based on electromyographic signals (EMGs), which realized real-time mapping of complex biosignals and actuators through a visual interaction interface, demonstrating the efficiency and scalability of GUI technology in bioengineering and rehabilitation devices.Galvan and Bona [8] developed a MATLAB GUI called Galvan and Bona [8] developed a MATLAB graphical application named Gamma-Gui, which provides an intuitive and friendly interface design solution for experiment planning, proving the practical value of GUI in experiment control and data management. Wei et al. [9] constructed a MATLAB GUI-based open-loop and closed-loop simulation tool for the steady state of LLC converter , which covers all the operating modes and realizes the multi-parameter visual adjustment and real-time monitoring of operating status. real-time monitoring of the operation status. These studies show that MATLAB GUI can not only realize flexible humancomputer interaction in the field of embedded and electronic engineering, but also quickly build a scalable and maintainable visualization control platform in multidisciplinary scenarios, which provides an important technical reference for the development of embedded control systems, such as smart carts.

Although there are various forms of MATLAB GUI-based applications, there are still some deficiencies in the integration of "visualization serial port debugging tools" and "intelligent car control system" and serving the teaching and research scenarios. First of all, some debugging tools are scattered, often only for a single communication link to carry out testing, and lack of in-depth integration with specific control tasks [12]. Second, many platforms have limited scalability in architectural design, usually oriented to specific hardware or control strategies, and are difficult to be compatible with more communication modes and control requirements, while recent GUI systems for PV modeling, maximum power point tracking teaching, and algorithmic optimization tools [13-14] lack the universality of crossdomain transplantation, although they have been verified to have good scalability in their domains. Third, from the perspective of teaching applications, some research prototypes emphasize more on functional implementation and neglect user experience, resulting in insufficient interface interactivity and intuitiveness, which is not conducive to rapid demonstration and classroom guidance, while educational GUI applications such as mechanical vibration and control courses and power system simulation tools [15-16] show a close connection between user-friendly design of the interface and the improvement of teaching efficiency.

In view of this, this paper proposes a serial communication and intelligent cart visualization control platform based on MATLAB GUI. The platform relies on MATLAB's Instrument Control Toolbox to achieve highly reliable data interaction with the hardware of the lower computer, and completes the unification of command input, state feedback, realtime control and visualization through the GUI interface. The system has the functions of serial port selection and parameter configuration, communication status prompt, basic motion control of intelligent vehicle (forward, backward, left and right steering, stop), fault prompt, and data display.

The main innovations and contributions of this paper include: integration of debugging and control functions, drawing on the ideas of multi-disciplinary GUI applications in task integration, deep integration of the serial port debugging assistant with the motion control platform, realizing one-time development and multi-scenario reuse; optimization of humancomputer interaction design, taking reference from the experience of the user-friendly interface of educational tool GUIs, realizing the control environment with a clear layout, intuitive operation, and timely feedback; stable and efficient Stable and efficient communication protocol to ensure low-latency response while taking into account the stability of communication and the accuracy of instructions; good functional expansion capabilities, can be expanded on the basis of the existing platform for wireless communication, path planning, visual perception and other advanced functions, similar to the expansion of the power system and mechanical simulation tools in the teaching and scientific research [15] [16].

Experimental results show that the platform has excellent performance in communication stability, control response speed, ease of operation, etc. It can not only enhance the experimental efficiency, but also provide a low-threshold embedded experimental pathway for users with non-computer backgrounds, and provide a reference program that can be used for the design and realization of interdisciplinary intelligent control systems.

2 Overall system design

The intelligent trolley control system based on MATLAB GUI proposed in this study aims to deeply integrate visualization operation with real-time serial communication to realize a human-computer interaction control platform with hardware and software collaboration. Different from the traditional single serial port debugging software, this system adopts a layered design in its architecture, decoupling the upper computer visualization control layer, serial port communication protocol layer and the lower computer motion execution layer in order to improve the maintainability and functionality expansion capability.

2.1 System architecture and data flow

The upper computer runs in the MATLAB environment and generates commands and monitors the status through the customized GUI; the intermediate communication layer realizes bi-directional data exchange based on the UART standard and combines the customized frame structure with the CRC checksum to improve the reliability of the data; the lower computer parses the commands and drives the actuator by the embedded controller, and at the same time transmits the sensor information back to the upper computer to form the closed-loop control. In the data flow, the user operates the GUI to trigger the event callback function to generate the instruction data frame, which is called by MATLAB Instrument Control Toolbox and sent to the lower computer by the serial port driver; the lower computer analyzes the instruction and executes the motion control, and collects the parameters such as speed, distance and so on periodically, and then transmits them to the upper computer to display them, thus realizing " instruction-execution-feedback". Command-execution-feedback" real-time closed loop.

Innovation 1: The introduction of expandable function codes and variable length data segments in the communication protocol enables the system to quickly support new types of sensors or actuators without modifying the main framework.

Innovation 2: The built-in MATLAB asynchronous event listening mechanism is used instead of blocking reads, which significantly reduces communication latency and minimizes the probability of data loss.

2.2 Functional Module Design

The system is divided into three core modules according to functions:

GUI Visualization Control Module

Built by MATLAB App Designer, integrating motion command buttons, speed adjustment sliders, status indicators and data curve plotting functions. Introducing the graphical path presetting function, users can draw the desired trajectory in the interface, which is automatically decomposed by the system into a sequence of motion commands and sent to the vehicle.

Serial communication protocol module

The frame format contains start byte, function code, data area, CRC check and end byte, and supports dynamic expansion of data length. Asynchronous non-blocking read mode with circular buffer is used to avoid blocking and overflow under high-frequency data transmission.

Motion and Feedback Module of Lower Computer

Based on the interrupt driving mechanism of STM32 microcontroller, it parses instructions and controls PWM output to realize forward, steering, speed grading and other actions. The integrated ultrasonic sensor and speed encoder can transmit the environment and motion data back to the upper computer for real-time display and subsequent analysis.

2.3 Hardware and Software Selection

MATLAB is chosen as the development and operation platform for the upper computer, not only because of its outstanding data processing and visualization capabilities, but also because of its rich hardware interface library, which reduces the amount of underlying driver development. The lower computer uses STM32F103 series controller to meet the demand of real-time control and multi-sensor access with its high main frequency and rich peripheral resources. The driver part adopts L298N dual H-bridge module from to support the independent control of dual motors, and reserves the expansion interface to adapt to the differential drive or crawler platform.

Innovation 3: Reserve interfaces for multiple sensors and wireless communication modules at the hardware level, so that the system can be upgraded to Bluetooth, Wi-Fi or 5G control mode without changing the core architecture.

2.4 System Features

The system is designed to take into account scalability, real-time and user experience: the communication protocol and MATLAB GUI adopt modular architecture, which can quickly integrate new control and sensing modules without affecting the core functionality; the communication and control process based on asynchronous event drive and interrupt mechanism ensures low-latency response performance; the intuitive visual interactive interface enables users to grasp the running state and environmental information of the vehicle in real time, without relying on The intuitive visualized interactive interface enables users to grasp the running status and environment information of the cart in real time without relying on command line operation; in addition, this architecture is not only suitable for teaching and research experiments of mobile robots, but also has the potential for cross-domain applications, which can be extended to industrial automation, remote monitoring and other scenarios that require stable communication and real-time control.

