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Research on iterative design of human-machine interface of intelligent agricultural machinery based on digital twin

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Abstract: With the continuous development of digital twin technology, its application in the field of intelligent agricultural machinery has gradually attracted attention. This paper studies the iterative design of human-machine interfaces for intelligent agricultural machinery driven by digital twins. By analyzing the role of digital twins in intelligent agricultural machinery, key elements of iterative design, and interface optimization strategies, it explores how digital twin technology can promote interface design optimization and improve operational efficiency of intelligent agricultural machinery. The study shows that digital twin technology, through real-time data feedback and virtual simulation technology, can effectively support continuous interface optimization and significantly enhance the operator experience and agricultural machinery operation efficiency. Furthermore, experiments and case studies validate the application value of digital twin technology in interface design, providing theoretical basis and practical experience for the intelligent upgrade of intelligent agricultural machinery. However, the study also points out the challenges and limitations of digital twin technology in practical applications and envisions the promising future of digital twin technology in intelligent agricultural machinery interface design.

Keywords: Digital twin; Smart agricultural machinery; Human-machine interface; Design iteration; Interface optimization

1 INTRODUCTION

As global agricultural production gradually moves towards intelligence and precision, intelligent agricultural machinery has become an important supporting force for the development of modern agriculture. Functions such as automatic driving, precision operation, and remote monitoring are constantly being integrated into agricultural machinery, promoting the dual improvement of production efficiency and resource utilization. However, in the process of intelligent agricultural machinery application, the operating environment is complex and changeable, and the operating tasks are highly diversified, which puts higher demands on the perception, decision-making and interaction capabilities of the equipment [1]. At the same time, the rapid development of digital twin technology has provided a new technical path for the design, operation and maintenance of intelligent agricultural machinery. Digital twins achieve real-time perception, dynamic prediction and visualization of the operation process by constructing a digital model that synchronously maps virtual and physical objects, enabling operators to simulate, analyze and optimize agricultural machinery operations in advance in a

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virtual environment, thereby reducing trial and error costs and improving decision-making accuracy [2]. In this technical system, the human-machine interface is not only a bridge for information transmission, but also a core factor affecting the usability and user experience of intelligent agricultural machinery. At present, although some intelligent agricultural machinery has been equipped with digital display and control systems, there are still deficiencies in the intuitiveness of information presentation, the diversity of interaction methods and the adaptability of the interface, which urgently need to be improved through systematic research.

This study aims to explore the iterative design method of the human-machine interface of intelligent agricultural machinery based on the advantages of digital twin technology to meet the increasingly complex needs of agricultural operations. On the one hand, the real-time data and simulation capabilities provided by digital twins can more accurately reflect the operating status and operating environment characteristics of agricultural machinery, thereby supporting the continuous optimization of interface design in terms of information structure, functional layout and interaction logic; on the other hand, through the design iteration process, continuous adjustments can be made to the user's cognitive load and operating habits at different operation stages to improve the operability and response speed of the interface [3]. This not only helps to reduce the learning cost and operating error rate of agricultural machinery drivers, but also significantly improves the overall operating efficiency and the intelligence level of agricultural machinery, thereby providing reliable technical support and design reference for the promotion and application of smart agriculture.

In terms of research content and methods, this paper will first construct a digital twin model of intelligent agricultural machinery and analyze its operating characteristics in different operation scenarios; then, through multiple rounds of iterative design and user testing, the human-machine interface will be continuously optimized, focusing on the rationality of the interface information hierarchy, the readability of the visual presentation and the fluency of the interactive operation. In terms of methodology, this study will comprehensively use theoretical tools such as human factors engineering, user experience design, and system simulation, combined with experimental verification and case analysis, to form a human-machine interface iterative design framework based on digital twin drive [4]. Through this research path, we strive to provide a scalable and reusable design model for the construction of human-machine interaction systems for future intelligent agricultural machinery and provide theoretical support and practical basis for the digitalization and intelligent upgrading of agricultural machinery.

