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Intelligent Clothing Design in Cultural Tourism - Fusion of Augmented Reality (AR) and Interactive Experience

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ABSTRACT
This study aims to explore the integration strategy of smart clothing design and augmented reality (AR) technology in cultural tourism to enhance tourists' interactive participation and cultural understanding. The study constructs a comprehensive assessment model based on subjective and objective empowerment and the TOPSIS method, designs three smart clothing-AR integration scenarios, and develops corresponding cultural tourism scenarios for empirical testing. This study conducted an empirical analysis through questionnaire surveys and behavioral data collection among 450 tourists from different age groups (18-60 years old) and diverse cultural backgrounds (spanning Asia, Europe, the Americas, and other regions)., combined with CRITIC empowerment and the TOPSIS ranking method, the experiential effect and technical performance of each fusion scenario are comprehensively evaluated. The experimental results show that Combination 1 scores centrally between 4-5 in visitor satisfaction, has the highest median cultural understanding, and a relative closeness of 0.832, which is better than Combination 2 (0.756) and Combination 3 (0.681); moreover, Combination 1 also performs better in objective indicators such as sensor stability and AR frame rate. The study concludes that the fusion of smart clothing and AR can effectively enhance the cultural tourism experience, which has application and promotion value but still needs to be further optimised in the aspects of sensor environment adaptability and in-depth integration of cultural content. The study provides theoretical support and practical reference for the digital upgrade of cultural tourism.

KEYWORDS
cultural tourism, smart clothing design, AR, interactive experience integration, TOPSIS

INTRODUCTION

With the booming development of cultural tourism, tourists' requirements for tourism experience are increasing. Traditional sightseeing-style tourism can no longer meet people's demand for a deep cultural experience [1]. As an emerging product of science and technology, the integration of smart clothing with augmented reality (AR) technology brings new development opportunities for cultural tourism. By embedding various sensors and smart modules, smart clothing can sense visitors' behaviour and environmental information in real time, adding interactivity and fun to cultural tourism experiences. Therefore, exploring the application of smart clothing in cultural tourism has important practical significance and theoretical value [2]. Smart clothing can sense tourists' behaviours and environmental information, while AR technology can superimpose virtual cultural elements into the real scene, and the combination of the two can create a unique interactive experience [3]. In cultural tourism, this fusion of smart clothing and AR makes tourists no longer passive viewers, but they can actively participate in the cultural scene [4]. Intelligent clothing combined with AR can show cultural elements such as rituals and costumes of folklore activities to tourists in an interactive form, making cultural heritage more vivid and interesting [5].

Some technology companies and research institutes have begun to explore the application of smart clothing in the field of tourism [6]. Jiang et al. [7] focus on using the sensor data of smart clothing to optimise the presentation of AR scenes and adjust the virtual elements in AR through the analysis of tourists' heart rates, movement trajectories, and other data. However, there is still room for strengthening the deep integration of cultural connotations and technology [8]. Domestic research has achieved some results in the production technology of intelligent clothing and the localised cultural construction of AR scenes [9]. However, it is relatively weak in the systematic evaluation of intelligent clothing design and AR interactive experience [10]. Currently, the following problems exist in the research on smart clothing design in cultural tourism [11]: 1) delay in data transmission, signal interference between different devices; 2) lack of in-depth cultural understanding, and simple piling up of cultural elements; and 3) lack of a comprehensive and scientific evaluation system to measure the effect of smart clothing design-AR interactive experience in cultural tourism.

Aiming at the above problems, this paper proposes a fusion method of intelligent clothing design-augmented reality (AR) and interactive experience in cultural tourism and adopts a subjective-objective combination [12,13] and TOPSIS assessment and analysis method [14] to construct a multi-dimensional, comprehensive, and scientific analysis model for the effect of intelligent clothing design-AR interactive experience. The main contributions of this paper include the following:(1) combining smart clothing design and augmented reality technology, and designing a fusion method of smart clothing design-augmented reality (AR) and interactive experience; (2) combining subjective and objective empowerment method and TOPSIS algorithm, proposing a smart clothing design-AR interactive fusion assessment and analysis method; (3) by collecting smart clothing samples and AR scene design data, The effectiveness of the fusion method is analysed and verified, and the effectiveness and superiority of the smart clothing design-AR interaction fusion assessment and analysis method are also carried out from multi-dimensional aspects.