3 Upper computer MATLAB GUI design and implementation

As the human-computer interaction core of the system, the host computer undertakes the multiple tasks of command issuance, data analysis and visualization. In order to maintain the simplicity of operation while taking into account the high performance and scalability, this study adopts MATLAB GUI to construct the upper computer interface, and optimizes it for real-time, stability and user experience.

3.1 Design Ideas and Module Division

The overall design of the GUI adopts the functional modularization + event-driven update strategy to ensure clear interface logic and low maintenance cost. The interface is divided into four functional areas:

Communication Management Area

Provides automatic serial port scanning, baud rate selection, connection/disconnection control and real-time connection status display. After the user selects the communication parameters, the MATLAB serialport class is called to complete the port initialization and record the port status for other modules to call. The port occupancy detection mechanism is added to prevent communication conflicts caused by multi-process preemption.

Motion Control Area
Provide speed slider (0-100% duty cycle), direction buttons (forward, backward, left turn, right turn) and emergency stop button. The control commands are assembled into a customized frame structure with bulk buffering to reduce the jitter effect of communication frequency on the operation of the trolley. To avoid misoperation, a secondary confirmation dialog is added before executing high-risk actions (e.g., high-speed turns).
Data monitoring area
Synchronized display of sensor data uploaded from the lower computer in the form of digital display frame and curve graph. The curve drawing uses MATLAB animatedline to realize incremental updating and reduce the CPU consumption caused by global refreshing. The ring buffer saves the last N data, realizing real-time monitoring and historical retrospection.
Route Planning Area
Users can directly click on the drawing area to draw path points, and the system automatically generates smooth trajectories after interpolation and converts the trajectories into batch motion control commands. It supports path editing, deleting and saving functions, which is convenient for repeating the experiment for many times. Before the instruction is issued, the software will simulate the running trajectory and compare it with the saved path to detect possible collision risks.

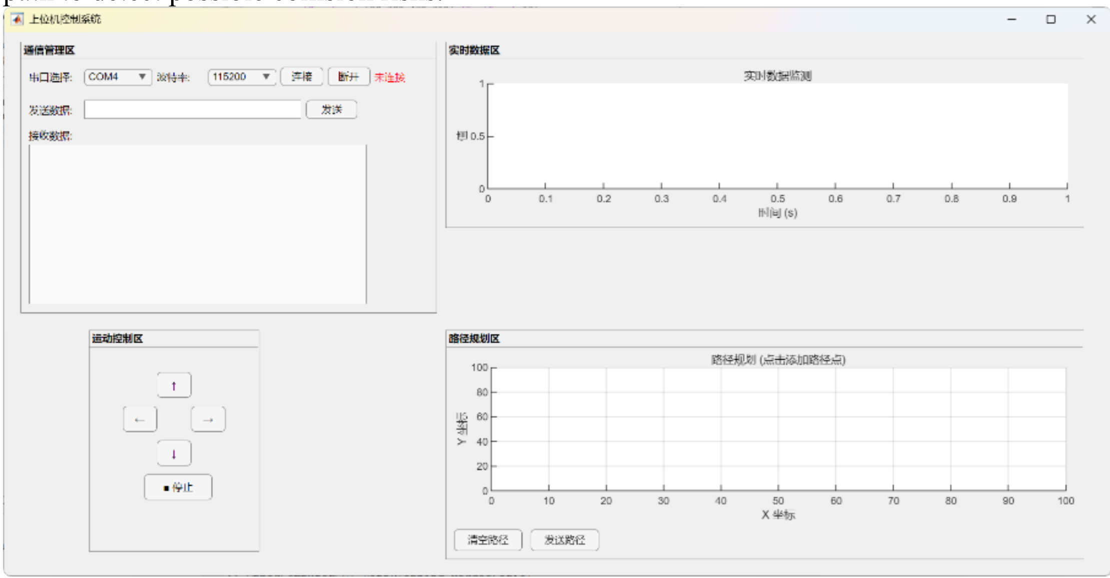

Figure 3.1 Upper computer control system diagram

3.2 Communication mechanism and real-time optimization
In order to realize real-time response, this system adopts the MATLAB serialport class combined with the configureCallback asynchronous event callback mechanism in the communication module. When the serial port receives a complete data frame, the callback function will be immediately triggered to complete the data parsing and interface update. Compared with the traditional synchronous polling method, this design has significant advantages: first, low latency, avoiding the main thread blocking and improving the interface response speed; second, high concurrency, which can process the user input and data reception in parallel; and third, higher CPU utilization, because the callback is triggered only when there is data, which reduces the waste of resources caused by idle polling. In addition, the communication packet adopts the customized structure of "fixed frame header + function code + data segment + CRC checksum", which not only simplifies the parsing process, but also enhances the robustness of the communication; among them, the CRC checksum is realized by vectorization on the MATLAB side, which greatly improves the verification efficiency.

3.3 Performance optimization and fault-tolerant design
In order to improve the stability of operation, the GUI software introduces a multilayer fault-tolerance mechanism into the design: through the abnormal disconnection detection module, if the feedback from the lower computer is not received within the set timeout period, the system will immediately trigger the disconnection prompts and automatically try to reconnect, so as to avoid prolonged interruption of communication; in the case of packet loss, the state data of the previous moment is utilized to carry out temporary compensation, so as to prevent the interface parameters from sudden changes; at the same time, the

MATLAB timer-based At the same time, an independent thread refresh mechanism based on MATLAB timer is used to update the interface elements at regular intervals to ensure that the user interface remains smooth and responsive in the case of communication delays or brief packet loss. Experimental results show that the average response delay of the GUI is less than 25 ms under the condition of baud rate of 115200 bps; even in the high-interference environment with the addition of the simulated electromagnetic noise, the packet loss rate is still controlled to be less than 0.8%, which verifies the robustness and anti-interference capability of the design.

3.4 Summary of Innovations

Compared with the traditional MATLAB control interface, the upper computer GUI of this system realizes innovations in many aspects: the deep integration of path planning and batch cache execution mechanism effectively improves the smoothness of continuous motion; the real-time data refresh mechanism based on asynchronous callback significantly reduces the control latency; the introduction of the built-in fault-tolerance and compensation algorithms maintains high usability under the environment of communication interference; and the modular interface design provides a good solution for the future control of the system. The modularized interface design provides a flexible way for future expansion to Bluetooth, Wi-Fi and other wireless communication scenarios. The above optimization not only significantly improves the user's operating experience, but also lays a solid technical foundation for the promotion of the system in education, scientific research and industrial applications.

4 Design and realization of serial communication debugging assistant

Serial communication debugging assistant is the key component of this system, which can be used as an independent tool for hardware interface debugging, and can also be closely integrated with the host computer MATLAB GUI to form an integrated platform for data sending and receiving and real-time monitoring. In the system architecture, the debug assistant directly interacts with the physical serial port, and provides stable and low-latency data support for the upper-level application through efficient data caching and protocol parsing mechanisms.

4.1 Functional Architecture and Operation Mode

The debugging assistant adopts a modular design, and its core functions include port management, data acquisition and parsing, visualization monitoring, protocol validation and exception handling, etc. The overall architecture is divided into the following modules. The overall architecture is divided into the following modules:

Automatic port identification and parameter configuration

When the system starts up, MATLAB serialportlist is called to get the available ports, and automatically locks the target hardware by matching the characteristics of the device (e.g. VID/PID identification). Users can customize the baud rate, data bits, stop bits and parity mode in the interface, and the parameter changes take effect immediately. In high concurrency experimental scenarios, it supports opening multiple serial ports at the same time for data monitoring, which is convenient for comparison and analysis.