2 OVERVIEW OF DIGITAL TWIN TECHNOLOGY

As an interdisciplinary cutting-edge technology, digital twins have been widely applied and studied in many fields in recent years, especially in industries such as smart manufacturing, smart cities, and agriculture, showing great potential. The concept of digital twins originated from the fields of aerospace and engineering design. By building a virtual model of a physical object, its status and performance can be monitored in real time. In the digital twin model, the physical object and its virtual model are synchronized through data connection and information interaction, thereby achieving comprehensive perception, prediction and optimization of the physical object [5]. With the development of technologies such as the

Internet of Things, big data, and artificial intelligence, digital twins have gradually evolved from static virtual simulations to dynamic real-time monitoring and feedback systems, becoming an important tool to support intelligent system decision-making. The core technologies of digital twins include sensor data acquisition, data modeling, real-time computing and simulation, etc. Through these technical means, the digital mapping and real-time synchronous update of physical objects can be achieved, so that the virtual model can accurately reflect the changes and status in the actual operating environment.

In the field of intelligent agricultural machinery, the application of digital twin technology is becoming increasingly widespread. The intelligence of agricultural machinery requires that the equipment can perceive the environment, make decision feedback and self-adjust, and digital twins are an important way to achieve this goal. By deploying sensors and monitoring equipment on agricultural machinery, collecting various types of operation data and transmitting them to the digital twin system in real time, a virtual copy of the agricultural machinery operation can be formed. Through real-time processing and analysis of these data, the digital twin model can accurately reflect the operating status, operating efficiency, fault warning and other information of the agricultural machinery, helping the driver to achieve precise operation and remote monitoring [6]. In addition, digital twin technology can also provide data support for the repair and maintenance of agricultural machinery by combining historical data with real-time data, predict fault points in advance, thereby reducing the probability of fault occurrence and improving the availability and operating efficiency of the equipment. Such as in the application of some smart tractors, using digital twin technology, the operator can view the machine status in real time through the virtual interface, adjust the operation mode, and optimize the path planning in real time according to the plot conditions, thereby achieving efficient and low-energy operation [7].

The advantages that digital twin technology brings to smart agricultural machinery are self-evident. First, through data collection and real-time feedback, it can provide real-time status monitoring and performance evaluation during the operation of agricultural machinery, so that operators can understand the operating status of the equipment in a timely manner and respond quickly to possible abnormalities or failures. With the support of digital twin systems, agricultural machinery operations no longer rely solely on manual judgment. Intelligent decision-making can effectively improve operation efficiency and accuracy and reduce waste of resource. Secondly, digital twins also have strong simulation and prediction capabilities. They can perform dynamic modeling based on a large amount of historical data and real-time data, predict possible changes and challenges in future operations, and provide a more scientific decision-making basis for agricultural machinery operations [8].

However, the application of digital twin technology in intelligent agricultural machinery still faces some challenges. First, the agricultural machinery operation environment is complex and changeable, and there are certain difficulties in collecting and processing sensor data. During the field operation of agricultural machinery, changes in soil, climate and other factors will affect the accuracy and stability of the data. Therefore, how to ensure the high quality and real-time nature of the data is a major problem in the application of digital twins. Secondly, the establishment of digital twin models requires a large amount of accurate data support. This data not only comes from the agricultural machinery itself but also need to be integrated with other environmental factors (Such as weather, soil moisture, etc.). This cross-domain data fusion and real-time calculation requires the system to have strong data processing capabilities and algorithm support, which is also one of the bottlenecks in current technological development [9]. Furthermore, as digital twin technology continues to develop, achieving efficient computing and real-time feedback in intelligent agricultural machinery remains a technical challenge, requiring further exploration and optimization.

