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A Sensor-based Multi-modal Evaluation Framework for Optimizing Redesigned Interdisciplinary Human–Machine Interfaces by Webcam-based Eye-tracking in Intelligent Manufacturing

Hong-Yi Chen*

Department of Product Design, Tainan University of Technology,
No. 529, Zhongzheng Rd., Yongkang Dist., Tainan City 71002, Taiwan

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In this study, a sensor-based evaluation framework is developed to validate a redesigned interdisciplinary human–machine interface (HMI) by webcam-based eye-tracking in intelligent manufacturing systems. Traditional industrial HMIs often contain excessive and mixed information for different user roles, which reduces operational clarity and increases cognitive burden. To improve interface performance, a role-oriented redesign strategy is implemented on the basis of user interface/user experience design principles. A sensor-enhanced evaluation approach is adopted by integrating webcam-based eye-tracking measurement, behavioral performance data, and System Usability Scale assessment, where the eye-tracking sensor captures visual attention distribution during task execution. Experimental results showed that the redesigned interface produces a more concentrated visual attention pattern and reduces unnecessary visual scanning. The task error rate decreases from 66.7% in the original interface to 13.3% in the redesigned interface, while usability perception also improves after redesign. Overall, the results demonstrated that sensor-based visual attention measurement combined with quantitative usability assessment provides a practical and reproducible approach for evaluating HMI design optimization in industrial applications, highlighting its relevance to sensor-based sensing systems and intelligent human-centered interface technologies.

1. Introduction

The rapid development of intelligent manufacturing systems has increased the demand for efficient and reliable human–machine interfaces (HMIs). As industrial equipment becomes more automated and information-intensive, operators must process large amounts of real-time data during task execution. However, many industrial control interfaces remain function-

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*Corresponding author: e-mail: te0068@mail.tut.edu.tw
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oriented and information-dense, which may reduce operational clarity and increase cognitive burden in real manufacturing environments.(1)

To address these challenges, interdisciplinary approaches integrating industrial design, human–computer interaction, and usability engineering have been increasingly adopted to improve HMI performance. Previous studies on interface evaluation emphasize that effective usability assessment requires structured evaluation processes and measurable performance indicators rather than relying solely on subjective judgments.(2) These approaches highlight the importance of combining interface redesign with systematic evaluation methods to ensure that design improvements can be objectively validated.

With the advancement of sensing technologies, sensor-based evaluation methods have been gradually introduced into usability research and industrial human-factor studies.(3,4) In particular, eye-tracking sensors provide valuable information about visual attention, gaze distribution, and user interaction behavior during task execution, serving as a sensing mechanism for capturing user attention and interaction patterns in human–machine systems. Recent studies have demonstrated that eye-tracking metrics can support user experience analysis and help reveal interface complexity and visual search behavior in digital interaction environments.(5)

Among these approaches, webcam-based eye-tracking systems have attracted growing attention owing to their accessibility and low deployment cost. Compared with laboratory-grade eye-tracking hardware, webcam-based solutions enable practical data collection in real operating environments while maintaining acceptable levels of gaze estimation accuracy.(6–8) Furthermore, recent research indicates that sensor-supported usability evaluation frameworks can provide meaningful behavioral insights even when lightweight sensing technologies are used, demonstrating the applicability of sensor-based sensing systems in real-world industrial scenarios.(9)

On the basis of this background, a sensor-based multi-modal evaluation framework is developed in this study for assessing redesigned interdisciplinary HMIs using webcam-based eye-tracking in intelligent manufacturing equipment. By integrating webcam-based eye-tracking measurement, behavioral performance metrics, and usability assessment, in this research, we aim to provide a practical and reproducible approach for validating interface optimization in industrial applications, with a focus on sensor-based evaluation for human-centered system design and sensing applications.

2. Related Work

Recent studies related to sensor-based interface evaluation and interdisciplinary HMI design are reviewed in this section. The discussion focuses on eye-tracking applications in usability assessment, sensor-supported interaction analysis, and their relevance to intelligent manufacturing systems. By examining these studies, in this section, we aim to clarify the research context and identify the research gap addressed in the present work, particularly the limited integration of sensor-based visual attention measurement with multi-modal evaluation approaches in real industrial HMI redesign scenarios.

While previous studies have investigated eye-tracking for usability analysis and sensor-supported evaluation methods independently, there remains a lack of comprehensive frameworks that combine webcam-based eye-tracking, behavioral performance metrics, and usability assessment for evaluating redesigned interdisciplinary HMIs in intelligent manufacturing environments. In this study, we address this gap by proposing a sensor-based multi-modal evaluation framework that integrates these components into a unified and practical evaluation approach.

2.1 Sensor-based eye-tracking in interface evaluation

In recent years, sensor-based eye-tracking has become an important method for evaluating interface usability and visual attention distribution. Compared with traditional questionnaire-based assessments, eye-tracking sensors provide objective data on users' gaze behavior, fixation duration, and visual search patterns during interaction.(10) These sensor-derived metrics enable researchers to quantitatively analyze how users process interface information in real time, highlighting their role as sensing mechanisms for capturing dynamic human–machine interaction behaviors. Methodological research has also emphasized that eye-tracking metrics can serve as reliable indicators for usability evaluation and accessibility analysis in interactive systems.(11)

Recent studies have demonstrated that eye-tracking indicators can effectively reveal interface complexity and layout efficiency. Zhang *et al.*(12) showed that different layout orders significantly affect visual search behavior and perceived interface complexity. Their findings indicate that gaze distribution patterns can be used as measurable indicators for evaluating interface structure. Similarly, Falkowska *et al.*(13) applied eye-tracking metrics to assess user experience in web design, demonstrating that fixation time and gaze transition patterns are strongly associated with perceived usability and interaction clarity.

Although these studies confirm the effectiveness of sensor-based eye-tracking in interface evaluation, most existing applications focus on web interfaces or general human–computer interaction environments. Research applying eye-tracking sensors to intelligent manufacturing equipment remains relatively limited. In addition, few studies integrate sensor-based measurements with interdisciplinary design-driven interface redesign, particularly in the context of real industrial operation scenarios using accessible sensing technologies such as webcam-based eye-tracking systems. Therefore, further investigation is needed to explore how sensor-based evaluation methods can support systematic HMI optimization in industrial environments, which forms the basis of the proposed multi-modal evaluation framework in this study.

