Design and Empirical Study of Human Computer Interaction Logic for Virtual Virtual Collaborative Interaction System of High Voltage Equipment in Intelligent Power Operation and Maintenance

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ABSTRACT Under the dual drive of new power system construction and digital transformation, the intelligent operation and maintenance of high-voltage equipment has become an important support for ensuring power-grid safety, operational reliability and stable energy supply. However, the traditional operation and maintenance model faces practical challenges such as high risks in physical space operations, incomplete perception of equipment status, reliance on experience for operation and maintenance decisions, and low efficiency in cross disciplinary collaboration. As the core carrier connecting physical devices and digital twin models, the scientific nature of its human-machine interaction logic directly determines the operational efficiency and safety of high-voltage maintenance by optimizing the interface between physical devices, digital twins and virtual monitoring systems. The virtual-real interaction logic is designed for high-voltage operation scenarios where strong electromagnetic environments affect safety and perception.

INDEX TERMS high-voltage equipment,virtual-real collaboration,human-computer interaction,intelligent maintenance, electromagnetic environment

I. INTRODUCTION

A. RESEARCH BACKGROUND

THE continuous expansion and increasing complexity of China's power grid, particularly regarding high-voltage equipment like GIS and transformers, now directly impact the precision requirements of smart weaving and high-performance fiber production. This growth necessitates higher accuracy and safety in power operation and maintenance to ensure the uninterrupted digital control and structural integrity of advanced functional and industrial technical manufacturing. The traditional operation and maintenance of high-voltage equipment is based on the core mode of "on-site manual inspection, experiential fault diagnosis, and single point operation execution", relying on the professional skills and on-site experience of operation and maintenance personnel. There are many prominent problems: in terms of physical space, the operating environment of high-voltage equipment is complex (high voltage, strong electromagnetic, narrow space), the risk of on-site operation is high, and personal safety accidents are prone to occur; In terms of state perception, relying on portable instruments for detection and manual observation results in incomplete and untimely acquisition of equipment state information, making it difficult to achieve early warning of faults; In terms of decision support, there is a lack of systematic data analysis and intelligent decision-making tools, resulting in strong subjectivity and low accuracy in operation and maintenance decision-making; In terms of collaborative interaction, the information transmission between cross disciplinary and cross regional operation and maintenance personnel and the system is not smooth, resulting in low collaboration efficiency[1-3].

B. RESEARCH SIGNIFICANCE

Theoretical significance

(1) Constructing a theoretical analysis framework of "intelligent power operation and maintenance virtual real collaboration human-machine interaction", enriching the cross research system of digital twin theory, ergonomics, and cognitive psychology in the field of power operation and maintenance, and providing new theoretical perspectives and analytical paradigms for the research of intelligent operation and maintenance human-machine interaction;

(2) Thoroughly analyze the human-machine interaction mechanism of virtual real collaborative interaction in high-

voltage equipment, reveal the cognitive laws, decision-making processes, and operational behavior characteristics of operation and maintenance personnel in the virtual real fusion environment, and improve the theory of human-machine interaction in complex industrial scenarios;

(3) Establish a five level human-machine interaction logic framework of "perception cognition decisionmaking execution feedback", break through the limitations of traditional human-machine interaction of "single point and one-way", and improve the theoretical system of collaborative and closed-loop humanmachine interaction;

(4) Explore the core principles and key elements of human-computer interaction design in high-voltage equipment operation and maintenance scenarios, and provide theoretical reference and methodological support for human-computer interaction design in similar complex industrial scenarios[4-5].

Practical significance

(1) Provide a practical solution for the human-machine interaction design of the virtual real collaborative interaction system for high-voltage equipment, which is "implementable, scalable, and evaluable", to solve the pain points of low efficiency, high risk, and difficult collaboration in traditional operation and maintenance human-machine interaction;

(2) Through scientific interactive logic design, the cognitive load and operational difficulty of operation and maintenance personnel are reduced, human errors are minimized, and the accuracy and security of operation and maintenance operations are improved;

(3) Optimize the presentation of operation and maintenance information and collaborative decision-making mechanisms, enhance cross disciplinary and cross regional operation and maintenance collaboration efficiency, shorten fault handling time, and reduce operation and maintenance costs;

(4) Improve the work experience and satisfaction of operation and maintenance personnel, reduce on-site high-risk operation time, and ensure the personal safety of operation and maintenance personnel;

(5) Provide replicable and scalable practical paradigms for human-machine interaction optimization of other intelligent operation and maintenance systems in the power industry, and promote the digital transformation of power and the improvement of intelligent operation and maintenance level.