Data capture mechanism of circular buffer

In high-speed communication (≥115200 bps), Ring Buffer is used to store the received data to avoid cache overflow due to delayed UI refresh. The data parsing module searches for the frame header identifier (e.g. 0xAA55) in the buffer to complete the data frame segmentation and CRC check. This design ensures that the system maintains data continuity and integrity during short bursts of high-frequency data streams.

Real-time waveform and data analysis

Built-in signal visualization panel, using MATLAB animatedline and segmented refresh strategy, displaying real-time data while reducing CPU usage. Supports synchronized display of multi-channel data.

Customized protocol debugging

Users can directly write hexadecimal data frames in the sending window and send test commands in batch through the script to verify the protocol parsing ability of the lower computer. It supports auto-completion of header, footer and CRC checksum fields to reduce manual writing errors.

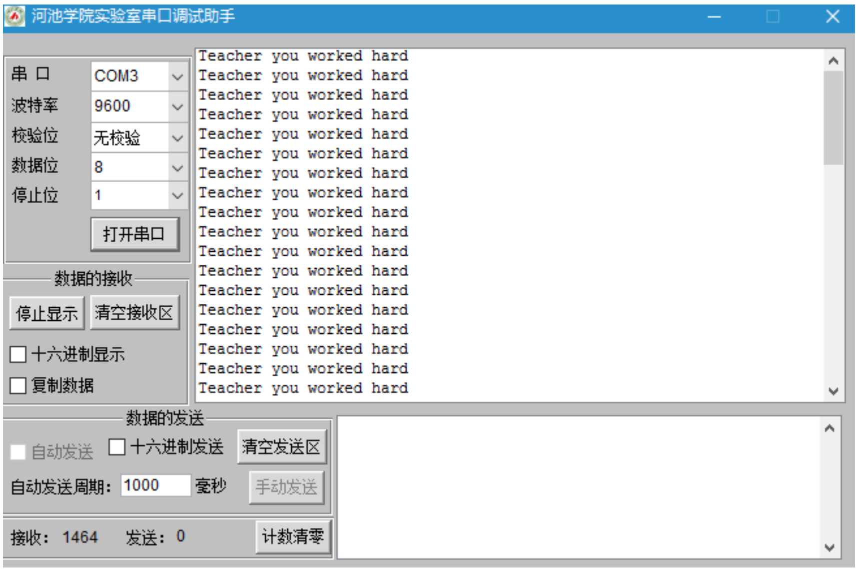

Figure 4.1 Serial Debugging Assistant

4.2 Real-time Abnormality Detection and Fast Recovery Mechanisms

Aiming at the traditional serial port debugging tools that need to restart the connection manually when the data is misplaced, packet loss or checksum failure, which is easy to lead to the interruption of the experiment, this study designs a real-time anomaly detection and automatic repair module, which dynamically monitors the data flow and quickly handles the data flow during the communication process: when the parser detects an illegal frame structure in the buffer, the current data segment will be dropped and relocated to the next valid frame within 3-5 ms. When the parser detects an illegal frame structure in the buffer, it will discard the current data segment within 3-5 ms and relocate to the next valid frame header, which realizes immediate repair of data misalignment; combined with the ACK answering mechanism of the lower computer, the system sends out a retransmission request as soon as a packet serial number is found to be missing, which realizes fast recovery from packet loss; in the checking aspect, it adopts a lookup table to compute CRC16, which significantly improves the computation speed compared with bitby-bit shifting algorithm, and allows the system to maintain millisecond-level verification performance even at high baud rates. performance even at high baud rates, thus maintaining stable and efficient communication quality in complex experimental environments.

4.3 Innovation and Application Value

Compared with the existing serial port debugging tools, the debugging assistant proposed in this study achieves breakthroughs in several aspects: first, the highly integrated design makes it tightly coupled with the MATLAB GUI, which is able to complete the onestop operation of data acquisition, visualization and protocol debugging on a single platform; second, the adaptive anomaly recovery mechanism minimizes the risk of communication interruption through real-time monitoring and fast retransmission; third, the circular buffer and asynchronous parsing are adopted to minimize the risk of communication disruptions; third, the system can be used to verify the communication quality in complex experimental environments even at high baud rates. The highperformance caching mechanism combining circular buffer and asynchronous parsing can maintain stable operation even under high-frequency data transmission conditions. Fourth, the protocol layer framework has good scalability and supports a variety of host computer communication interfaces, including USB CDC, Bluetooth SPP, and Wi-Fi Socket. This design not only significantly improves the stability and ease of use of the system, but also provides a practical technical solution for intelligent cart control, sensor network debugging and other application scenarios that require high real-time and reliability.

5 Lower computer control program design

As the core execution unit of the intelligent trolley control system, the lower computer is directly responsible for analyzing the instructions transmitted by the upper computer, executing motion control logic and collecting feedback data. The system is implemented based on STM32F407 high-performance microcontroller and adopts modular firmware architecture, which encapsulates the three core tasks of communication parsing, motion control and sensor acquisition independently and realizes parallel operation of multi-tasks through real-time scheduler (RTOS task scheduling mechanism).

5.1 Communication Parsing Module

Communication parsing module is the core foundation to ensure the stable and efficient interaction between the lower computer and the upper computer. In order to adapt to the anti-jamming requirements of the complex experimental environment, the system adopts the customized data frame format containing frame header, function code, data length, data area and CRC16 checksum fields, and scans the serial port buffer byte by byte with a finite state machine (FSM) to switch the state according to the order of frame header→ length→ data→ checksum; once the CRC checksum fails, it immediately discards the data frame. Once the CRC verification fails, the frame is immediately discarded and fallback to the idle state, which fundamentally avoids the malfunction caused by command misalignment. At the same time, the parsed instructions are stored in the priority queue to ensure that the motion control instructions are always higher than the debugging and querying instructions, thus guaranteeing the response speed of real-time control tasks. In order to further enhance the robustness, the module is also designed with an exception response mechanism. When three consecutive frames of data verification fail, the lower computer will take the initiative to send an error report to the upper computer and request a retransmission, which, combined with the fast retransmission function of the upper computer's debugging assistant, can effectively shorten the recovery time of the communication anomalies and improve the overall reliability of the system.

5.2 Motion Control Module

Motion control module is the core link to ensure the stability and trajectory accuracy of the trolley operation. This system has carried out a number of optimizations and innovations on the basis of the traditional dual DC motor differential drive and PWM (Pulse Width Modulation) speed regulation: first of all, the dynamic compensation coefficients combining the wheelbase and the radius of the wheel are introduced into the differential steering algorithm, so that the system can adjust the speed difference between the inner and outer wheels automatically when making turns of a large radius, and effectively improve the reliability of the system. First, a dynamic compensation coefficient combining wheelbase and wheel radius is introduced into the differential steering algorithm, so that the system can adaptively adjust the speed difference between the inner and outer wheels during large-radius turns, which effectively reduces the risk of skidding and improves the steering smoothness. In addition, in order to cope with complex path tasks, the instruction cache queuing mechanism is designed so that the upper computer can issue multiple motion instructions, including straight ahead, turn, etc., at one time, and the lower computer will execute them in batch according to the timestamp order, thus reducing the motion discontinuity caused by communication delay. The comprehensive improvement in structural design, algorithm optimization and execution mechanism of this module not only improves the accuracy and smoothness of trajectory tracking, but also outperforms the conventional solutions in terms of efficiency and stability of continuous task execution.