INTELLIGENT CLOTHING DESIGN IN CULTURAL TOURISM

Intelligent Clothing Design

Smart clothing refers to clothing that realises the perception and processing of data such as physiological parameters and environmental information of the wearer through embedding electronic components such as sensors, microprocessors, and communication modules [15], which is specifically defined as shown in Figure 1 that illustrates the concept of intelligent clothing design, highlighting its key components and functions. Intelligent clothing design needs to comprehensively consider functionality, comfort, aesthetics, and other aspects. In cultural tourism scenarios, smart clothing can provide personalised services and experiences for tourists by sensing their location, movements, and other information [16].

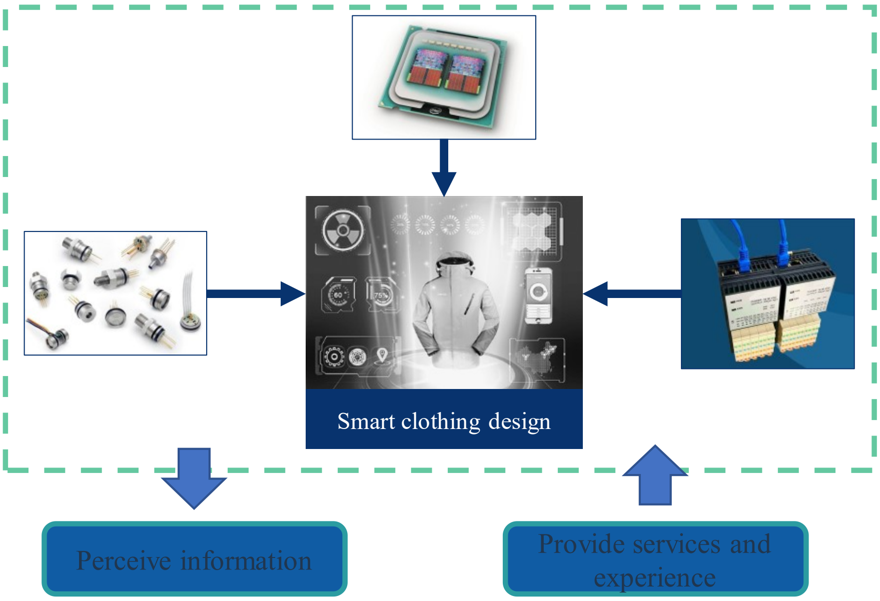

Figure 1. Intelligent Clothing Design Concept

Smart garments have the following core characteristics [17]: 1) smart garments can perceive a variety of information through embedded sensors; 2) smart garments support interaction with the human body and external devices; 3) smart garments can automatically adjust their functions and states based on the perceived information; and 4) even though smart garments are integrated with a variety of electronic components, their design needs to focus on the comfort of wearing them and the appearance of their aesthetics. The specific features of smart clothing design are shown in Figure 2, which showcases the specific features of smart clothing design, including functionality, interaction, and user comfort.