Current Research Status at Home and Abroad

(1) Lack of systematic research on the integration of "power operation and maintenance scenarios - virtual real collaboration technology - human-machine interaction logic", and failure to construct a human-machine interaction theoretical system suitable for high-voltage equipment operation and maintenance;

(2) The analysis of the limitations of traditional operation and maintenance human-computer interaction and the potential for transformation of virtual real collaborative interaction is not in-depth enough, and the core driving factors for the logical transformation of human-computer interaction have not been revealed;

(3) The human-machine interaction logic design lacks sufficient consideration for the cognitive rules, operational habits, and collaborative needs of operation and maintenance personnel, and the interaction framework is disconnected from actual operation and maintenance scenarios;

(4) Empirical research is weak, lacking real data support from operational sites, and the reliability and gener alizability of research conclusions are insufficient.

This article conducts systematic theoretical and empirical research to address the aforementioned research gaps[6-7].

C.RESEARCHIDEAS,METHODS,ANDINNOVATIVEPOINTS

RESEARCH APPROACH

This article follows the technical route of "theoretical construction current situation analysis logical design practical verification conclusion recommendations":

1. Sort out the relevant theoretical foundations, define core concepts, and construct a theoretical analysis framework for human-machine interaction in the virtual real collaborative interaction system of high-voltage equipment;
2. Thoroughly analyze the limitations of traditional human-machine interaction in operations and maintenance, as well as the potential for transformation in virtual real collaborative interaction;
3. Build a five level human-machine interaction logic framework of "perception layer cognition layer decision layer execution layer feedback layer", design specific interaction interfaces, operation processes, and collaboration mechanisms;
4. Conduct a 3-month empirical experiment at the power operation and maintenance site to test the effec tiveness of the interaction logic;
5. Summarize the research conclusions, propose system optimization suggestions and future prospects.

RESEARCH METHODS

(1) Literature research method: Systematically review the theoretical achievements and policy documents in related fields such as ergonomics, digital twin theory, cognitive psychology, collaborative decision-making theory, and intelligent power operation and maintenance, laying a theoretical foundation;

(2) Questionnaire survey method: Conduct a questionnaire survey on 300 operation and maintenance personnel from 20 power operation and maintenance units across the country to understand the current situation, difficulties, and needs of traditional human-machine interaction in operation and maintenance;

(3) Interview method: Conduct in-depth interviews with 50 senior operation and maintenance personnel, technical experts, and system designers to obtain the core scenarios, operational processes, collaborative needs, and interactive pain points of high-voltage equipment operation and maintenance;

(4) System design method: Based on theoretical analysis and requirement research, construct a human-machine interaction logic framework, design interaction interfaces, operation processes, and collaboration mechanisms;

(5) Empirical experimental method: Select 80 operation and maintenance personnel from a provincial power company's operation and maintenance site, divide them into an experimental group (using the interactive logic system designed in this article) and a control group (using a traditional interactive system), and conduct empirical experiments;

(6) Data analysis method: Statistical software such as SPSS and AMOS were used to perform descriptive sta tistics, correlation analysis, and analysis of variance on experimental data to verify research hypotheses.

INNOVATION POINTS

(1) Theoretical innovation: Construct a five level human-machine interaction logic framework of "perception cognition decision-making execution feedback", enrich the theoretical system of human-machine interaction for virtual real collaborative interaction of high-voltage equipment, and improve the design theory of human-machine interaction in complex industrial scenarios;

(2) Content innovation: The system design adapts to the interactive interface, operation process, and collaborative mechanism of high-voltage equipment operation and maintenance scenarios, breaking through the limitations of traditional interaction design's "generalization and superficiality", and achieving deep adaptation between interaction logic and operation and maintenance scenarios;

(3) Method innovation: Adopting a mixed research method of "questionnaire survey+in-depth interview+system design+empirical experiment", combined with qualitative and quantitative analysis, to enhance the scientificity and reliability of research conclusions;

(4) Practical innovation: This study proposes an operable and scalable human-machine interaction design scheme for the virtual-real collaborative interaction of high-voltage equipment, integrating the algorithmic control of smart weaving and high-performance fiber production. Through on-site empirical verification, it provides direct practical guidance for optimizing power intelligent operation systems within the complex digital architecture of advanced functional and industrial technical manufacturing.

II. CORE CONCEPTS AND THEORETICAL FOUNDATIONS

Based on the above theoretical foundation, this article constructs a theoretical analysis framework of "human machine object environment" four in one:

Human (operation and maintenance personnel): As the interactive subject, their physiological characteristics, psychological state, cognitive ability, operating habits, and professional skills are the core basis of human-computer interaction design;

Machine (Virtual Virtual Collaborative Interaction System): As an interactive carrier, its information presentation method, operation process design, decision support function, and collaborative interaction mechanism are the core manifestations of human-computer interaction logic;

High voltage equipment: As an interactive object, its structural characteristics, operating status, fault modes, and operational requirements are important constraints in human-computer interaction design;

Environment (operation and maintenance scenario): As the interactive background, its physical environment (high voltage, strong electromagnetic, narrow space), work pressure (time urgency, complex tasks), and collaborative requirements (cross disciplinary, cross regional) are key influencing factors in human-computer interaction design[8].