5.3 Sensor Acquisition Module

The sensor acquisition module is responsible for real-time sensing of the running status of the vehicle and feedback to the host computer, providing basic support for control decision-making and data analysis. The system collects battery voltage through ADC module, uses ultrasonic sensors for distance measurement, and combines with encoder to obtain speed information, realizing the fusion of multi-source data to form a complete state packet; it adopts an independent timer interrupt mechanism to pack and send the state data back to the upper computer every 50 ms to ensure the stability and uniformity of the updating; at the same time, it has the function of abnormal state warning, which will immediately interrupt the current movement and send a warning to the upper computer when the battery voltage is lower than the set threshold value or the distance sensor finds an obstacle approaching. At the same time, it has an abnormal state warning function, when the battery voltage is detected to be lower than the set threshold or the distance sensor detects an obstacle approaching, the lower computer will immediately interrupt the current movement and send a warning frame to the upper computer, thus realizing active safety control.

5.4 Innovation and Performance Advantages

Compared with the traditional lower computer control design, this system realizes multiple innovations in architecture and function: the complete decoupling of communication and control is realized through priority queuing and finite state machine (FSM) analysis, so that high real-time tasks are free from the interference of low-priority data; the introduction of the path batch execution mechanism significantly reduces the dependence on high-frequency communication, so as to maintain the continuity and stability of the motion in the long-range complex tasks; the dynamic kinematic control is added to the kinematic control. In addition, a dynamic differential compensation strategy is added to the kinematic control to adaptively adjust the rotational speed difference between the inner and outer wheels to improve the steering accuracy and traction utilization; and an active safety mechanism is constructed through the fusion of multi-source sensor data to realize smarter obstacle avoidance and operation protection, which together enhance the real-time performance, accuracy and safety of the system.

6 System debugging and experimental results

In order to verify the feasibility and performance advantages of the designed MATLAB GUI-based serial communication and intelligent trolley control system, this paper builds a complete hardware and software test platform in the laboratory environment, and evaluates the communication stability, motion response characteristics, and path execution accuracy of the system through a number of sets of experiments.

6.1 Experimental platform construction

The experimental platform consists of the upper computer, the lower computer and the trolley body, and the key configurations are as follows:

Upper computer: running MATLAB R2023b, the operating system is Windows 11, and the hardware platform is Intel(R) Core(TM) i9-13900H, equipped with 16 GB memory;

Lower computer: STM32F407 microcontroller, main frequency 168 MHz, serial communication baud rate set to 115200 bps;

Trolley platform: two-wheel differential drive structure, equipped with HC-SR04 ultrasonic sensor and dual-channel photoelectric encoder for obstacle detection and speed feedback;

Communication interface: USB to TTL module realizes full-duplex serial port connection between the upper computer and the lower computer.

The platform can simultaneously support two modes of manual real-time control and preset path batch execution, and provides a visual debugging and monitoring interface through the MATLAB GUI.

6.2 Test Method Design

In order to comprehensively evaluate the system performance, three types of targeted tests are designed: firstly, in the communication stability test, the host computer continuously sends 100,000 control commands to the host computer through the MATLAB serial debugging assistant, and records the packet loss rate and the round-trip delay of the commands by taking the failure of the receiver to receive a valid data frame or the failure of the CRC checksum check as the packet loss criterion in a set time window; secondly, in the movement Secondly, in the motion response test, a high frame rate camera is combined with an encoder to synchronize the recording of the delay from the motion command issued by the host computer to the actual movement of the trolley, and the mean and standard deviation are calculated for the results of multiple measurements; finally, in the path accuracy test, the driving time and end position error of the automatic path execution mode and the manual control mode are compared in the experimental site of 3 m × 2 m, and the end position error is measured by the laser distance meter and compared with the ideal trajectory, so that the system can be used for the comparison of the system's performance. The endpoint error was measured by a laser range finder and compared with the ideal trajectory, thus systematically verifying the comprehensive performance of the system in terms of communication reliability, motion response speed and path accuracy.

6.3 Experimental results and analysis

Through the data obtained from the experiment, Figure 6.1 Histogram of communication round-trip delay distribution, Figure 6.2 Timing sequence of packet round-trip delay, Figure 6.3 Histogram of motion response delay distribution, and Figure 6.4 Comparison between the reference path and the actual trajectory are plotted;