2.2 Multi-modal sensor integration in usability and HMI research

Beyond single-sensor eye-tracking analysis, recent research increasingly emphasizes the integration of multiple evaluation metrics to achieve a more comprehensive understanding of user interaction. In human–computer interaction research, combining physiological sensing data with behavioral performance measurements has been shown to improve the robustness of usability evaluation. Recent studies also demonstrate that eye-tracking indicators can be integrated with usability assessment methods to evaluate interaction affordances and design performance in complex systems,(14) highlighting the role of multi-modal sensing systems in capturing diverse aspects of human–machine interaction.

Eye-tracking alone can reveal visual attention patterns; however, gaze data do not fully represent operational efficiency or task performance.(15) For this reason, several studies recommend combining sensor-derived indicators with behavioral performance metrics such as task completion time, error rates, and standardized usability scales.(16) This multi-modal evaluation approach allows researchers to triangulate user performance from multiple dimensions, including cognitive load, interaction efficiency, and subjective user satisfaction, thereby enhancing the reliability of sensor-based evaluation in applied environments.

Furthermore, emerging research in human–machine systems highlights the importance of applying sensor-based evaluation methods to complex operational environments rather than relying solely on laboratory-controlled experiments.(17) Industrial systems typically involve higher information density and stricter performance requirements, which require evaluation frameworks capable of capturing both visual attention and practical operation outcomes, particularly when using accessible sensing technologies such as webcam-based eye-tracking systems in real-world scenarios.

Despite these advances, limited research has systematically combined interdisciplinary design-driven HMI redesign with multi-modal sensor evaluation in intelligent manufacturing contexts. This limitation motivated us to develop and validate a sensor-based, multi-modal framework specifically designed for industrial HMI optimization, integrating webcam-based eye-tracking, behavioral performance metrics, and usability assessment into a unified evaluation approach.

2.3 Research gap and positioning of the present study

Although previous studies have demonstrated the value of sensor-based eye-tracking and multi-modal usability evaluation, several limitations remain in current research. First, most eye-tracking applications focus on web interfaces, educational platforms, or general human–computer interaction environments, while relatively fewer studies address industrial HMIs characterized by high information density and operational complexity. Some recent studies applying eye-tracking methods to practical interaction scenarios also suggest that usability evaluation can benefit from combining gaze analysis with contextual system design considerations,(18) highlighting the need for sensor-based evaluation approaches tailored to complex industrial systems.

Second, existing research often evaluates interface performance without integrating systematic design-driven redesign processes. In many cases, sensor-based measurements are used primarily for observation rather than as part of a comprehensive optimization framework that connects industrial design principles with quantitative performance validation, indicating a lack of unified sensing-based frameworks for design optimization in industrial HMI contexts.

Third, limited research has applied webcam-based eye-tracking systems to industrial interface evaluation. Although laboratory-grade eye trackers can provide high measurement precision, cost-effective sensing solutions may offer practical alternatives for applied design research and industry-oriented collaboration, especially in real-world environments where scalable sensing technologies are required.

To address these limitations, a sensor-based multi-modal evaluation framework is proposed in this study, integrating interdisciplinary HMI redesign with eye-tracking analysis, behavioral metrics, and standardized usability assessment. By applying this framework to intelligent manufacturing equipment, in this work, we aim to bridge the gap between design-driven interface optimization and sensor-supported performance validation in industrial contexts, offering a practical and reproducible sensing-based evaluation approach that combines accessible webcam-based eye-tracking with multi-modal performance analysis.

3. Materials and Methods

In this section, we describe the materials and methods used to evaluate the redesigned interdisciplinary HMI for intelligent manufacturing equipment. In this study, we integrated interdisciplinary interface redesign with sensor-based measurement and behavioral evaluation methods, with a particular emphasis on webcam-based eye-tracking as a sensing technology for capturing visual attention during human–machine interaction. A multi-modal evaluation framework was established, combining eye-tracking data, behavioral performance metrics, and usability assessment to analyze the effectiveness of the redesigned interface. The overall research framework and experimental procedures are described in the following subsections.

3.1 Research framework

The overall research framework of this study is illustrated in Fig. 1. The framework integrates interdisciplinary design methods with sensor-based evaluation to assess the effectiveness of redesigned interdisciplinary HMIs in intelligent manufacturing environments.

First, relevant studies on HMIs, usability evaluation, and sensor-based eye-tracking methods were reviewed to establish the theoretical background of the study. On the basis of the findings of such studies, an interface redesign was conducted using industrial design and user interface/user experience (UI/UX) principles to simplify the information structure and improve visual guidance.

Next, a sensor-based evaluation approach was implemented with webcam-based eye-tracking to capture users' visual attention patterns during interface interaction, serving as a sensing mechanism for analyzing human–machine interaction behavior in real time. Behavioral performance metrics, including task completion time and operational errors, were also recorded. In addition, usability perception was assessed using the System Usability Scale (SUS).

Finally, the collected sensor data, behavioral metrics, and usability scores were analyzed to compare the performance characteristics of the original and redesigned interfaces. Through this integrated framework, in this study, we aim to provide a systematic method for evaluating design