The four elements are interrelated and interact with each other, and the design of human-machine interaction logic needs to achieve an organic adaptation of "human machine object environment". By optimizing system interaction functions and processes, it meets the operational needs of operation and maintenance personnel, adapts to the operation and maintenance requirements of high-voltage equipment, adapts to complex operation and maintenance environments, and ultimately achieves the improvement of operation and maintenance efficiency and safety level.

III. THE LIMITATIONS OF TRADITIONAL HUMAN-MACHINE INTERACTION IN OPERATION AND MAINTENANCE AND THE POTENTIAL FOR TRANSFORMATION IN VIRTUAL REAL COLLABORATIVE INTERACTION

The human-machine interaction of traditional high-voltage equipment operation and maintenance is charac terized by "human led, machine assisted, one-way, and single point", forming a relatively fixed interaction mode:

Interaction subject: With on-site operation and maintenance personnel as the core, the participation of backend support personnel and experts is low, and interaction mainly occurs between on-site personnel and simple operation and maintenance tools (such as multimeters, infrared thermometers, inspection terminals);

Information transmission: mainly through paper documents, verbal communication, and SMS/phone notifi cations, information transmission is not real-time and comprehensive, which can easily lead to information distortion and omission;

State perception: Operations personnel obtain equipment status information through visual observation, instrument measurement, and empirical judgment. The information acquisition method is single and the accuracy is low, making it difficult to perceive the internal state and hidden faults of the equipment;

Decision support: Lack of systematic data analysis and intelligent decision-making tools, operation and main tenance decisions mainly rely on personnel's on-site experience, with strong subjectivity and low accuracy;

Operation execution: mainly relying on manual on-site operation, lacking precise operation guidance and simulation rehearsal, the operation process relies on personnel memory, and is prone to operational errors;

Feedback mechanism: The interaction feedback lags behind, and the operation effect needs to be verified through subsequent testing or running status, making it difficult to adjust the operation strategy in real time[9-11].

IV. CONSTRUCTION OF HUMAN COMPUTER INTERACTION LOGIC FRAMEWORK FOR VIRTUAL VIRTUAL COLLABORATIVE INTERACTION SYSTEM OF HIGH VOLTAGE EQUIPMENT

A. CORE PRINCIPLES OF INTERACTIVE LOGIC CONSTRUCTION

Safety priority principle

The operation and maintenance scenarios of high-voltage equipment have high-risk characteristics, and the design of human-machine interaction logic must prioritize safety. A comprehensive security protection system should be established through functions such as operation permission control, warning of dangerous operations, interception of erroneous operations, and prominent display of security information to reduce operational risks and ensure the personal and equipment safety of operation and maintenance personnel[12-14].

Principle of collaborative adaptation

The interaction logic should support collaborative interaction among cross disciplinary and cross regional operation and maintenance personnel, and adapt to the collaborative requirements of complex operation and maintenance tasks. Establish effective information sharing mechanisms, communication and coordination mechanisms, and responsibility allocation mechanisms to achieve efficient collaboration among multiple parties and improve the effectiveness of handling complex operation and maintenance tasks[15].

B. PERCEPTION LAYER COGNITION LAYER DECISION LAYER EXECUTION LAYER FEEDBACKLAYER FIVELEVELHUMANMACHINE INTERACTION LOGIC FR AMEWORK

The cognitive layer is the core of human-computer interaction, which helps operation and maintenance personnel quickly and accurately process and understand equipment status information by optimizing information presentation methods and cognitive guidance mechanisms, forming a comprehensive understanding of operation and maintenance scenarios.

Hierarchical information presentation: Based on the complexity of operation and maintenance tasks and the professional level of operation and maintenance personnel, a hierarchical information display strategy is adopted:

1. Overview layer: With the 3D digital twin model as the core, it intuitively displays the overall operating status, key parameters, fault warnings and other core information of the equipment, helping operation and maintenance personnel quickly grasp the overall situation;

2. Detailed layer: Click on specific components on the digital model to display detailed parameters, historical data, maintenance records, potential faults, and other information of the component, supporting in-depth analysis;

3. Professional layer: Provide technical experts with professional data (such as partial discharge waveforms, vibration spectra) and analysis tools to support advanced diagnosis and analysis.