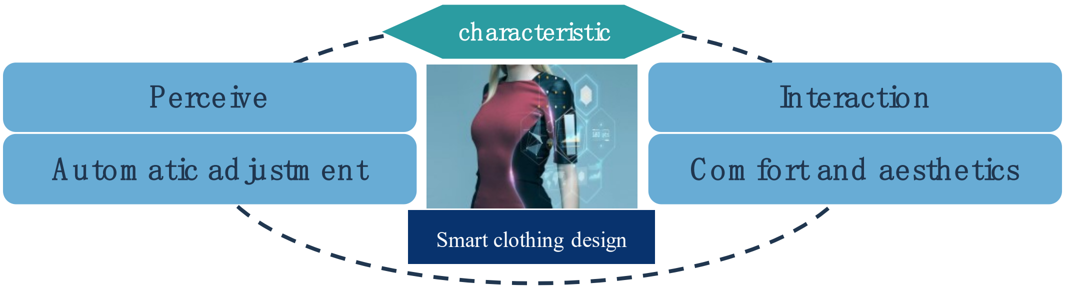

Figure 2. Smart clothing design features

The design of smart clothing needs to follow the principles of user-centredness, unity of function and form, safety and reliability, and sustainability. Intelligent clothing design mainly includes two main research contents, such as functional design and material selection, as shown in Figure 3, which details the two main research contents of intelligent clothing design: functional design and material selection.

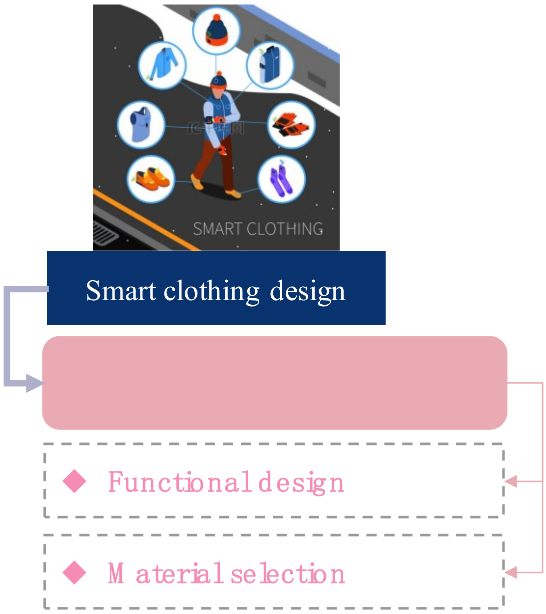

Figure 3. Intelligent Clothing Design Content

The functional design of smart clothing in cultural tourism includes a sensing function and an interaction function. The sensing function is realised by embedding sensors in the garment, such as temperature sensors and pressure sensors [18]. The interaction function, on the other hand, is embodied in the communication between the garment and external devices (e.g., AR devices), e.g., the Bluetooth module on the garment can send the sensor data to the AR device for processing. The selection of materials suitable for cultural tourism scenarios is crucial. Both the comfort of the material and its compatibility with electronic components should be considered [19].

Augmented Reality (AR)

Augmented reality (AR) [20] is a technology that subtly integrates virtual information with the real world, as shown in Figure 4, which explains the principle of augmented reality (AR) technology, demonstrating how it integrates virtual information with the real world. It identifies and analyses the real scene through computer vision technology, and then superimposes virtual images, videos, or 3D models onto the real scene.

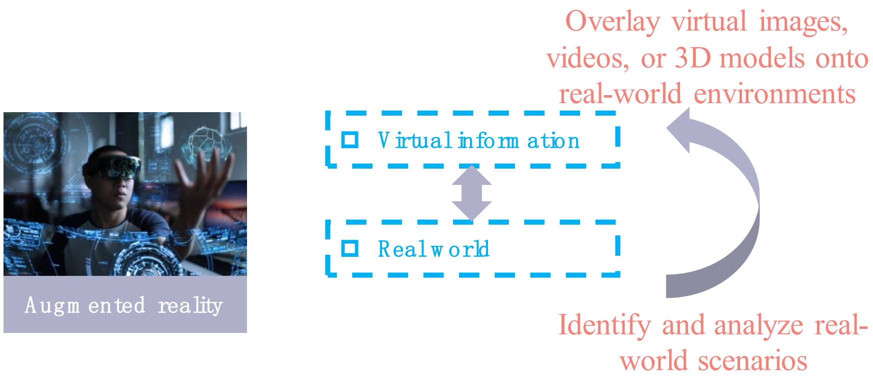

Figure 4. Principle of AR technology

In cultural tourism, AR can present a variety of forms, as shown in Figure 5 in which showcases various applications of AR technology in cultural tourism, such as tour-guide AR and experiential AR. For example, tour-guide AR provides tourists with a virtual tour guide to introduce the history and cultural connotations of cultural attractions; experiential AR allows tourists to participate in virtual cultural activities, such as ancient sacrificial ceremonies [21].