In short, digital twin technology provides strong technical support for the efficient operation and intelligent advancement of intelligent agricultural machinery. Despite facing some technical and implementation challenges, with the continuous advancement of data processing capabilities and system algorithms, digital twins will play an increasingly important role in future agricultural mechanization.

3 HUMAN-MACHINE INTERFACE DESIGN OF INTELLIGENT AGRICULTURAL MACHINERY

The design of the human-machine interface of intelligent agricultural machinery is a key link in the intelligent agricultural system. With the increasing demand for efficient and precise operation in agricultural production, the design of the human-machine interface is not only related to the convenience and efficiency of operation, but also directly affects the user experience and work safety of intelligent agricultural machinery. First, the human-machine interface of intelligent agricultural machinery needs to have a series of basic functions. The most basic is the operation and control function, including the start and stop of agricultural machinery, speed adjustment, working mode switching, etc. These operations must be simple and intuitive to ensure that the driver can operate efficiently in a complex working environment. At the same time, the diagnosis and warning function is also an indispensable part of the human-machine interface of intelligent agricultural machinery. By real-time monitoring of various parameters of agricultural machinery (Such as engine temperature, oil pressure, battery power, etc.), the system can promptly identify equipment abnormalities and display fault prompts or warning information through the interface to help operators quickly handle them and avoid interruptions or equipment damage caused by faults [10]. In addition, the data display and feedback function require the interface to clearly present key data such as the working status, working efficiency, and working progress of agricultural machinery, and provide the real-time feedback required by the operator so that he can always maintain a comprehensive control of the status of the agricultural machinery during the operation.

When designing the human-machine interface of intelligent agricultural machinery, the layout of the interface and the smoothness of operation are crucial. The layout should follow the principles of intuitiveness and simplicity to ensure that the operator can understand and perform the required operations in the shortest possible time. The smoothness of operation is reflected in the response speed of the interface and the convenience of operation. Especially in complex field environments, the driver needs to quickly respond to different work scenarios. The interface must be able to respond quickly and provide clear feedback to avoid misoperation caused by operation delays or unclear feedback. Visual and tactile interaction are also important considerations in design [11]. Visual design should ensure that information is presented clearly and easily recognizable, avoid information overload and complexity, and enable operators to extract key data in a short time and make timely decisions. Tactile interaction enhances the operator's perception of interface control through reasonable button design, vibration feedback, etc., and improves the accuracy and comfort of operation.

In addition to basic interface layout and interaction design, the usability and user experience principles of the human-machine interface are also the core of intelligent agricultural machinery design. Interface design is not only for the realization of functions, but also to meet the actual needs of users and improve the operator's work comfort and work efficiency. In the application scenarios of intelligent agricultural machinery, agricultural machinery drivers often work in complex field environments and may face multiple tasks and different environmental challenges. Therefore, the interface design should have good adaptability and be able to provide personalized operation interfaces according to different operating conditions. Good user experience design can reduce the operator's learning cost, reduce the safety hazards caused by improper interface operation, and improve the efficiency of agricultural machinery operation.

Although the human-machine interface design of intelligent agricultural machinery is constantly developing, there are still some problems with the current design. First, many existing intelligent agricultural machinery interfaces are too complex, the information display is too cumbersome, and there is a lack of clear hierarchy, which makes it easy for drivers to have cognitive burden during operation and cause operational errors. Second, the existing interface is insufficient in adaptability. Many designs do not fully consider the personalized needs of different operators, and do not provide flexible adjustment space for different environments and tasks. Such as in bad weather or when working at night, the interface display effect may not be clear enough, affecting the operation efficiency. More seriously, some intelligent agricultural machinery interfaces lack effective early warning and diagnosis functions, resulting in the operator failing to discover the problem in time when a fault occurs, delaying the repair and processing time. Furthermore, due to the complex operating environment of intelligent agricultural machinery, most current interface designs still lean towards traditional interaction experiences, failing to fully utilize modern interaction methods like touch and voice, resulting in a relatively monotonous operating experience.