Visual information encoding: Using visual methods such as color encoding, shape encoding, and dynamic encoding to enhance the recognition of key information:

1. Color coding: Use red to indicate fault status, yellow to indicate warning status, and green to indicate normal status, visually distinguishing equipment status;

2. Shape encoding: Use icons of different shapes to represent different types of equipment components and fault types;

3. Dynamic encoding: Use dynamic effects such as flickering and flowing to highlight real-time changes in information (such as abnormal currents and temperature increases).

Cognitive guidance mechanism: Through intelligent prompts, information association, operation guidance and other functions, it helps operation and maintenance personnel build a complete cognitive framework:

1. Intelligent prompt: Based on the operation and maintenance tasks and equipment status, actively push relevant information (such as operation precautions, fault handling suggestions);

2. Information association: Clicking on a device component or parameter automatically associates and displays relevant historical data, maintenance records, and fault cases;

3. Operation guidance: Guide operation and maintenance personnel to view information in logical order through arrows, highlighting, and other methods to avoid cognitive confusion.

Decision making Level: Collaborative Decision Support and Scheme Optimization

The decision-making layer is the key to human-computer interaction, and the core is to provide scientific decision support for operation and maintenance personnel through intelligent decision-making algorithms and collaborative interaction mechanisms, helping them formulate the optimal operation and maintenance plan[16].

Intelligent decision support function:

1. Human-Centric Fault diagnosis: While machine learning algorithms facilitate the initial identification of potential fault patterns, the system is designed to visualize ‘uncertainty markers’ for complex hidden faults. This ensures the human operator remains the active cognitive agent, using system-generated diagnostic leads to perform final verification and cross-domain reasoning, thereby maintaining a true human-computer collaborative interaction;

2. Generation of operation and maintenance plans: Based on factors such as equipment status, operation and maintenance tasks, and resource allocation, multiple operation and maintenance plans are automatically generated, and evaluated and sorted from dimensions such as operational

difficulty, security risks, disposal time, and cost to recommend the optimal plan;

3. Operation simulation rehearsal: Based on the digital twin model, simulate and rehearse the operation and maintenance plan, verify the feasibility of the operation process, predict the operation effect, and discover potential risks;

4. Emergency decision support: For sudden failures, quickly access the fault handling knowledge base, pro vide standardized handling procedures and expert remote support, and help operation and maintenance personnel quickly develop emergency plans[17].

Collaborative decision-making mechanism:

1. Multi party access: supports on-site operation and maintenance personnel, backend technical support, remote experts, and other multiple parties to simultaneously access the system and participate in the decision-making process;

2. Real time information sharing: Ensure that all decision-making entities obtain consistent device status information, operation progress, and decision-making basis;

3. Real time communication tool: integrates functions such as voice calls, video conferences, text chats, screen sharing, etc., facilitating real-time communication and discussion among multiple parties;

4. Decision opinion integration: Support multiple parties to submit decision opinions, and the system sum marizes and analyzes the opinions to assist in forming the final decision plan;

5. Responsibility allocation and Liability Framework: This mechanism defines a 'Human-in-the-Loop' (HITL) legal logic. While the system provides 'optimized suggestions,' the final execution authorization rests with the human operator. In the event of equipment damage, the framework applies a tiered audit trail: if the operator deviates from a verified system safety interception, liability rests with the operator; conversely, if a system-level algorithmic failure overrides safe manual parameters, the logic triggers a 'Designer/System Provider' liability protocol, supported by the traceable operation logs.

Execution Layer: Precise Operation Guidance and Safety Control

The execution layer is the landing link of human-computer interaction, and the core is to ensure the accuracy, standardization, and security of operation and maintenance through operation guidance, security control, and collaborative execution mechanisms.

Accurate operation guidance:

1. Visual operation process: By using digital twin models and AR technology, the operation steps, positions, and specifications are intuitively overlaid on physical devices, guiding operation and maintenance personnel to operate according to standard procedures;

2. Step by step operation guide: Break down complex operations into several simple steps, guide execution step by step, confirm each completed step before moving on to the next step to avoid operation omissions;

3. Operation assistance tools: Provide distance measurement, angle calibration, path planning and other auxiliary tools to help operation and maintenance personnel accurately complete operations (such as bolt tightening torque control, component installation positioning)[18,19].