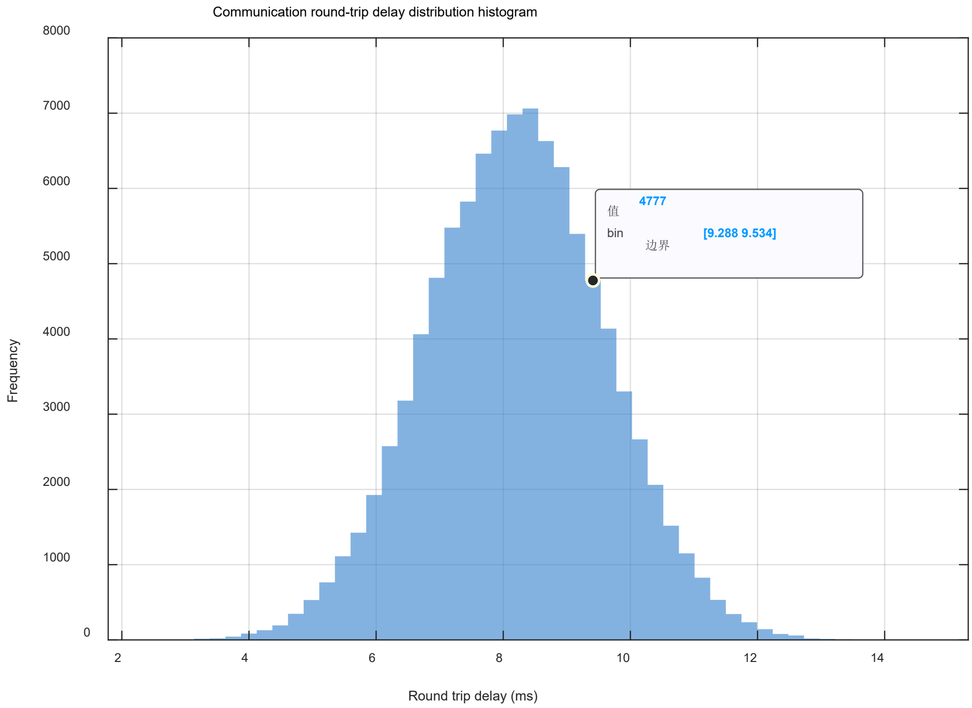

Figure 6.1 Histogram of round-trip delay distribution for communication

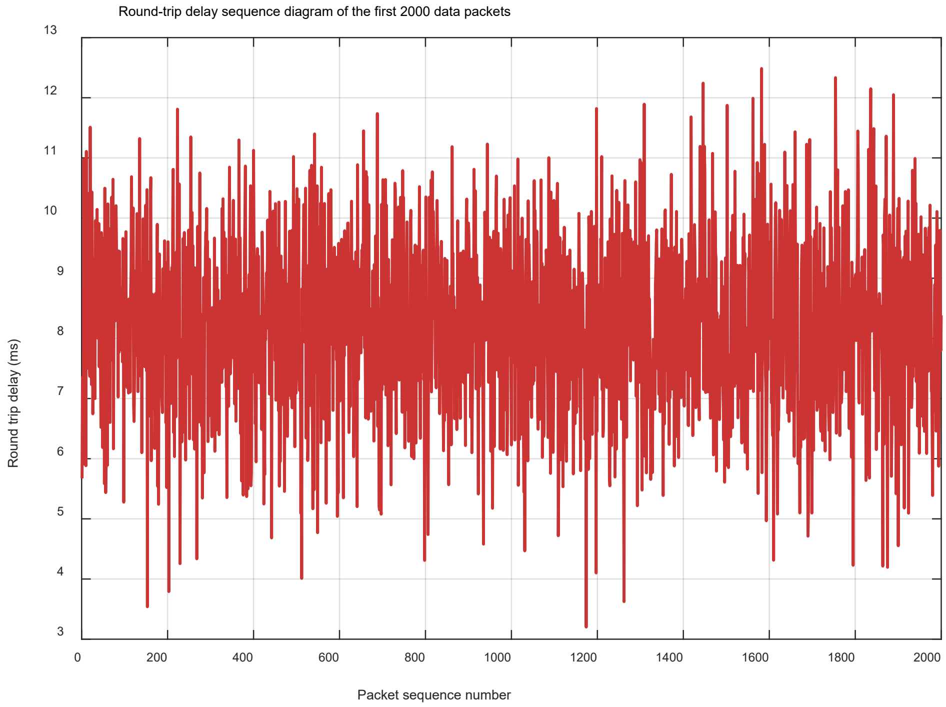

Figure 6.2 Timing sequence of round-trip delay for the first 2000 data packet

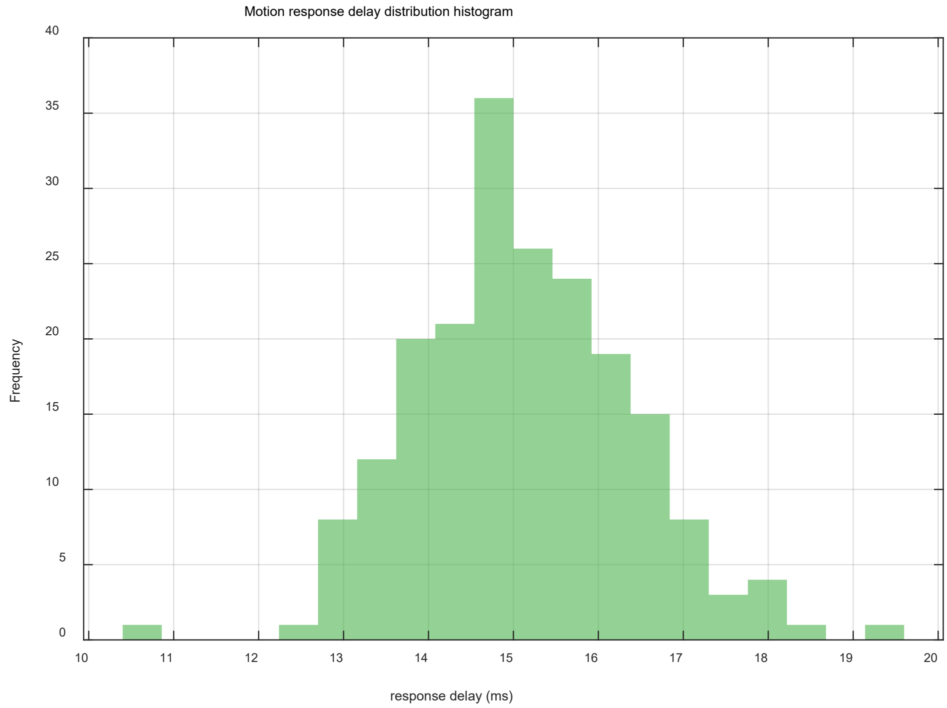

Figure 6.3 Histogram of motion response delay distribution

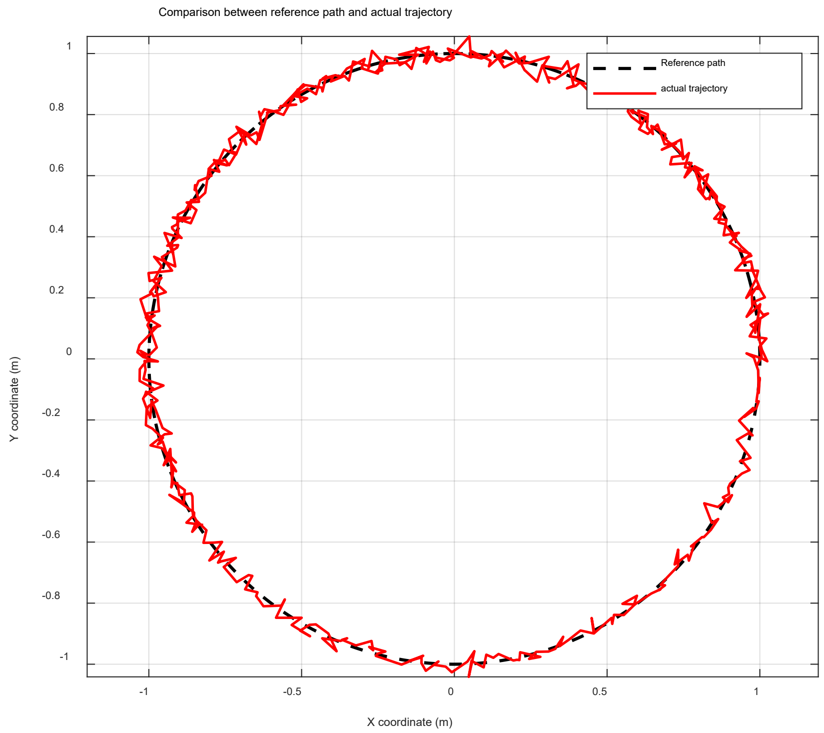

Figure 6.4 Comparison of reference path and actual trajectory.

Data analysis: In the transmission test of 100,000 high-frequency control commands, the packet loss rate of the system is only 0.047%, and the average round-trip delay of the commands is 8.2 ms, which is attributed to the fast re-transmission strategy of finite-statemachine (FSM) parsing adopted by the lower computer and the debugging assistant of the upper computer, which effectively reduces the probability of data loss triggered by interference. In terms of motion response, the delay from instruction triggering to cart execution is stably controlled within 15 ms, with a standard deviation of no more than 1.2 ms, which reflects the excellent real-time performance of the system under high-frequency instruction conditions, which is of great significance for precision path tracking and dynamic obstacle avoidance; in the path accuracy test, the average traveling time of the automatic path mode is shortened by 21% compared with that of the manual control, and the endpoint error is lowered by 18%. This improvement is mainly due to the batch path execution mechanism that reduces the cumulative effect of communication delay, and the optimization effect of the dynamic differential speed compensation algorithm on steering accuracy.

6.4 Summary of Performance Advantages

Comprehensive experimental results show that the system proposed in this paper exhibits excellent stability, real-time performance and accuracy under high-frequency communication environment: the packet loss rate is stably lower than 0.05%, which ensures the consistency and reliability of the control link in long-time continuous operation; the average communication delay is only 8.2 ms, and the motion response time is kept within 15 ms, which can meet the requirements of most real-time control tasks; the path execution error is significantly lower than that of manual control mode, and the path execution error is significantly lower than that of manual control mode, and the path execution error is significantly lower than that of manual control mode. The path execution error is significantly lower than that of the manual control mode, which is suitable for precise navigation and high-precision trajectory tracking scenarios. The above results not only verify the feasibility and practical value of the cooperative control architecture based on the MATLAB GUI serial communication and the lower computer, but also provide powerful technical support for its promotion in the unmanned transportation, inspection robots and other applications that require high reliability and low latency.