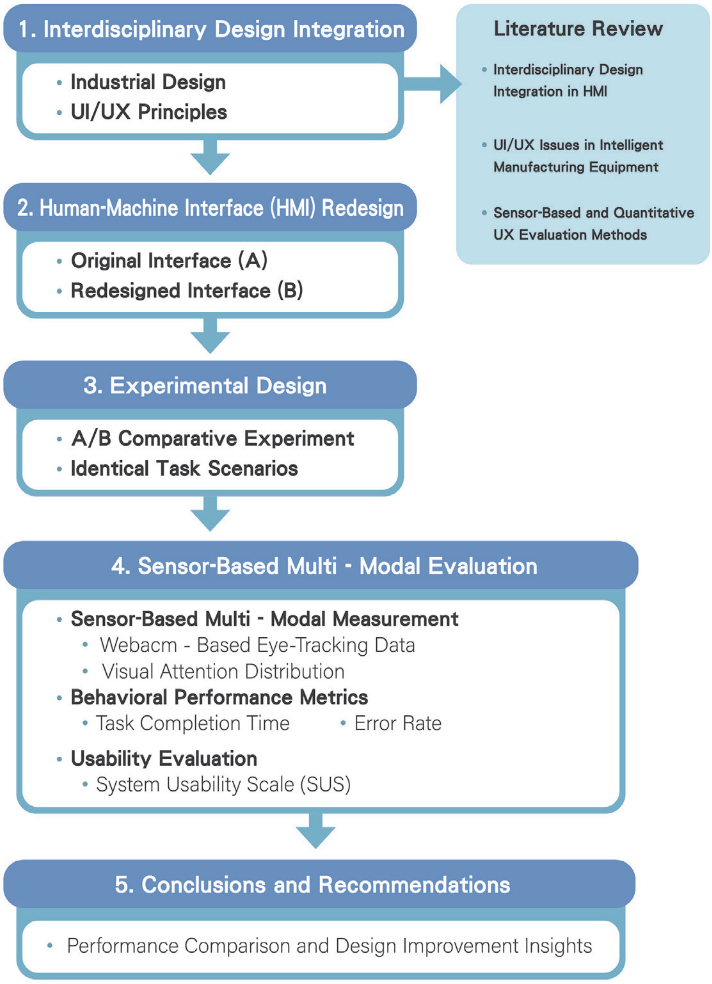


Fig. 1. (Color online) Research framework of the proposed sensor-based multi-modal evaluation approach for evaluating redesigned interdisciplinary HMIs by webcam-based eye-tracking in intelligent manufacturing.

improvements in intelligent manufacturing interfaces, by integrating multi-modal sensing data with design-driven interface optimization.

3.2 Interface redesign and system context

The original interface used in the industrial equipment contained a large number of operational parameters displayed simultaneously on the control panel. While this layout allowed operators to access all parameters on a single screen, the high density of information often made it difficult to quickly locate critical operational data. Such interface characteristics may increase visual search effort and cognitive workload during operation, especially in time-sensitive manufacturing environments.

To address these issues, an interdisciplinary design approach was applied to reorganize the interface layout. The redesign focused on improving visual hierarchy and grouping-related parameters, and reducing unnecessary visual clutter. Key operational indicators were positioned in visually prominent areas to facilitate rapid information recognition and decision-making, reflecting the principles of redesigned interdisciplinary HMI optimization.

The redesigned interface is part of a larger industrial HMI system used in intelligent manufacturing equipment. The system integrates multiple information modules, including operational parameters, status monitoring indicators, and control functions. Understanding the overall structure of the interface environment is important for interpreting user interaction behavior during the evaluation process, particularly in relation to the sensor-based observation of user attention and interaction patterns.

As illustrated in Fig. 2, the redesigned interface is embedded within a hierarchical HMI system architecture that organizes different categories of operational information. This structure supports clearer information grouping and provides a more intuitive interaction environment for operators.

On the basis of usability principles and visual hierarchy design strategies,(12) the interface was redesigned to simplify the information structure and improve interaction clarity. The redesigned interface (Interface B) reorganized parameter groups, reduced the number of redundant visual elements, and emphasized key operational information through the improved layout structure and visual guidance, representing a redesigned interdisciplinary HMI optimized for improved usability and visual efficiency.

Figure 3 presents a comparison between the original interface and the redesigned interface used in the experiment. While the original interface distributes attention across multiple parameters simultaneously, the redesigned interface guides users' visual focus toward critical operational information, thereby improving visual efficiency and usability, which supports a more effective sensor-based observation of user attention patterns during interaction.

3.3 Sensor-based measurement and data collection

Participants in the experiment consisted of 15 individuals, including 10 machine operators and 5 UI designers. The machine operators had prior experience interacting with industrial equipment interfaces, whereas the UI designers had professional experience in interface design but did not have practical machine operation experience. This participant composition was intended to represent both practical equipment users and interface design perspectives in the

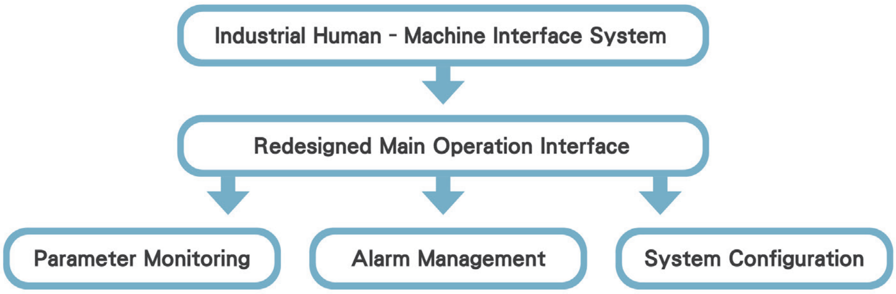
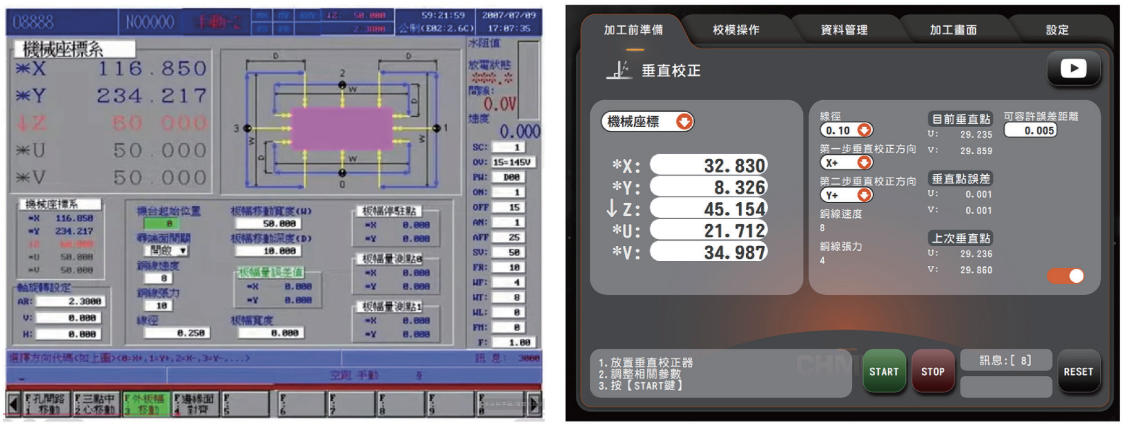


Fig. 2. (Color online) System architecture of the redesigned interdisciplinary HMI used in the experiment.