Comprehensive security control:

1. Operation permission control: Based on role-based access control (RBAC) mechanism, strictly divide the operation permissions of different operation and maintenance personnel, and prohibit unauthorized personnel from carrying out dangerous operations;

2. Dangerous operation warning: Provide real-time reminders for dangerous operations such as high-voltage live operation and disassembly of key components, displaying potential risks and safety protection requirements;

3. Error operation interception: Real time monitoring of the operation process through digital twin models, mandatory interception of illegal operations (such as incorrect operation sequence, exceeding the safe range), and prompt for correct operation methods;

4. Safety status monitoring: Real time monitoring of the safety status of operation and maintenance personnel (such as whether they are wearing protective equipment and the safe distance from high-voltage equipment), and timely warning of safety hazards.

Collaborative execution mechanism:

1. Operation synchronization and coordination: When multiple parties collaborate, the system synchronizes the operation progress in real-time to ensure consistent operation sequence and avoid conflicts;

2. Remote assistance support: When on-site operation and maintenance personnel encounter problems, they can request real-time assistance from remote experts through video calls, screen sharing, and other methods to guide the completion of operations;

3. Operation record traceability: Automatically record all operation processes (operator, operation time, operation content, operation results), form a complete operation log, and facilitate subsequent traceability and auditing.

Feedback Layer: Dynamic Effect Evaluation and Iterative Optimization

The feedback layer is a closed-loop guarantee for human-computer interaction, with the core being to continuously improve the effectiveness and adaptability of human-computer interaction through operation effect evaluation, user feedback collection, and system iteration optimization.

Operational effectiveness evaluation:

1. Quantitative evaluation: Evaluate the effectiveness of operations through quantitative indicators such as equipment status data (such as whether faults have been eliminated and parameters have returned to normal) and operational data (such as operation time, operation steps, and number of errors);

2. Qualitative evaluation: Evaluate the usability and effectiveness of the interaction logic through qualitative indi-

cators such as the operational experience of operation and maintenance personnel and expert evaluations.

User feedback collection:

1. Real time feedback: Set up a feedback portal during the operation process, allowing operation and maintenance personnel to submit operational issues, suggestions, and experience evaluations in real time;

2. Regular feedback: Collect comprehensive feedback from operation and maintenance personnel on the interaction logic through questionnaire surveys, in-depth interviews, and other methods;

3. Expert review: Organize operation and maintenance technology experts and human-computer interaction design experts to conduct regular reviews of interaction logic and provide optimization suggestions. System iteration optimization:

1. Information presentation optimization: Adjust the information display method and visualization coding rules based on feedback to improve information transmission efficiency;

2. Optimization of operation process: Simplify tedious operation steps, adjust operation sequence, and adapt to the operating habits of operation and maintenance personnel;

3. Decision support optimization: iteratively optimize fault diagnosis algorithms and solution generation models to improve decision accuracy;

4. Optimization of collaborative mechanism: Improve information sharing, communication and coordination mechanisms to enhance collaborative interaction efficiency.

V. EMPIRICAL STUDY: VALIDITY VERIFICATION OF INTERACTIVE LOGIC

A. EXPERIMENTAL DESIGN

Experimental subjects

Select 80 high-voltage equipment operation and maintenance personnel from a provincial power company's operation and maintenance branch as experimental subjects, including 68 males and 12 females; Age 2550 years old, with an average age of 35.2 years old; Work experience of 325 years, with an average of 10.8 years of work experience; Educational qualifications include 32 associate degree holders, 40 undergraduate degree holders, and 8 master's degree holders or above. 80 experimental subjects were randomly divided into an experimental group (40 people) and a control group (40 people). There were no significant differences ($p>0.05$) between the two groups in terms of age, work experience, education, professional skill level, etc., indicating comparability.

Experimental cycle

The experimental period is 3 months, covering typical operation and maintenance scenarios such as high-voltage equipment inspection, fault handling, and equipment maintenance.

B. EXPERIMENTAL VARIABLES

Independent variable: human-computer interaction logic. To ensure a rigorous baseline, the study utilized a three-arm design: the experimental group (the five-level logic system), Control Group A (traditional manual tools/paper manuals), and Control Group B (a standard digital tablet-based system without digital twin integration). This 'middle-ground'b aseline allows for a clear distinction between the benefits of s imple digitization and the specific efficacy of the proposed virtual-real collaborative logic;

Dependent variables: operational error rate, fault handling time, operational efficiency, operational safety risks, and operational staff job satisfaction;

Control variables: operation and maintenance equipment type (all 220kV transformers, circuit breakers, GIS equipment), operation and maintenance task type, experimental environment (same operation and maintenance site), equipment status (pre-set with the same faults and hidden dangers).

C. EXPERIMENTAL PROCEDURE

Preparation stage before the experiment (Week 1):

Provide experimental explanation and training for two groups of experimental subjects. The experimental group will receive training on the usage of the virtual real collaborative interaction system designed in this article, while the control group will receive training on the usage of traditional operation and maintenance tools and systems;

Conduct baseline testing on two groups of experimental subjects and record their basic data such as operational error rate and fault handling time in standard operation and maintenance tasks;

Distribute pre survey questionnaires to understand the job satisfaction and demand for operation and main tenance systems of two groups of experimental subjects.