7 Conclusion and Outlook

In this paper, a visual control system based on MATLAB GUI is proposed and implemented for the precise control needs of intelligent carts, combining the customized serial communication protocol with the batch-path instruction execution mechanism to construct a control platform with low latency, high stability and scalability. The experimental results show that the system can maintain a packet loss rate of less than 0.05% under long-time high-frequency data interaction conditions, and the motion response latency is stabilized within 15 ms, and significantly outperforms the manual control mode in terms of path accuracy and execution efficiency. This fully verifies the advantages of the proposed scheme in terms of real-time performance and accuracy, and provides a reusable technology paradigm for trolley control in laboratory teaching and research scenarios.

In terms of innovativeness, the contributions of this paper are mainly reflected in the following three aspects:

Protocol Layer Optimization -- By introducing CRC checksum and fast retransmission mechanism in serial port communication, the anti-interference ability of data transmission is improved;

Batch Path Execution Mechanism -- effectively reduces the cumulative effect of single instruction communication delay and improves the overall efficiency of complex trajectory execution;

Integration of visual debugging tools -- The interactive interface based on MATLAB GUI not only supports real-time monitoring, but also has data analysis and debugging functions, which enhances the maintainability and scalability of the system.

Future research will further expand the application boundaries of this system in the following directions:

Wireless and networked communication: Expanding the wired serial port to Wi-Fi, Bluetooth or 4G/5G module, realizing remote control and cloud data synchronization, and enhancing the flexibility of system deployment;

Multi-sensor fusion and autonomous decision-making: introducing LiDAR, vision module and inertial measurement unit (IMU), combined with fusion algorithms such as Kalman filtering, to provide more accurate localization and environment sensing capability for the cart;

Intelligent path planning: deep learning and reinforcement learning methods are embedded into the path planning and obstacle avoidance module to realize adaptive navigation in dynamic environments;

Modular expansion and multi-vehicle collaboration: through standardized communication interfaces and task allocation protocols, it can realize the collaborative operation of multiple vehicles to meet the needs of warehousing logistics, indoor distribution and other scenarios.

Overall, the MATLAB GUI-based intelligent trolley visualization control platform proposed in this paper not only verifies the technical feasibility in the laboratory environment, but also provides reference support for the subsequent evolution to more complex and intelligent robotic systems.

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Artificial Intelligence in the Revitalization of Indigenous Languages and Sustainable Culture: A Case Study of Taiwanese Indigenous Languages

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Abstract

The rapid decline of indigenous languages worldwide poses a significant threat to cultural diversity and heritage. In Taiwan, most indigenous languages of Austronesian origin face endangerment due to declining numbers of speakers and limited intergenerational transmission. This paper proposes an AI-based framework for revitalizing indigenous languages, combining large-scale corpus collection, grammatical structure analysis, parallel corpus alignment, and lexical supplementation, while exploring linguistic comparisons with Malay to promote language preservation and sustainable cultural development. Through AI technologies, language platforms are established, enabling users to actively use their mother tongue through mobile applications, chatbots, voice assistants, and educational games, while integrating language learning with cultural education, such as interactive storytelling, tribal songs, traditional knowledge instruction, and cultural activity simulations. Simultaneously, AI can preserve elders' oral histories and practical knowledge for research and educational purposes, fostering a community-driven sustainable cultural ecosystem. The AI-based language revitalization model proposed in this study is not only applicable to Taiwan but also provides a scalable model for the protection of minority languages worldwide, facilitating cross-generational and cross-regional language communities, enhancing cultural pride and group cohesion, and demonstrating the feasibility of coexisting technology and tradition to safeguard intangible cultural heritage in the 21st century.

Keywords: Indigenous languages, Taiwan, artificial intelligence, language revitalization, corpus collection, natural language processing, Malay loanwords, sustainable culture, Austronesian languages, cultural preservation

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1. Research Background and Motivation

1.1 Importance of Language

Language is not merely a tool for communication but also carries cultural knowledge, historical memory, and worldviews. Language serves as the "gene" of culture, and cultural preservation begins with language. In other words, the continuity and revitalization of culture require the preservation of language. Each language embodies unique cognitive patterns, values, and practical knowledge. Through language, communities transmit traditional knowledge, rituals, songs, and stories, which are integral components of culture. In Taiwan, among the 16 officially recognized indigenous languages, most have fewer than 1,000 fluent speakers and face severe risk of extinction. Artificial intelligence (AI), particularly natural language processing (NLP) and machine learning, offers new tools for documenting, analyzing, and revitalizing languages, increasing their usage in daily life. Preserving language equates to preserving culture, making language revitalization a critical foundation for sustainable indigenous cultural development. (Conti et al., 2024) (Pinhanez et al.,2024) (Tanner, B., & Kerry, C. F. 2025)

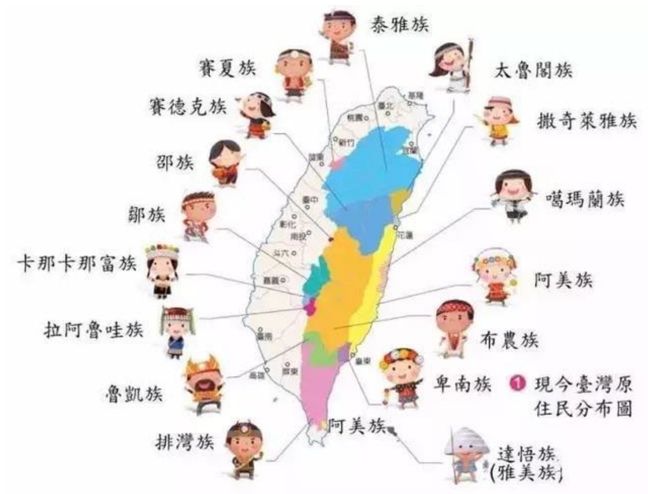

Figure 1: Distribution map of Taiwanese indigenous peoples

Research shows that the frequency of indigenous language use is positively correlated with the transmission of cultural knowledge. In other words, as daily use of the language declines, the passing down of associated traditional knowledge, customs, stories, and cultural values is also negatively affected. Therefore, maintaining active use of indigenous languages is a crucial factor in preserving and sustaining cultural heritage.