1. 放置垂直校正器
2. 調整相關參數
3. 按【START鍵】

Fig. 3. (Color online) Comparison of the original HMI (Interface A) and the redesigned interdisciplinary HMI (Interface B) used in the experiment.

evaluation process, with a greater emphasis on machine operators to reflect the real-world usage conditions of industrial HMI systems. All participants voluntarily took part in the experiment and provided informed consent before the study.

To analyze users' visual attention and interaction behavior during interface operation, we employed a sensor-based evaluation approach using webcam-based eye-tracking technology. Eye-tracking data were collected using GazeRecorder, a webcam-based eye-tracking system that enables gaze tracking through a standard computer camera. In this study, a Logitech C925e webcam was used as the image capture device. Compared with laboratory-grade eye-tracking devices, webcam-based systems provide lower measurement precision but offer higher accessibility and flexibility for practical design evaluation scenarios.

During the experiment, the webcam was positioned in front of the display, and the distance between the participant and the screen was maintained at approximately 60–80 cm, corresponding to the typical viewing distance observed when machine operators interact with industrial control panels. The experiment was conducted under normal indoor lighting conditions without additional lighting equipment to simulate realistic operating environments. Before the experiment began, calibration was performed according to the standard calibration procedure provided by the GazeRecorder software, in which participants sequentially looked at several calibration points displayed on the screen to establish the mapping relationship between gaze direction and screen coordinates, starting from a central fixation point and proceeding to calibration points located at the corners of the display.

In this study, the eye-tracking system was primarily used to observe visual attention distribution patterns and interaction focus during interface operation rather than to obtain high-precision physiological gaze measurements. Eye-tracking methods have been widely applied in usability and user experience research to analyze visual attention patterns in interface interaction.(19)

Previous studies have also demonstrated the feasibility of webcam-based gaze estimation for human–computer interaction analysis, showing that acceptable gaze estimation performance can be achieved without specialized eye-tracking hardware.(20) In addition, webcam-based eye-tracking approaches have been used in behavioral research environments where lightweight and easily deployable sensing technologies are required.(21)

Prior to formal data collection, each participant completed one practice trial to become familiar with the experimental procedure and to reduce potential learning effects and adaptation issues associated with the eye-tracking system. Only the data obtained from the second trial were used for analysis in this study.

During the experiment, participants performed identical operational tasks on both the original interface (Interface A) and the redesigned interface (Interface B), with the original interface evaluated first, followed by the redesigned interface. Each task was limited to a maximum duration of 40 s to simulate a realistic machine operation scenario in which operators identify and confirm critical parameters within a practical time window. Participants were required to complete parameter identification tasks within the time limit, and successful task completion was defined as correctly identifying the required information within 40 s. The eye-tracking system recorded users' gaze movements and generated visual attention heatmaps representing gaze concentration across interface elements.

The operational tasks were designed to simulate real industrial scenarios and included three main categories: (1) monitoring machine coordinate parameters during system initialization, (2) identifying initial position settings and wire-cutting parameters prior to machining, and (3) evaluating machine operating parameters during active processing to determine system status.

In addition to eye-tracking measurements, behavioral performance metrics were also recorded, including task completion time and operation error rate, to evaluate operational efficiency and accuracy. In this study, the operation error rate was defined on the basis of task completion performance rather than interaction mistakes. Owing to the error-tolerant nature of modern HMIs, incorrect selections or parameter misidentifications were not treated as critical errors. Instead, an error was defined as the failure to complete the required task within the specified time limit (40 s). Furthermore, perceived usability was assessed using the SUS, which was administered after participants completed all interface interaction tasks to capture their overall experience.

By integrating eye-tracking observations with behavioral performance data and usability evaluation results, we established a multi-modal evaluation framework for assessing interface redesign effectiveness. The experimental setup and evaluation metrics used in this study are summarized in Table 1.

4. Results

In this section, we present the experimental results obtained from the sensor-based multi-modal evaluation framework for redesigned interdisciplinary HMIs. The analysis focuses on three types of evaluation data collected during the experiment: eye-tracking observations, behavioral performance metrics, and usability assessment results.

First, visual attention patterns captured by the eye-tracking system are analyzed to compare gaze distribution between the original interface and the redesigned interface, providing sensor-

Table 1
Experimental setup and evaluation metrics for sensor-based multi-modal evaluation.

Category	Description	Purpose
Eye-tracking device	Logitech C925e webcam with GazeRecorder software	Visual attention measurement
Participant distance	60–80 cm from the display	Simulate machine operator viewing distance
Lighting condition	Indoor natural lighting	Maintain realistic operating environment
Calibration	Standard GazeRecorder calibration procedure	Establish gaze–screen coordinate mapping
Experimental interfaces	Interface A (original), Interface B (redesigned)	Comparative usability evaluation
Practice trial	One trial before formal experiment	Reduce learning effect and ensure familiarity with tasks and system
Operational tasks	Machine coordinate monitoring; initial position and wire-cutting parameter identification; machine operation status evaluation	Simulate real industrial operation scenarios
Behavioral metrics	Task completion time, time-based error rate (failure to complete within 40 s)	Operational performance analysis
Usability evaluation	SUS	Subjective usability assessment

based insights into user visual attention and interaction behavior. Next, behavioral performance indicators, including task completion time and operation error rate, are examined to evaluate operational efficiency. Finally, usability perception results derived from the SUS are presented to assess user satisfaction with the redesigned interface.

By combining these evaluation results, the effectiveness of the interface redesign is systematically examined and compared with the original interface, demonstrating the impact of multi-modal sensor-based evaluation on validating interface optimization performance.