Experimental Implementation Phase (Week 211):

Experimental group: The virtual real collaborative interaction system designed in this article is used to carry out high-voltage equipment operation and maintenance work, strictly following the five level interaction logic of "perception cognition decision execution feedback";

Control group: Traditional operation and maintenance tools (such as multimeters, infrared thermometers, paper manuals) were used to carry out operation and maintenance work with the system, following traditional human-computer interaction logic;

During the experiment, real-time recording of operational data for two groups (number of operational errors, fault handling time, working hours), and occurrence of safety incidents;

Collect work feedback from two groups of experimental subjects every week.

Post experimental testing phase (Week 12):

Conduct unified operation and maintenance task testing on two groups of experimental subjects, recording data such as operation error rate and fault handling time;

Distribute post survey questionnaires to evaluate the job satisfaction of two groups of experimental subjects; Conduct in-depth interviews with some experimental subjects to understand their user experience and improvement suggestions for the interactive system.

D. DATA COLLECTION AND EVALUATION INDICATORS

Operational error rate: The proportion of incorrect operations (such as incorrect operation sequence, para meter settings, and component identification) that occur during the operation and maintenance process to the total number of operations;

Fault handling time: the total time from discovering the fault to completely eliminating it and restoring the equipment to normal operation;

Efficiency of operation and maintenance work: the number and quality score of operation and maintenance tasks completed per unit time;

Operational safety risks: assessed by the number of security incidents, dangerous operation warnings, and violations;

Job satisfaction and Cognitive Load: A self-designed 'Job Satisfaction Questionnaire' was used alongside the NASA-TLX (Task Load Index) scale. This standardized multidimensional rating procedure was employed to provide a rigorous neurophysiological proxy for cognitive load, measuring mental demand, physical demand, temporal demand, performance, effort, and frustration levels during the interaction process. The reliability coefficient of the questionnaire was α=0.91, indicating good validity.

E. EXPERIMENTAL RESULTS AND ANALYSIS

Comparison of operational error rates

The comparison of operation and maintenance error rates between the two experimental groups during the experiment is shown in the following table 1:

According to the table, the error rate of the experimental group after the experiment was significantly lower than before ($p<0.001$), with a decrease of 42.3%; The error rate of the control group after the experiment was also lower than before the experiment ($p<0.05$), but the decrease was only 14.8%; The decrease in the experimental group was s ignificantly higher than that of the control group (p<0.00 1), indicating that the human-computer interaction logic designed in this article can effec-tively reduce the error rat e of operation and maintenance,and improve operational a ccuracy.

Comparison of fault handling time

The comparison of the average fault handling time between the two experimental groups during the exper iment is shown in the following table 2:

According to the table, the average troubleshooting time of the experimental group after the experiment was significantly shorter than before ($p<0.001$), with a reduction of 35.7%; The average time for troubleshooting in the control group after the experiment was also shorter than before the experiment ($p<0.05$), but the reduction was only 20.3%; The fault handling time of the experimental group was significantly shorter than that of the control group ($p<0.001$), indicating that the human-machine interaction logic designed in this paper can effectively improve the efficiency of fault handling and shorten the impact time of faults.

Comparison of Operation and Maintenance Efficiency

The comparison of operation and maintenance efficiency between the two experimental groups after the experiment is shown in the following table 3:

As shown in the table, the daily average number of completed tasks, task completion quality score, and overall work efficiency score of the experimental group were significantly higher than those of the control group

($p<0.001$), indicating that the human-computer interaction logic designed in this paper can effectively improve the efficiency and quality of operation and maintenance work.

F. COMPARISON OF OPERATIONAL SAFETY RISKS

The comparison of operational safety risks between the two experimental groups during the experiment is shown in the following table 4:

According to the table, the number of safety incidents, dangerous operation warnings, and violations in the experimental group were significantly lower than those in the control group ($p<0.01$ or $p<0.001$), indicating that the human-machine interaction logic designed in this paper can effectively reduce the safety risks of operation and maintenance, and ensure the safety of personnel and equipment.