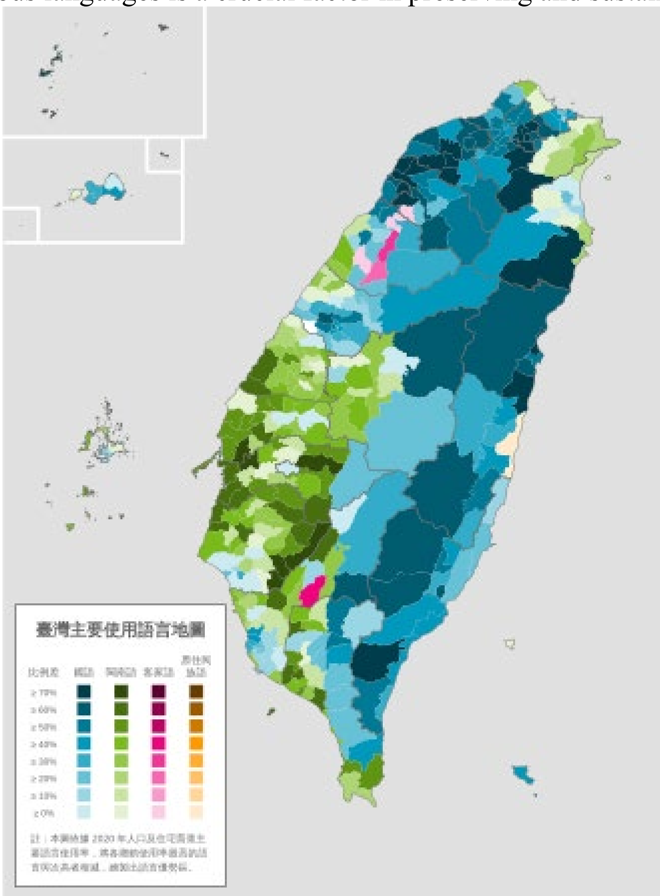

Figure 3: Indigenous language endangerment risk diagram

1.2 Current Status of Taiwanese Indigenous Language Preservation

Taiwan officially recognizes 16 indigenous languages: Amis, Atayal, Bunun, Paiwan, Rukai, Tsou, Saisiyat, Yami (Tao), Truku, Kavalan, Sakizaya, Seediq, Kanakanavu, Puyuma, Rara (Lala), and Kuku.

As of now, the total number of indigenous language speakers in Taiwan is approximately 185,000, out of a total population of 579,949, with an overall language usage rate of 64.6%. While legally recognized as national

languages, usage varies greatly among different languages.
Examples of language use:

- **Amis:** 108,000 speakers; 54.8% of the ethnic population; five dialects; language status 6b (threatened)
- **Bunun:** 38,000 speakers; 57.6%; five dialects; language status 5 (developing)
- **Paiwan:** 15,000 speakers; 78.1%; four dialects; status 6b
- **Atayal:** 10,000 speakers; 79.1%; six dialects; status 7 (shifting)
- **Tsou:** 4,000 speakers; 63.3%; one dialect; status 6b
- **Yami (Tao):** 3,800 speakers; 70.9%; one dialect; status 6b
- **Rukai:** 2,000 speakers; 73.3%; six dialects; status 6b
- **Saisiyat:** 2,000 speakers; 28.6%; one dialect; status 7
- **Puyuma:** 1,000 speakers; 29.4%; four dialects; status 8a (nearly extinct)
- **Seediq:** 650 speakers; status 8a
- **Sakizaya:** 590 speakers; status 7
- **Kavalan:** 70 speakers; status 8b (critically endangered)
- **Rara (Lala):** 25 speakers; status 8b
- **Thao:** 4 speakers; status 9 (no native speakers)
- **Kanakanavu:** 4 speakers; status 8b

The preservation situation varies: some languages like Amis and Atayal are still used in communities and schools but face declining usage among youth. Others rely mainly on elders, with significant generational gaps. Highly endangered languages depend on academic research and cultural associations for preservation. Overall, Taiwanese indigenous languages face three main challenges: declining speakers, low educational and media usage, and modern lifestyle impacts.

1.3 Role of AI in Indigenous Language Preservation

AI plays multiple roles in preserving indigenous languages, addressing limited resources and transmission gaps. AI-based speech recognition can rapidly convert elders' oral histories, tribal stories, and oral literature into text, preserving phonetic details and intonation to build high-quality corpora. NLP and machine learning allow analysis of grammar, vocabulary, and phonology, supporting rule-based or neural language models for smart translation, language generation, and educational applications. (Brixey, 2024)
Practical AI applications include:

- **Educational apps and interactive courses:** Gamified design, voice practice, and instant feedback provide youth-friendly learning environments.
- **Smart translation and chatbots:** Automatic mapping between indigenous languages, Mandarin, and English allows easier daily use.
- **Digital cultural preservation platforms:** Digitizing tribal stories, songs, and knowledge for community and academic sharing.

These AI tools enable complete documentation, revitalization, and integration of indigenous languages into modern society, creating a dynamic linguistic ecosystem. AI empowers communities to independently preserve languages, reducing reliance on elders or educational resources, achieving a sustainable model where technology coexists with tradition.

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2. Research Methods

2.1 Corpus Collection

Systematic collection of all available vocabulary, phrases, sentence patterns, and oral records from elders, archival texts, folk literature, and field recordings. AI-assisted speech-to-text tools preserve phonetic and dialectal features, with automated annotation for syntax and semantics. A scalable digital corpus supports future language analysis, model training, and educational applications. Community participation ensures the corpus reflects real language use and cultural context.

2.2 Grammatical Structure Analysis

AI-driven language parsing systematically analyzes syntax, morphology, vocabulary variation, and phonology. Statistical grammar analysis and neural models allow the creation of rule-based or neural language models, supporting language generation, smart translation, and educational tools. Variants and dialect differences are also identified to provide a complete structural map for preservation.

2.3 Parallel Alignment and Lexical Gap Filling

A parallel corpus between indigenous languages, Mandarin, and English is created. Lexical gaps may be supplemented with Malay words due to structural and lexical similarities within Austronesian languages, with all borrowings community-approved. Automated algorithms align vocabulary and complete semantic gaps, generating high-frequency word lists, grammar templates, and example sentences for educational apps and interactive games. (Mozilla Foundation. 2025)

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3. Results and Discussion

3.1 Grammatical Consistency between Taiwanese Indigenous Languages and Malay

Taiwanese indigenous languages, as part of the Austronesian family, share grammatical similarities with Malay, including:

- **Syntax:** VSO or VOS word order (unlike Mandarin SVO)
- **Verb marking:** Prefixes or suffixes indicating subject, object, or tense
- **Reduplication:** Expressing continuity, repetition, or emphasis
- **Noun classification and numeral classifiers:** Functional similarity to Malay

Malay can serve as a reference to fill missing grammatical patterns in AI models.

3.2 Shared Vocabulary and Roots

Common Austronesian roots exist in numerals, nature terms, daily objects, and social concepts. Examples:

- **Numerals:** Amis *telu* vs. Malay *tiga* (“three”)
- **Nature & objects:** Bunun *pata* vs. Malay *patah* (mountain/fall), Paiwan *ruma* vs. Malay *rumah* (house)
- **Social terms:** Bunun *datu* vs. Malay *datuk* (leader/ancestor)

3.3 Malay Loanwords

Malay has incorporated words from Arabic, Sanskrit, Portuguese, Dutch, and English, e.g.,

- Arabic: *kitab*, *masjid*, *imam*
- Sanskrit: *raja*, *desa*
- Portuguese: *keju*
- Dutch: *polisi*
- English: *telefon*

These loanwords can inform lexical supplementation for modern concepts in indigenous language AI models. (ITU News. 2022)

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4. Conclusion

AI-based indigenous language platforms provide diverse interactive experiences—including mobile apps, chatbots, voice assistants, and educational games—encouraging frequent mother tongue use. These platforms promote active language use while integrating cultural education through interactive stories, tribal songs, traditional knowledge instruction, and cultural activity simulations, strengthening youth identification with language and culture.