4.1 Visual attention analysis

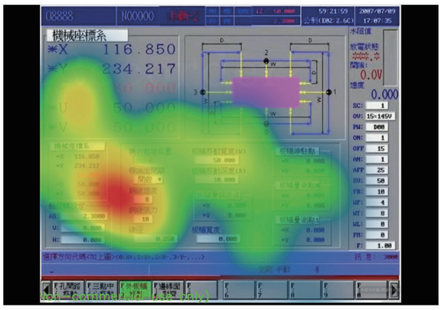
To investigate users' visual attention patterns during interface interaction, the eye-tracking data collected from the experiment were analyzed. The gaze data were visualized using heatmaps generated by the GazeRecorder system, which represent the distribution and concentration of visual attention across different areas of the interface, serving as a sensor-based visualization of user attention behavior during task execution. Warmer colors in the heatmap indicate regions that received higher levels of visual attention, whereas cooler colors represent areas with lower gaze concentrations.

The heatmap analysis was conducted across three operational task scenarios, including machine coordinate monitoring, initial position and parameter identification, and machine operation status evaluation, to reflect realistic industrial interaction conditions.

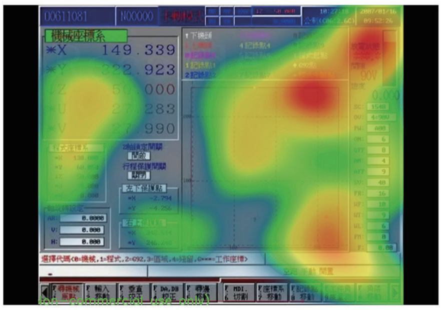
Figure 4 presents the heatmap visualization of users' visual attention while interacting with the original interface (Interface A) and the redesigned interface (Interface B).

In contrast, the redesigned interface demonstrates a more concentrated visual attention pattern, where users' gaze is more focused on key operational areas, indicating improved visual guidance and reduced unnecessary visual scanning.

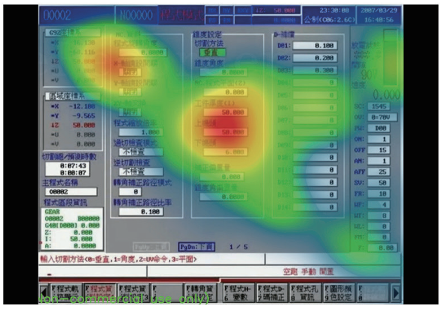
Original



(a) Task 1



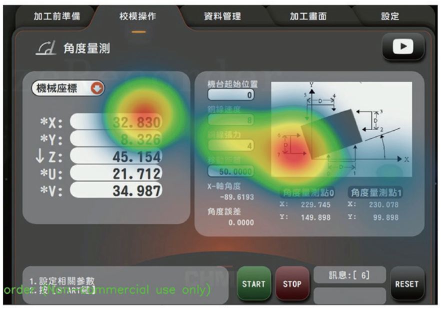
(b) Task 2



(c) Task 3

Redesigned

(d) Task 1



(e) Task 2

(f) Task 3

Fig. 4. (Color online) Eye-tracking heatmap comparison between the original HMI (Interface A) and the redesigned interdisciplinary HMI (Interface B) across three operational tasks. (a–c) Original interface: (a) Task 1 – machine coordinate monitoring, (b) Task 2 – initial position and parameter identification, (c) Task 3 – machine operation status evaluation, and (d–f) Redesigned interface: (d) Task 1, (e) Task 2, (f) Task 3.

As shown in Fig. 4, the visual attention pattern of the original interface is distributed across multiple interface regions, indicating that users needed to scan a wider range of interface elements to locate relevant operational information. The heatmap shows that gaze activity spreads over a relatively large area with fewer highly concentrated fixation hotspots. This dispersed gaze distribution suggests that the original interface required greater visual search effort during task execution, resulting in increased cognitive load and reduced efficiency in identifying critical parameters.

In contrast, the redesigned interface demonstrates a more concentrated visual attention pattern. As illustrated in Fig. 4, gaze activity is more strongly focused on key operational information areas, and several high-intensity fixation hotspots (red regions) appear near critical interface elements. This indicates that users were able to identify important parameters more quickly and maintain their attention on relevant information areas. The improved visual hierarchy and grouped information structure appear to guide users' visual attention toward important interface elements, thereby reducing unnecessary visual scanning, which is consistent with the intended design objective of improving intuitive interaction performance.

To further interpret the visual attention patterns observed in the heatmap visualization, the qualitative differences between the two interface conditions were summarized on the basis of the three operational tasks described in Sect. 3.3. Table 2 presents a comparison of visual attention characteristics between the original interface and the redesigned interface, including gaze distribution patterns, fixation hotspot intensity, and visual search behavior.

In addition to the qualitative observations derived from the heatmap visualization, the structure of the eye-tracking data exported from the experimental system was examined to provide supplementary insight into the sensor-based data acquisition process. Table 3 shows a summary of the key parameters and data structure obtained from the GazeRecorder output files, including the numbers of tracking frames and gaze samples recorded during the experiment, which support the interpretation of visual attention patterns observed in the heatmap analysis.

As shown in Table 3, the eye-tracking system recorded multiple gaze samples within each tracking frame, providing sufficient observational data for visual attention analysis and supporting the reliability of the sensor-based data collection process. These data support the heatmap visualization and enable the comparison of visual attention patterns between the original interface and the redesigned interface, primarily for qualitative interpretation rather than highly precise quantitative eye-tracking measurement.

4.2 Task performance analysis

In addition to visual attention analysis, task performance metrics were analyzed to evaluate the operational efficiency of the two interface conditions. In this study, task completion time and

Table 2
Comparison of visual attention characteristics between the original HMI (Interface A) and the redesigned interdisciplinary HMI (Interface B).

Visual attention metrics	Interface A (original interface)	Interface B (redesigned interface)
Gaze distribution pattern	Widely distributed across multiple interface regions	Concentrated around key operational information areas
Fixation hotspot intensity	Few highly concentrated fixation hotspots	Several high-intensity fixation hotspots near critical parameters
Visual search behavior	Frequent visual scanning across different interface areas	Reduced visual scanning and more direct attention to key information
Information recognition efficiency	Lower efficiency due to dispersed attention	Higher efficiency due to clearer visual hierarchy
Cognitive load and interaction efficiency	Higher cognitive effort required during operation	Improved clarity and more efficient visual interaction

Table 3
Summary of eye-tracking data structure and sensor output parameters used for visual attention analysis.