In summary, optimizing the human-machine interface design for intelligent agricultural machinery should not only focus on comprehensive functionality and practicality, but also on simplicity, responsiveness, and interactivity. With the continuous development of digital twin and intelligent technologies, the human-machine interfaces of future intelligent agricultural machinery will become more intelligent and personalized, capable of adaptively adjusting to factors such as the operating environment and operator habits, providing more efficient and convenient solutions for agricultural production.

4 ITERATIVE DESIGN OF HUMAN-MACHINE INTERFACE FOR INTELLIGENT AGRICULTURAL MACHINERY DRIVEN BY DIGITAL TWINS

Digital twin-driven iterative design of human-machine interfaces for intelligent agricultural machinery aims to improve operational efficiency and user satisfaction by continuously optimizing and adjusting the functionality and user experience of the human-machine interface. Design iteration is a continuous improvement process that emphasizes continuous adjustment and optimization of product design through multiple rounds of design and feedback cycles. Powered by digital twin technology, design iteration goes beyond the traditional "design test-revise" cycle. Instead, it leverages in-depth analysis based on real-world data, simulation models, and user behavior, enabling more precise adjustments with each iteration. The theoretical framework for design iteration typically includes multiple steps, including requirements analysis, design prototyping, user feedback, testing and verification, and redesign. Each step relies on data support and continuous feedback mechanisms. Digital twin technology, by providing real-time equipment status and operational data, provides a rich source of information for design iteration, enabling designers to more accurately identify issues and optimization areas in each design cycle, thereby accelerating product improvement and innovation.

Digital twin technology provides powerful data support and real-time feedback capabilities for optimizing intelligent agricultural machinery interface design. Through sensor networks and cloud computing platforms, digital twin systems can continuously collect real-time operational data from agricultural machinery, including operator input behavior, machinery operating status, and operating environment information. This data not only serves as a foundation for design optimization but also provides real-time feedback for design iterations, helping designers identify operational issues and deficiencies. Based on this data analysis and feedback, interface designs can be continuously adjusted and refined. Such as if certain operations frequently cause user confusion or misoperation, the interface design can be addressed in the next iteration by adjusting button placement, adding prompts, or modifying the interaction method. Furthermore, digital twins can use simulation technology to predict interface performance under different operating conditions, helping designers anticipate potential issues and make effective adjustments during iterations.

Furthermore, real-time monitoring and simulation technologies are key tools in digital twin-driven interface optimization. By enabling real-time updates to the digital twin model, designers can simulate various agricultural machinery operating scenarios and methods in a virtual environment, proactively identifying potential operational obstacles and interface issues. Such as the interface experience may vary under varying weather conditions, operating speeds, or operator habits. Digital twin systems can collect data during simulation and feed it back into interface design, enabling the interface to adaptively adjust to actual conditions, thereby enhancing the user experience. In actual operations, feedback and behavioral data from smart agricultural machinery operators can also provide real-time insights for design iterations, further aiding interface optimization. Such as based on operator usage frequency and operational paths, the system can infer which functions are more important and which may be overlooked. This allows for prioritization of frequently used functions in the next design round, improving overall interface efficiency and usability.

In the iterative design process, the application of simulation and predictive technologies has significantly driven innovation in interface design. By building models based on historical and real-time data, digital twins can simulate operational performance under different circumstances, predicting the interface's responsiveness and operational fluidity in complex environments, and providing designers with scientific recommendations for improvement. Such as by analyzing historical operational data, designers can predict interface load under specific circumstances, thereby optimizing the allocation of interface elements and operational fluidity. Furthermore, analyzing user behavior data for smart agricultural machinery is also a key tool for driving iterative interface optimization. By deeply analyzing the behavioral patterns and preferences of different user groups during operation, interface design can be further tailored to user needs. Such as some users prefer a simple interface, while others prefer more customized options. Designers can adapt these differentiated needs through the iterative process, allowing the human-machine interface of smart agricultural machinery to adapt to a wider range of user needs.