At the community level, AI enables digital preservation of elders’ oral histories and practical knowledge for research and education, fostering self-sustained cultural ecosystems. This AI-driven revitalization model is scalable beyond Taiwan, offering a template for minority language preservation globally. By embedding language use into daily digital life, AI reduces extinction risk, enhances cultural pride, and strengthens community cohesion, while building cross-generational and cross-regional language networks that support sustainable cultural interaction.

In summary, applying AI to indigenous language revitalization not only preserves linguistic heritage but also empowers communities to reshape their cultural narratives. Taiwan’s example demonstrates the coexistence of technology and tradition in safeguarding intangible cultural heritage in the 21st century.

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JTAS: Japan–Thailand AI and Sustainability:
From Just Tech to Joint Industrial Transformation

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Abstract

JTAS is an acronym with multiple interpretations, including Japan–Thailand AI and Sustainability Summit, Joint Technology, AI and Sustainability, and Just Tech, AI and Sustainability Summit. It represents a multidimensional framework for addressing the intersection of advanced technology and equitable sustainability. The Japan–Thailand industrial landscape is undergoing strategic transformation: Taiwan Semiconductor Manufacturing Company (TSMC) has established a plant in Kumamoto, Japan, reinforcing Japan's semiconductor ecosystem, while Thailand has emerged as a major hub for printed circuit board (PCB) manufacturing. This evolving cross-border supply chain underscores the technological complementarity between the two nations. Artificial Intelligence (AI) is accelerating innovation across semiconductor, PCB, and smart manufacturing sectors, while sustainability imperatives are driving energy efficiency, carbon reduction, and circular economy practices.

The concept of Just Tech emphasizes that technological advancement must be accompanied by ethical data governance, environmental justice, and social inclusion, ensuring that benefits are equitably shared rather than exacerbating inequalities. JTAS serves not only as an international dialogue platform but also as a strategic blueprint for transnational cooperation. By integrating AI innovation with sustainability principles, Japan and Thailand can jointly shape a resilient, low-carbon, and socially responsible technology ecosystem. This paper explores JTAS as a model for regional collaboration, offering an "Asia-led" perspective on global technology governance and sustainable industrial development.

Keywords: Japan–Thailand cooperation, AI, sustainability, Just Tech, semiconductor, PCB, ethical technology, supply chain, circular economy, regional collaboration.

1. Global Supply Chain Reorganization and TSMC's Strategic Layout

1.1. U.S.–China Trade War and Supply Chain Security

Since the outbreak of the U.S.–China trade war in 2018, global semiconductor and high-tech industry supply chains have been severely disrupted. Trade barriers, export controls, and tariff policies have pushed companies to reassess production layouts in order to reduce dependency on single countries or regions. The Asia-Pacific has become a central focus due to its technological capabilities, integrated industrial chains, and market potential. Against this backdrop, TSMC's global expansion strategy, including the establishment of a semiconductor plant in Kumamoto, Japan, represents a critical response to geopolitical risk (Staples, 2024).

1.2. Regional Strategic Significance of TSMC in Japan

TSMC's facility in Japan not only strengthens Japan's semiconductor ecosystem but also provides the Asia-Pacific with a more stable chip supply. The plant reduces global supply chain uncertainty, enhances technological autonomy, and secures sustainable access to critical components. For Japan, this investment provides an opportunity to enhance competitiveness in the global semiconductor industry while reinforcing cooperation and complementarity with Southeast Asian economies (Staples, 2024).

2. Environmental Challenges of the High-Tech Industry

2.1. Environmental Impacts of Semiconductor and PCB Manufacturing

While the high-tech industry brings innovation and economic benefits, semiconductor and PCB production requires massive energy, water, and chemical inputs, while producing greenhouse gas emissions and hazardous waste. These processes place significant stress on local ecosystems and communities, leading to water shortages, wastewater treatment challenges, and air pollution. Without proper environmental management, long-term impacts may threaten both public health and biodiversity (Schröder et al., 2025).

2.2. Sustainability and Corporate Social Responsibility

In this context, high-tech companies must balance economic interests with environmental responsibility.

TSMC's expansion into Japan goes beyond industrial and economic considerations and must integrate sustainability principles such as energy efficiency, pollution control, and corporate social responsibility. Environmental impact assessments, along with partnerships with local stakeholders, can reduce ecological burdens and drive the transition toward green manufacturing, low-carbon production, and circular economy practices (Schröder et al., 2025).

3. AI and Sustainable Development in High-Tech Industries

3.1. AI in Manufacturing Process Optimization

AI is increasingly recognized as a key enabler of sustainable development in high-tech manufacturing. Applications include process optimization, energy management, and monitoring of wastewater and emissions. By leveraging real-time data analytics, AI can predict maintenance needs, reduce raw material waste, and enhance production efficiency. These innovations lower environmental impacts while strengthening competitiveness and industrial resilience (Liu et al., 2025).

3.2. AI for Supply Chain Transparency and Social Responsibility

AI also plays a vital role in promoting supply chain transparency and accountability. By enabling digital monitoring and data-driven decision-making, AI allows companies to track environmental impacts across the entire product life cycle—from raw material sourcing to final products. This ensures alignment with low-carbon goals, resource reuse, and circular economy strategies. Beyond ecological improvements, AI supports socially responsible practices, contributing to sustainable and ethical industrial models (Liu et al., 2025).

4. Just Tech: Ethical and Moral Dimensions

4.1. Technological Innovation and Moral Responsibility

Every technological advancement carries ethical obligations. AI, big data, and automation can result in privacy violations, biased decision-making, and rising inequalities if left unchecked. The framework of Just Tech calls for innovators and corporations to ensure that technological development aligns with fairness, inclusivity, and long-term social responsibility.

4.2. Data Ethics in Just Tech

As AI depends heavily on data, ethical practices in data collection, analysis, and usage are crucial. Without transparency, accountability, and fairness, technological systems risk perpetuating inequality. Just Tech advocates for data ethics, emphasizing privacy protection, fairness, and responsibility in AI governance.

4.3. Social Participation in Technology Governance

Just Tech also requires multi-stakeholder participation. Policymakers, corporations, academics, and civic groups must collaborate to ensure technology governance avoids concentration of power and inequitable benefit distribution. Multi-level dialogue ensures that technology aligns with ethical, social, and environmental standards.

4.4. Indicators for Evaluating Just Tech

To measure Just Tech, evaluation indicators such as social equity, environmental impact, data transparency, and ethical compliance can be adopted. These metrics allow organizations and governments to assess technology's actual contributions to sustainable and just development.

5. From Theory to Practice: Implementing Just Tech

5.1. Industrial Practices of Just Tech

At the enterprise level, Just Tech can combine AI with green manufacturing strategies. For instance, semiconductor companies can integrate AI-based energy monitoring, waste management, and resource reuse with the United Nations Sustainable Development Goals (SDGs), achieving greener and more equitable operations (Liu et al., 2025).

5.2. Cross-Border Cooperation and Technology Sharing

Just Tech also requires international cooperation. In globalized supply chains, cross-border technology sharing ensures that developing economies can access technological benefits equitably, avoiding a widening digital divide. This enhances the social value of technological development.

5.3. Future Prospects of AI for Sustainability and Equity

As AI matures, Just Tech can more effectively address global challenges such as resource allocation, environmental protection, and social justice. Through continuous monitoring, smart decision-making, and cross-sector collaboration, AI will not only improve efficiency but also ensure that technological progress aligns with ethical and sustainable goals.

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