Data category	Parameter	Value	Description
System parameters	Model parameter count	98	Number of parameters used in the gaze estimation model exported by the system
Tracking structure	Key frames	6	Number of gaze tracking frames recorded during the experiment
Head tracking data	Samples per frame	426	Number of gaze samples recorded in each head-tracking frame
Eye model data	Left eye samples	204	Number of samples used for the left eye model in each frame
Eye model data	Right eye samples	204	Number of samples used for the right eye model in each frame

Note: The parameters listed in this table are used to describe the structure of the eye-tracking data generated by the sensor system and to support the interpretation of visual attention patterns observed in the heatmap analysis, rather than for high-precision quantitative measurement.

operational error rate were used as quantitative indicators to measure users' interaction performance when operating the original interface (Interface A) and the redesigned interface (Interface B).

Task completion time refers to the duration required for participants to locate and confirm the required operational information during the experiment. To simulate realistic machine operation scenarios, each experimental task was limited to a maximum duration of 40 s, representing the typical time window for operators to identify key parameters on an industrial control panel. Owing to the practical constraints of the experimental setup, task completion time was evaluated on the basis of observed time ranges rather than precise numerical recordings. The redesigned interface generally enabled users to complete tasks within approximately 15–20 s, whereas the original interface typically required approximately 30–35 s to complete the same tasks.

The operational error rate in this study was defined on the basis of task completion performance rather than interaction mistakes. Specifically, an error was defined as the failure to complete the required task within the specified time limit of 40 s, while incorrect selections or parameter misinterpretations were not considered critical errors owing to the error-tolerant nature of modern HMIs.

The comparison of task performance metrics between the two interface conditions is shown in Table 4. As shown in Table 4, the redesigned interface demonstrates a substantially lower error rate than the original interface. When interacting with the original interface, several participants experienced difficulties locating the correct operational parameters within the time limit. Some participants selected incorrect information, while others clicked incorrect parameters owing to the complex layout of the interface. In addition, three participants were unable to locate the required information within the 40s time limit, indicating that the original interface required considerable visual search effort, resulting in increased cognitive load and reduced task efficiency.

In contrast, the redesigned interface significantly reduced these operational errors. Only a small number of participants selected incorrect information or clicked incorrect parameters, and all participants were able to complete the task within the allowed time. These results suggest that the improved visual hierarchy and grouped parameter layout of the redesigned interface helped

Table 4
Comparison of task performance metrics between the original HMI (Interface A) and the redesigned interdisciplinary HMI (Interface B).

Metric	Interface A (original)	Interface B (redesigned)
Average observed task completion time (s)	30–35	15–20
Wrong information identified	4	1
Wrong parameter selection	3	1
Task not completed (>40 s)	3	0
Total error	10	2
Error rate (%)	66.7	13.3

Note: In this study, errors were defined on the basis of task completion failure (i.e., exceeding 40 s). Incorrect selections and parameter misidentifications were not treated as critical errors owing to the error-tolerant nature of the HMI. The reported task completion times represent observed time ranges rather than precise recorded values.

users locate critical information more efficiently, which is consistent with the observed reductions in task completion time and error rate.

To further illustrate the difference in operational error rate between the two interface conditions, a visual comparison is presented in Fig. 5, providing an intuitive representation of performance differences between the two interfaces.

As illustrated in Fig. 5, the overall error rate decreased from 66.7% in the original interface to 13.3% in the redesigned interface. This substantial reduction indicates that the redesigned interface improved operational clarity and reduced the likelihood of incorrect actions during task execution, as defined by task completion failures within the specified time limit. The results of the task performance analysis therefore support the findings of the eye-tracking analysis presented in Sect. 4.1, suggesting that the redesigned interface provides more effective visual guidance and facilitates more efficient interaction in industrial HMI environments, particularly in terms of reducing visual search effort and improving task completion efficiency.

4.3 Usability evaluation using the SUS

To further evaluate users' perceived usability of the interface, a questionnaire-based usability assessment was conducted. While Sects. 4.1 and 4.2 focused on objective performance indicators such as visual attention patterns and task performance obtained from the eye-tracking experiment, in this section, we present the results of subjective usability evaluation using standardized questionnaire data.

Note that the questionnaire survey and the eye-tracking experiment were conducted with different participant groups for different evaluation purposes. The eye-tracking experiment involved 15 carefully selected participants who all had practical experience in operating industrial equipment interfaces, including machine operators and interface designers with field operation knowledge. This participant selection ensured the reliability of the behavioral experiment and the accuracy of the visual attention measurements.

In contrast, the SUS questionnaire survey targeted a broader group of professionals involved in the design and planning stages of industrial systems. These participants included industrial designers, interface developers, and system planning personnel who are familiar with interface

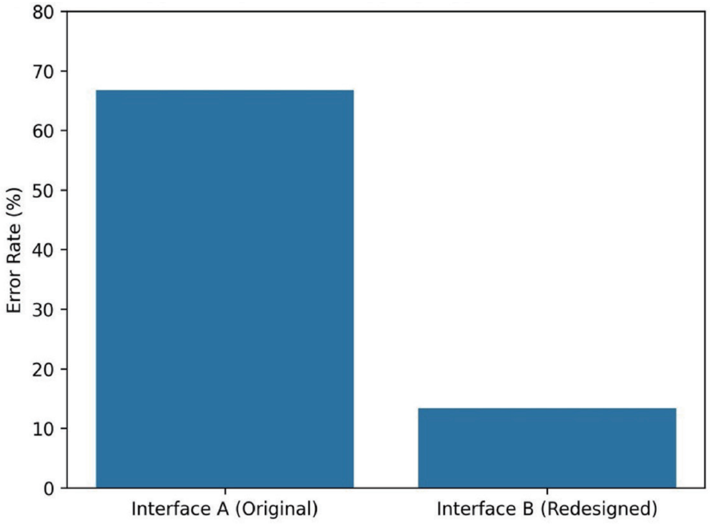


Fig. 5. (Color online) Comparison of task error rates between the original HMI (Interface A) and the redesigned interdisciplinary HMI (Interface B), where errors are defined as task completion failures exceeding the 40s time limit.

design and evaluation practices. Therefore, the questionnaire survey provided complementary usability insights from a design and system development perspective, strengthening the validity of the overall multi-modal evaluation framework.