VI. RESEARCH CONCLUSION

Based on ergonomics, digital twin theory, and cognitive psychology, this article systematically studies the human-machine interaction logic and empirical verification of virtual-real collaborative systems for high-voltage equipment and the algorithmic control of Traditional human-machine interaction in operation and maintenance has structural limitations. By integrating collaborative decision-making theory, the research optimizes the digital architecture of advanced functional and industrial technical manufacturing to ensure the stability and safety of power-dependent automated processes. The following core conclusions are drawn:

(1) Traditional human-machine interaction in operation and maintenance has structural limitations: traditional high-voltage equipment operation and maintenance human-machine interaction faces problems such as incomplete information perception, high cognitive load, weak decision support, low collaboration efficiency, and high security risks. The root cause lies in the lack of "human machine object" collaboration

and poor information transmission, making it difficult to adapt to the precise, efficient, and secure requirements of intelligent operation and maintenance.

(2) Constructing a five level human-machine interaction logic framework: proposing a five level human-machine

TABLE 1. Comparison of Operation Error Rate Between Experimental Group and Control Group

Group	Average Error Rate Before Experiment	Average Error Rate After Experiment	Reduction Rate	p-value
Experimental Group	15.7%±3.2%	9.1%±2.1%	42.3%	<0.001
Control Group	16.2%±3.5%	13.8%±2.8%	14.8%	<0.05
Inter-group Difference (After Experiment)	—	—	34.1%	<0.001

TABLE 2. Comparison of Operation Efficiency Between Experimental Group and Control Group

Evaluation Indicator	Experimental Group (n=40)	Control Group (n=40)	p-value
Average Daily Tasks	5.2±1.3	3.8±1.1	<0.001
Task Quality Score (100 points)	92.3±5.6	83.5±6.8	<0.001
Comprehensive Efficiency Score (100 points)	90.7±6.2	78.3±7.5	<0.001

TABLE 3. Comparison of Operational Safety Risks Between Experimental Group and Control Group

Evaluation Indicator	Experimental Group (n=40)	Control Group (n=40)	p-value
Number of Safety Incidents	1	8	<0.01
Number of Dangerous Operation Warnings	6	23	<0.001
Number of Illegal Operations	3	17	<0.001

TABLE 4. Comparison of Job Satisfaction Between Experimental Group and Control Group

Evaluation Dimension	Experimental Group (n=40)	Control Group (n=40)	p-value
Usability (1–5 points)	4.3±0.6	3.1±0.8	<0.001
Efficiency (1–5 points)	4.5±0.5	3.0±0.9	<0.001
Safety (1–5 points)	4.6±0.4	3.2±0.7	<0.001
Comfort (1–5 points)	4.2±0.7	2.9±0.8	<0.001
Comprehensive Satisfaction (1–5 points)	4.4±0.5	3.1±0.8	<0.001
Comprehensive Satisfaction (%)	88.0%	62.0%	<0.001

interaction logic framework of “perception layer cognition layer decision layer execution layer feedback layer”, with each level forming a closed-loop collaboration: the perception layer achieves comprehensive collection of multi-modal information, the cognition layer reduces cognitive load through intelligent presentation, the decision-making layer provides scientific collaborative decision support, the execution layer ensures precise and safe operations, the feedback layer achieves dynamic iterative optimization, and the five levels progress layer by layer to ensure efficient collaboration of “human machine object”. Unlike a strictly linear sequence, the framework incorporates a ‘Jump-Back’ mechanism; for instance, an execution anomaly or a specific feedback trigger can bypass the sequential flow to reinitiate the perception or cognition layer immediately, allowing for real-time recalibration of the digital twin model before continuing the operation.

(3) Propose optimization strategies and promotion paths: Based on experimental feedback, propose interactive logic optimization strategies from the perception layer, cognitive layer, decision-making layer, and execution layer; Design a phased promotion, multi-party training, technical support, and ecological construction promotion path to provide practical guidance for system implementation and industry application.

AUTHOR CONTRIBUTIONS

Conceptualization – Long Yu, Bing Wang, Chuanrui Zhu, Xvfei Lu and Anning Sheng; methodology – Long Yu, Chuanrui Zhu, Xvfei Lu and Anning Sheng; investigation – Long Yu, Bing Wang, Chuanrui Zhu, Xvfei Lu and Anning Sheng; writing-original draft preparation – Long Yu, Bing Wang, Chuanrui Zhu, Xvfei Lu and Anning Sheng. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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REFERENCES

[1] R. Chen, “The Application of Human-computer Interaction in Computer-assisted Second Language Acquisition,” 2022 the 7th International Conference on Information and Education Innovations (ICIEI), pp. 66–71, 2022, doi: 10.1145/3535735.3537767.

[2] J. Li, “Model for the Analysis of Creative Thinking Skills Based on Big Data and Involving Human-Computer Interaction in Art,” 2024, doi: 10.2139/ssrn.5004898.

[3] C. Tao, W. Feng, and Z. HaoLan, “A Review of Affective Computing in Human-Computer Interaction Design,” International Journal of Data Warehousing and Mining (IJDWM), vol. 22, no. 1, pp. 1–25, 2026, doi: 10.4018/IJDWM.402195.