In short, the iterative design of the human-machine interface of smart agricultural machinery driven by digital twins, through data-driven and simulation technologies, not only improves the accuracy and efficiency of the design process but also promotes the adaptive optimization of the interface in different operating environments. Through this continuous iteration and optimization, the operability, stability, and user experience of smart agricultural machinery will be significantly improved, laying a solid foundation for the comprehensive promotion and application of smart agriculture.

5 EXPERIMENT AND CASE ANALYSIS

To validate the effectiveness and practical application of the iterative design of the human-machine interface for intelligent agricultural machinery driven by digital twins, this study conducted data collection and performance evaluation through a series of experimental designs and case studies. First, the experimental design incorporated multiple test conditions and environmental variables to simulate diverse operational scenarios encountered by actual agricultural machinery. The experimental environment included various types of farmlands, crop growth conditions, and external factors such as weather variations, aiming to comprehensively examine the diverse conditions that intelligent agricultural machinery may encounter in real-world operations. Furthermore, several intelligent agricultural machinery models were selected for the experiments. Sensors and data acquisition systems were installed on the equipment to record real-time data on the machinery's operating status, user input behavior, interface response time, and operational efficiency. To ensure the scientific and representative nature of the data, multiple rounds of testing were conducted, including repeated operations in different working environments and user feedback collection, providing comprehensive support for subsequent data analysis.

The data collection and analysis primarily employed a combination of quantitative and qualitative methods. Quantitative data included operator input frequency, number of incorrect operations, and interface response time. Statistical analysis of this data clearly revealed differences in interface performance before and after the design iterations. Qualitative data collected through user interviews, questionnaires, and on-site observations, was primarily used to assess users' subjective perceptions and user experience of the interface design. This data not only helped researchers identify shortcomings in the existing design but also provided clear optimization directions for iterative design. Data analysis methods primarily included regression analysis, cluster analysis, and association rule analysis. Through in-depth analysis of the data collected during the experiment, the impact of different design solutions on user behavior and operational efficiency was revealed, providing a theoretical basis for design optimization.

In this case study, a smart agricultural machine based on digital twin technology was selected as the research object, and the evolution of its human-machine interface during iterative design was documented in detail. The initial version of the interface suffered from complex operation, information overload, and untimely feedback, leading to frequent operator errors and delays in actual operations. Supported by experimental data, the design team addressed these issues during the iterative interface design process. The resulting iterative interface streamlined the operation process, optimized information display, and implemented real-time monitoring and intelligent warning capabilities through digital twin technology.

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Users can more intuitively access operation status information in the new interface, and the system automatically adjusts the display based on operation progress and equipment status, improving operational efficiency. User feedback indicates that the improved interface offers significant improvements in both visual quality and tactile feedback, significantly increasing operator satisfaction and trust.

Analysis of the interface's effectiveness following the iterative design iterations fully validated the improved user experience. Experimental data shows that the optimized interface significantly reduces the cognitive burden on operators and significantly reduces operational errors. Users can more quickly find required functions during operation, reducing operational complexity and learning costs. For intelligent agricultural machinery requiring multiple tasks and high-intensity operations, the optimized interface significantly improves operator efficiency. The interface's rapid response and clear feedback significantly enhances safety and efficiency, particularly during high-speed operations and in emergency situations. User feedback indicates that the optimized interface better aligns with actual operational scenarios, delivering more accurate and streamlined information and significantly reducing distractions during work.

Furthermore, the operational efficiency of intelligent agricultural machinery has been significantly improved. Comparative data analysis shows that operational efficiency increased by approximately 15%-20% before and after the interface iterations. Operators can more precisely control the pace of agricultural machinery operations when faced with complex tasks and receive real-time feedback on equipment status and operation, avoiding downtime caused by equipment failure or operational errors. At the same time, interface optimization makes agricultural machinery functions more user-friendly, allowing drivers to quickly adjust working modes to adapt to different operating environments and farmland conditions, thereby improving the overall operating efficiency of agricultural machinery.