Thirty-six participants provided valid responses to the questionnaire. Usability perception was evaluated using the SUS, a widely adopted standardized questionnaire for assessing the perceived usability of interactive systems. In addition to the SUS questionnaire, several five-point Likert-scale evaluation items were included to examine specific usability dimensions, including operation convenience, interface intuitiveness, visual aesthetics, and overall user satisfaction, allowing a more detailed interpretation of user experience beyond the overall SUS score. The SUS evaluation results are summarized in Table 5.

As shown in Table 5, the redesigned interface achieved a higher average SUS score than the original interface. The original interface obtained a mean SUS score of 58.4 ± 8.6, which is generally interpreted as a marginal usability level requiring improvement. In contrast, the redesigned interface achieved a significantly higher SUS score of 72.6 ± 7.9, corresponding to an acceptable level of usability. This improvement suggests that users perceived the redesigned interface as easier to use and more suitable for practical operational tasks, reflecting enhanced usability in terms of interaction efficiency, interface clarity, and user satisfaction.

To provide a clearer visual comparison of usability scores between the two interface conditions, the SUS score distribution is illustrated in Fig. 6, offering an intuitive representation of the difference in perceived usability between the two interfaces.

In addition to the overall SUS score, detailed usability dimensions were further analyzed using Likert-scale questionnaire responses. The evaluation results across different usability aspects are summarized in Table 6, providing a more detailed breakdown of perceived usability

Table 5
Comparison of SUS scores between the original HMI (Interface A) and the redesigned interdisciplinary HMI (Interface B).

Interface	Number of participants (*n*)	SUS score (*mean* ± *SD*)
Interface A (original)	36	58.4 ± 8.6
Interface B (redesigned)	36	72.6 ± 7.9

Note: SUS scores range from 0 to 100, with higher scores indicating higher perceived usability.

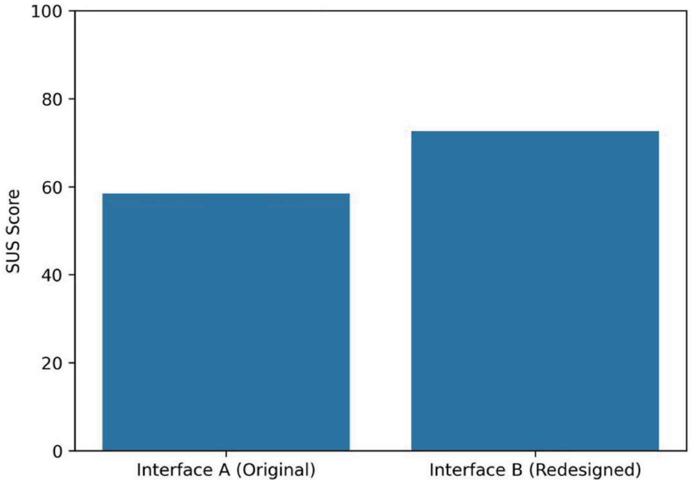


Fig. 6. (Color online) Comparison of SUS scores between the original HMI (Interface A) and the redesigned interdisciplinary HMI (Interface B).

Table 6
Comparison of quantitative usability evaluation results based on Likert-scale ratings between the original HMI (Interface A) and the redesigned interdisciplinary HMI (Interface B).

Evaluation dimension	Interface A (*mean* ± *SD*)	Interface B (*mean* ± *SD*)
Operation Convenience	2.8 ± 0.9	3.9 ± 0.8
Interface Intuitiveness	3.0 ± 0.7	4.1 ± 0.6
Visual Aesthetics	2.9 ± 0.8	3.8 ± 0.7
Overall Satisfaction	3.1 ± 0.8	4.0 ± 0.7

Note: All items were evaluated using a five-point Likert scale, where higher scores indicate higher perceived usability.

across specific dimensions, including operation convenience, interface intuitiveness, visual aesthetics, and overall satisfaction.

As shown in Table 6, the redesigned interface demonstrates consistent improvements across all evaluated usability dimensions. Operation convenience increased from 2.8 to 3.9, indicating that users perceived the redesigned interface as easier to operate during task execution. Interface intuitiveness improved from 3.0 to 4.1, suggesting that the redesigned layout and visual structure helped users understand interface functions more quickly.

Visual aesthetics satisfaction also increased from 2.9 to 3.8, reflecting that the redesigned interface was perceived as visually clearer and more appealing. Furthermore, overall user satisfaction improved from 3.1 to 4.0, indicating a more positive overall interaction experience.

Overall, the quantitative usability evaluation results demonstrate that the redesigned interface outperforms the original interface across all measured dimensions, reinforcing the effectiveness of the proposed interdisciplinary design approach. These findings are consistent with the visual attention patterns observed in the eye-tracking analysis (Sect. 4.1) and the task performance improvements reported in Sect. 4.2, collectively supporting the validity of the sensor-based multi-modal evaluation framework and confirming that the interdisciplinary UI/UX redesign contributes to improved usability and user experience in intelligent manufacturing equipment interfaces.

5. Discussion

The results presented in Sect. 4 demonstrate that the redesigned interface significantly improves both objective performance and perceived usability in intelligent manufacturing environments. By integrating interdisciplinary design strategies with sensor-supported evaluation methods, we provide empirical evidence supporting the effectiveness of UI/UX redesign in industrial HMIs, contributing to the development of practical evaluation approaches for industrial interface optimization.

The eye-tracking analysis revealed clear differences in visual attention patterns between the original interface and the redesigned interface. In the original interface, gaze distribution was dispersed across a wider visual area, indicating that users needed to search multiple interface regions to locate relevant information. In contrast, the redesigned interface demonstrated a more concentrated visual attention pattern, with fixation hotspots appearing near key operational parameters. This suggests that the redesigned interface improved visual hierarchy and reduced unnecessary visual search behavior during operation, which is consistent with the intended design strategy of enhancing intuitive interaction and information clarity.