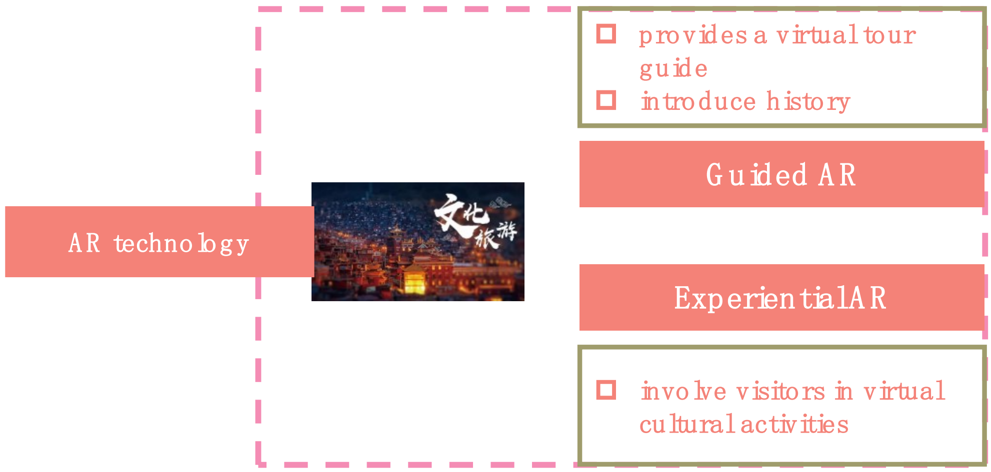

Figure 5. Application of AR technology in cultural tourism

Intelligent Clothing Design - Fusion of Augmented Reality (AR) and Interactive Experience

Mode of integration

The integration of smart clothing design-augmented reality (AR), and interactive experience is mainly carried out from the hardware and software levels, as shown in Figure 6, illustrating the integration of smart clothing design with augmented reality (AR) and interactive experience, from both hardware and software levels.

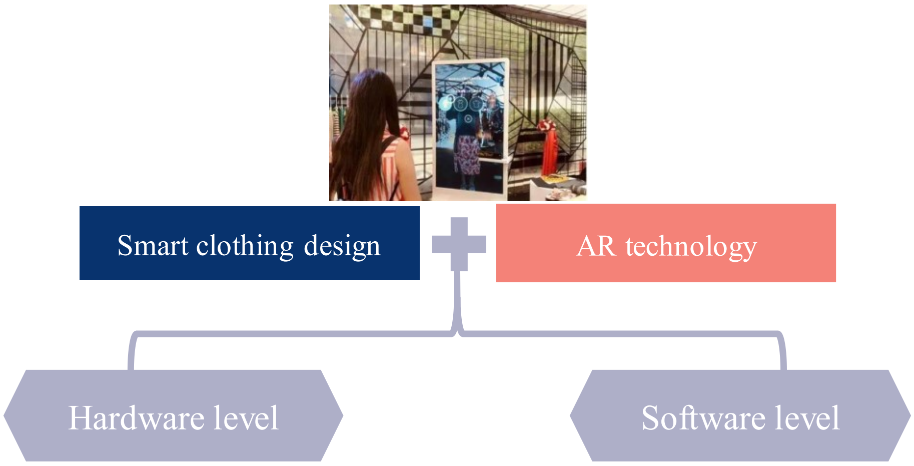

Figure 6. Smart Clothing Design - Fusion of Augmented Reality and Interactive Experience

From the hardware level, the sensor data in the smart garment provides the trigger and interaction basis for the AR scene [22]. When the acceleration sensor in the smart garment detects a tourist's hand-raising action, the AR device can trigger the display of cultural elements related to it, such as the cultural explanations corresponding to ancient ceremonial gestures.