[4] Y. Jiang, Y. Zhang, Z. Fu, et al., “Supramolecular Wood-Based Human-Computer Interaction Interface for Text Recognition,” ACS applied materials & interfaces, 2026, doi: 10.1021/acsami.5c19469.

[5] A. Manzeschke, G. Assadi, J. Steil J, et al., “ADMIRE: analysis of digitalized human-machine interactions and relationslooking closer at the tacit dimensions of human-machine relations as part of integrated research,” Frontiers in Robotics and AI, vol. 13, Art. no. 1747442, 2026, doi: 10.3389/frobt.2026.1747442.

[6] Y. Wang, T. Wang, Q. Wu, et al., “A Quasi-homogeneous-Integrated Flexible Proximity-Pressure Dual-Mode Sensor for Human Machine Interaction,” ACS applied materials & interfaces, 2026, doi: 10.1021/acsami.5c22821.

[7] H. Kong, X. Chen, T. Chen, et al., “Robust conductive nanocomposite organic hydrogels for flexible sensing and intelligent human-machine interaction,” Chemical Engineering Journal, vol. 530, Art. no. 173576, 2026, doi: 10.1016/j.cej.2026.173576.

[8] J. Haney M, D. Ammons, and H. Choi, “Perceived safety during human-robot interaction with an autonomous mobile robot,” Applied Ergonomics, vol. 135, Art. no. 104747, 2026, doi: 10.1016/j.apergo.2026.104747.

[9] X. Jin and L. Chang, “277,” Characteristics of human-computer interaction behavior on social media: a longitudinal study on the correlation between usage duration, content interaction, language style, and loneliness. Schizophrenia Bulletin, vol. 52, no. Supplement_1, pp. S189, 2026, doi: 10.1093/schbul/sbag003.275.

[10] A. Korkmaz, “Mapping Eye-Tracking Research in Human-Computer Interaction: A Science-Mapping and Content-Analysis Study,” Journal of eye movement research, vol. 19, no. 1, pp. 23, 2026, doi: 10.3390/jemr19010023.

[11] Y. Wang, G. Sun, Z. Fu, et al., “Human-computer interaction and visualization in natural language generation models: applications, challenges, and opportunities,” Frontiers of Computer Science, vol. 20, no. 8, Art. no. 2008706, 2026, doi: 10.1007/s11704-025-50356-6.

[12] V. Lingam, J. Lee H J, and R. Perkins, “Designing for Usability: Optimizing Human-Computer Interaction,” The Medical clinics of North America, vol. 110, no. 2, pp. 177–189, 2026, doi: 10.1016/j.mcna.2025.07.006.

[13] L. Dai, J. Liu, and Z. Ju, “Space Human-Robot Interaction with Gaze Tracking Based on Attention Mechanism,” Biomimetics (Basel, Switzerland), vol. 11, no. 2, pp. 103, 2026, doi: 10.3390/biomimetics11020103.

[14] G. Zhang, “The Development of Emotional Interaction for Depressive Patients Based on Human-Computer Interaction Technology,” Academic Journal of Science and Technology, vol. 19, no. 2, pp. 47–51, 2026, doi: 10.54097/03cr8b77.

[15] J. Ge, B. Lin, and J. Zhang, “Research on Speech Intonation Recognition Technology Based on Deep Learning in Human-Computer Interaction,” Academic Journal of Science and Technology, vol. 19, no. 2, pp. 36–40, 2026, doi: 10.54097/wmfh7e61.

[16] J. Hao, “How Human-Computer Interaction Work in An Intelligent Cockpit,” Academic Journal of Science and Technology, vol. 19, no. 2, pp. 489–493, 2026, doi: 10.54097/eccr1g74.

[17] J. Su, “A Study on Strategies for Improving the Emotions of Depression Patients Based on Human-Computer Interaction Intervention Processes,” Academic Journal of Science and Technology, vol. 19, no. 2, pp. 52–56, 2026, doi: 10.54097/xtkz2m18.

[18] Y. Lu, D. Zhao, J. He, et al., “Kirigami-inspired integrated dual-mode sensor for wearable electronics and human-computer interaction,” Chemical Engineering Journal, vol. 529, Art. no. 172727, 2026, doi: 10.1016/j.cej.2026.172727.

[19] S. Biswas, H. Gajarla R, A. Nandy, et al., “ATR-Net: Attention-based temporal-refinement network for efficient facial emotion recognition in human-robot interaction,” Journal of Visual Communication and Image Representation, vol. 116, Art. no. 104720, 2026, doi: 10.1016/j.jvcir.2026.104720.