These findings are further supported by the task performance results. The error rate analysis shows that operational errors were significantly reduced when participants used the redesigned interface. The clearer layout structure and grouped information organization appear to help users identify relevant parameters more efficiently, thereby reducing the number of incorrect selections and improving task completion success. This improvement indicates that interface redesign can directly affect operational efficiency in industrial HMI systems, particularly in reducing task completion time and minimizing cognitive load during operation.

In addition to objective performance improvements, the usability evaluation results also demonstrate significant improvements in user perception. The SUS evaluation indicates that the redesigned interface achieved a higher usability score than the original interface. Furthermore, Likert-scale usability dimensions—including operation convenience, interface intuitiveness, visual aesthetics, and overall satisfaction—all showed consistent improvements. These results suggest that the redesign not only improved operational performance but also enhanced users' overall interaction experience, reinforcing the effectiveness of interdisciplinary UI/UX design integration in industrial applications.

The combination of eye-tracking analysis, task performance metrics, and usability evaluation provides a multi-dimensional understanding of interface effectiveness. Such multi-modal evaluation frameworks are increasingly emphasized in human–computer interaction research, as they allow researchers to capture both behavioral and perceptual aspects of user interaction. By integrating sensor-based measurement with interdisciplinary design methods, in this study, we demonstrate a practical approach for evaluating industrial interface optimization, highlighting the value of accessible sensor technologies in applied design research.

From a practical perspective, the findings of this research highlight the importance of applying UI/UX design principles in industrial equipment interface development. Traditional industrial control interfaces are often developed primarily from engineering perspectives, focusing on functional completeness rather than interaction clarity. The results of this study indicate that incorporating industrial design and usability principles can significantly improve both operational efficiency and user satisfaction in intelligent manufacturing systems, suggesting a shift toward user-centered interface development in industrial contexts.

Despite these contributions, several limitations should be acknowledged. First, the eye-tracking measurements in this study were obtained using a webcam-based eye-tracking system rather than laboratory-grade eye-tracking hardware. Although such systems provide higher accessibility and flexibility for applied research, their measurement precision may be lower than those of specialized eye-tracking devices, and the analysis was primarily based on qualitative interpretation rather than high-precision quantitative metrics. Second, the experimental tasks were conducted in a simulated environment rather than during actual machine operation. Real industrial environments may introduce additional factors such as environmental noise, operator stress, and time pressure, which may affect user interaction behavior and performance outcomes.

Future research may extend this study by applying higher-precision eye-tracking devices and conducting experiments in real industrial production environments. In addition, further studies may explore the integration of additional physiological sensors or behavioral indicators to provide a more comprehensive understanding of operator interaction behavior in intelligent manufacturing systems, further enhancing the robustness of sensor-based multi-modal evaluation frameworks.

6. Conclusion

A sensor-based multi-modal evaluation framework was proposed in this study for assessing the effectiveness of interdisciplinary HMI redesign in intelligent manufacturing equipment. By integrating eye-tracking analysis, task performance metrics, and usability evaluation, we provided a systematic method for evaluating interface optimization in industrial environments, offering a practical and reproducible approach for applied design research.

The experimental results demonstrate that the redesigned interface significantly improves both visual interaction efficiency and operational usability. Eye-tracking analysis revealed that the redesigned interface produced a more concentrated visual attention pattern, indicating that users were able to identify critical operational information more efficiently. Compared with the original interface, the redesigned layout reduced unnecessary visual scanning and improved visual guidance during task execution, thereby reducing cognitive load and enhancing interaction efficiency.

The task performance evaluation further confirmed these improvements. The redesigned interface significantly reduced operational errors, decreasing the error rate from 66.7% in the original interface to 13.3% in the redesigned interface. This result indicates that improved information organization and visual hierarchy can effectively support users in locating and interpreting operational parameters within complex industrial interfaces, particularly within limited time constraints.

The usability evaluation results also demonstrate clear improvements in user perception. The redesigned interface achieved a higher SUS score than the original interface, indicating that users perceived the redesigned interface as easier to use and more intuitive. In addition, Likert-scale usability evaluations showed consistent improvements across multiple usability dimensions, including operation convenience, interface intuitiveness, visual aesthetics, and overall user satisfaction, confirming the positive impact of interdisciplinary UI/UX design on perceived usability.

Overall, the results of this study highlight the importance of integrating industrial design principles and usability evaluation methods into the development of intelligent manufacturing interfaces. Traditional industrial control interfaces often emphasize functional completeness while overlooking interaction clarity. The findings of this research demonstrate that interdisciplinary design-driven interface optimization can significantly improve both operational performance and user experience, supporting the transition toward user-centered design in industrial HMI development.

The proposed sensor-based evaluation framework also contributes to applied design research by demonstrating the feasibility of using webcam-based eye-tracking systems for practical usability evaluation in industrial contexts. Compared with laboratory-based eye-tracking systems, such approaches offer higher accessibility and flexibility for real-world design evaluation and industry–academia collaboration, making them suitable for scalable and cost-effective evaluation scenarios.

Future research may further extend this work by conducting experiments in real industrial production environments and incorporating additional behavioral or physiological sensing methods. Such studies may provide deeper insights into operator interaction behavior and support the development of more efficient and user-centered HMIs for intelligent manufacturing systems, further strengthening the robustness and applicability of sensor-based multi-modal evaluation frameworks.

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About the Authors

Hong-Yi Chen received his B.S. degree in industrial design from Dayeh University, Taiwan, in 2006, his M.S. degree in design from Dayeh University, Taiwan, in 2008, and his Ph.D. degree in design from National Yunlin University of Science and Technology, Taiwan, in 2018. From 2014 to 2018, he was a lecturer in the Department of Computer-aided Industrial Design at Overseas Chinese University, Taiwan. From 2018 to 2022, he served as an associate professor in the Vehicle Engineering program at Zhaoqing University, China. In 2023, he was an associate professor in the Product Design program at Shaoguan University, China. Since 2023, he has been an assistant professor in the Department of Product Design at Tainan University of Technology, Taiwan. His research interests include industrial design, human–machine interface (HMI) design, UI/UX design, intelligent manufacturing equipment design, and sensor-based usability evaluation. (te0068@mail.tut.edu.tw)