From the software level, the control logic of smart clothing is integrated with the scene rendering logic of AR through the development of a specialised software platform to achieve a seamless interactive experience [23].

Interactive experience building

The interactive experience includes the interaction between the visitor and the smart costume, the visitor and the AR scene, and the smart costume and the AR scene [24], as shown in Figure 7, which details the content of the interactive experience building, including interactions between visitors, smart costumes, and AR scenes.

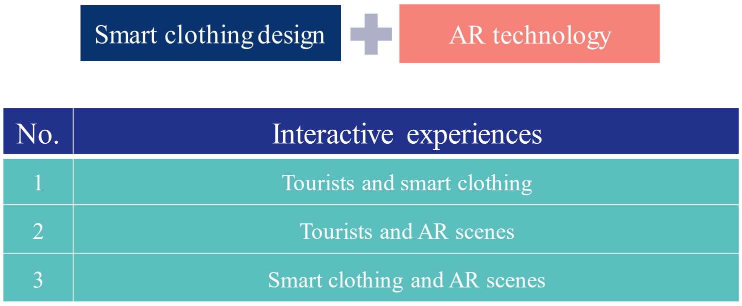

Figure 7. Interactive experience building content

(1) The interaction between visitors and smart costumes is reflected in changing the status of the costumes (e.g., glowing, sounding, etc.) through their movements and behaviours, which in turn affects the changes in the AR scene.

(2) Visitors interact with the AR scene by operating in the AR scene (e.g., touching virtual objects, selecting different cultural displays, etc.).

(3) The interaction between the smart clothing and the AR scene is based on the clothing sensor data and the dynamic response of the AR scene, e.g., if the smart clothing detects a change in the visitor's body temperature, the AR scene can be adjusted accordingly to a cultural scene suitable for that temperature state (e.g., displaying a warm indoor cultural activity in a cold state).

To enhance the depth and educational value of cultural tourism experiences, future research could consider incorporating artificial intelligence semantic modelling and creating cultural knowledge maps. Through these technologies, cultural elements can be presented to visitors more vividly and systematically, thereby enhancing their understanding and appreciation of cultural heritage.

To overcome the superficiality of cultural content in current AR scenarios, future work should integrate AI-driven semantic modelling tools and cultural knowledge graphs. These technologies can: Automatically generate context-aware cultural narratives based on user behaviour and location data; Embed symbolic cultural elements (e.g., rituals, historical metaphors) into AR interactions via ontological mapping; Enable dynamic storyline branching, allowing tourists to explore multiple layers of cultural meaning interactively.

INTELLIGENT CLOTHING DESIGN-AR INTERACTIVE FUSION EVALUATION AND ANALYSIS

Subjective-objective-TOPSIS assessment analysis

Subjective assessment

The subjective assessment is mainly based on tourists' experience feedback [25]. The subjective assessment index system was constructed using the Delphi method, with three rounds of expert consultation (N=15) identifying core dimensions: (1) user experience satisfaction (5-point Likert scale), (2) cultural awareness improvement (pre-post comparison), and (3) interaction pleasure (semantic differential scale). Indicator weights were determined by AHP (CR<0.1), ultimately forming a comprehensive evaluation system with 3 first-level and 9 second-level indicators. Through the questionnaire survey, on-site interviews, and other ways to collect the tourists' evaluation of the smart clothing design-AR interactive experience in terms of satisfaction, fun, cultural understanding, etc., the specific subjective assessment methodology is shown in Figure 8. In the questionnaire survey and on-site interviews, the question "Do you think that this smart clothing and AR interactive experience has enhanced your understanding of the cultural tourist attractions?" was set. The tourists can score according to their feelings.