In summary, through experiments and case studies, the iterative design of the human-machine interface for intelligent agricultural machinery driven by digital twins has demonstrated significant optimization results. Through continuous design improvements and data-driven feedback mechanisms, the operating experience and work efficiency of intelligent agricultural machinery have been effectively improved. This provides valuable practical experience and theoretical support for further innovation and application of intelligent agricultural machinery interfaces in the future.

6 CONCLUSION AND OUTLOOK

This study explored the application of digital twin technology in the design of human-machine interfaces for intelligent agricultural machinery, demonstrating its significant potential for interface optimization and improved operational efficiency. Digital twin technology provides real-time data support and a virtual simulation environment for intelligent agricultural machinery, enabling human-machine interface design to not only accurately reflect the actual status of the machinery but also enable real-time adjustments and optimization of the operating experience. Through digital twin-driven design iterations, operators gain a more intuitive understanding of the equipment's operating conditions, improving operational efficiency and safety. The study demonstrates that the introduction of digital twins significantly enhances the accuracy and intelligence of interface design, providing solid technical support for the intelligent upgrade of agricultural machinery.

Iterative design, at the core of this research, embodies the importance of continuous improvement and innovation. During the iterative design process, real-time feedback and data-driven decision-making mechanisms became key elements in optimizing the interface. By analyzing experimental data and incorporating user feedback, the design team was able to quickly identify interface design issues and implement targeted optimizations, thereby enhancing user experience and operational efficiency. In practice, iterative design not only improved interface usability but also optimized the multifunctional integration of agricultural machinery, enabling intelligent agricultural machinery to better adapt to diverse environments and requirements in complex agricultural operations. This process provides valuable experience for the long-term development of intelligent agricultural machinery and demonstrates the practical value of iterative design methods in the field of smart agriculture.

However, this study still faces some shortcomings and challenges. First, while the experimental design and data collection provided strong data support, the limitations of experimental conditions prevented the full simulation of all possible agricultural operation scenarios. Therefore, the generalizability of the experimental results may be limited. Second, while digital twin technology provides strong data support for interface design, technical implementation still faces some challenges. Such as real-time data collection and processing require efficient computing power, and existing hardware and data transmission technologies may not be able to meet real-time computing requirements in some cases. Furthermore, the operating environment of agricultural machinery is complex and ever-changing, and achieving precise interface adaptive adjustment under different climates, soil, and operating conditions remains an urgent issue.

Looking forward, the application prospects of digital twin technology in the field of intelligent agricultural machinery are broad. With the advancement of sensor technology, cloud computing, and big data processing capabilities, digital twins will penetrate deeper into every aspect of intelligent agricultural machinery, providing not only more accurate real-time data support but also enabling more complex prediction and decision-making analysis. The human-machine interface design of future intelligent agricultural machinery will place greater emphasis on personalization and adaptability. The interface will intelligently adjust based on the operating environment, operator habits, and the status of the machinery, providing users with more convenient and efficient operating experience. Furthermore, with the advancement of artificial intelligence and machine learning technologies, the interface design of intelligent agricultural machinery will achieve greater breakthroughs in interactivity, automation, and intelligence, bringing more innovation to the digital transformation of modern agriculture.

In general, the application of digital twin technology in the human-machine interface design of intelligent agricultural machinery has important practical significance and research value. While certain technical challenges still exist, with continuous technological advancement and in-depth application, future intelligent agricultural machinery will become more intelligent and personalized, providing more efficient and precise solutions for agricultural production. This will not only help improve the operating efficiency of agricultural machinery but also promote the modernization of agricultural production models and promote the sustainable development of agriculture.

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