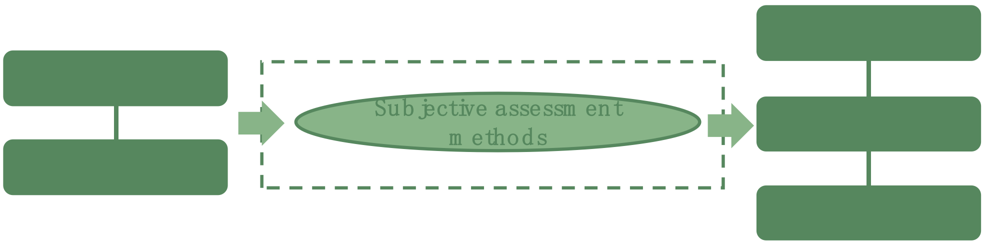

Figure 8. Subjective assessment framework

Objective assessment

The objective assessment starts from the technical indicators, including the sensor accuracy of the smart clothing, the rendering frame rate of the AR scene, the latency of the data transmission, etc., and the specific assessment system is shown in Figure 9 which outlines the construction of an objective assessment system, focusing on technical indicators like sensor accuracy and AR frame rate.

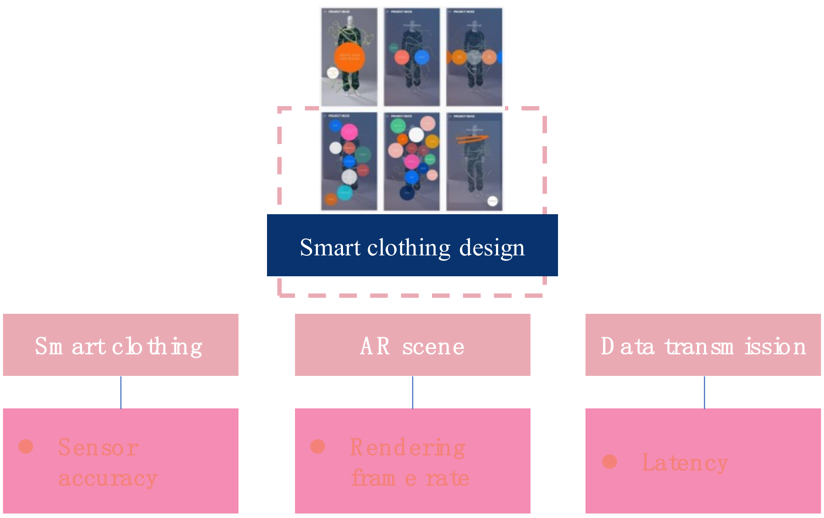

Figure 9. Construction of an objective assessment system

The CRITIC method [26] is mainly based on the comparative strength and correlation of the indicators to determine the objective weights, which usually reflect the variability among the indicators and their contribution to the evaluation results. The CRITIC assignment method integrates two dimensions, comparative strength and conflict, when analysing the information content of the indicators. Among them, contrast strength is based on the concept of mean square deviation, which is used to measure the variability among different evaluation indicators, thus revealing the degree of importance of the indicators in the overall evaluation; while conflict is based on the calculation of correlation coefficients, which is used to reflect the correlation among indicators, i.e., the degree to which they influence each other.

The steps for evaluating the interactive fusion of smart clothing design-AR based on the CRITIC method are as follows:

(1) To ensure the accuracy and consistency of the evaluation, firstly, the power quality index matrix E is normalised to construct a normalised evaluation index matrix X. This process usually adopts the min-max normalisation method;

2) Use the concept of the product of deviations to measure the closeness of association between two variables;

3) Using the matrix of correlation coefficients of the evaluation indicators, define the informativeness measure based on the concepts of comparative strength and conflictiveness;

4) The weights of the indicators were calculated using the amount of information.

TOPSIS method

The TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) method [27] is a multi-attribute decision-making method, as shown in Figure 10. It calculates the distance of each solution from the ideal solution and the negative ideal solution by constructing the ideal solution and the negative ideal solution, and then orders the solutions. In the smart clothing design-AR interactive fusion assessment, the subjectively and objectively assessed metrics are used as attributes to comprehensively assess different fusion solutions through the TOPSIS method.

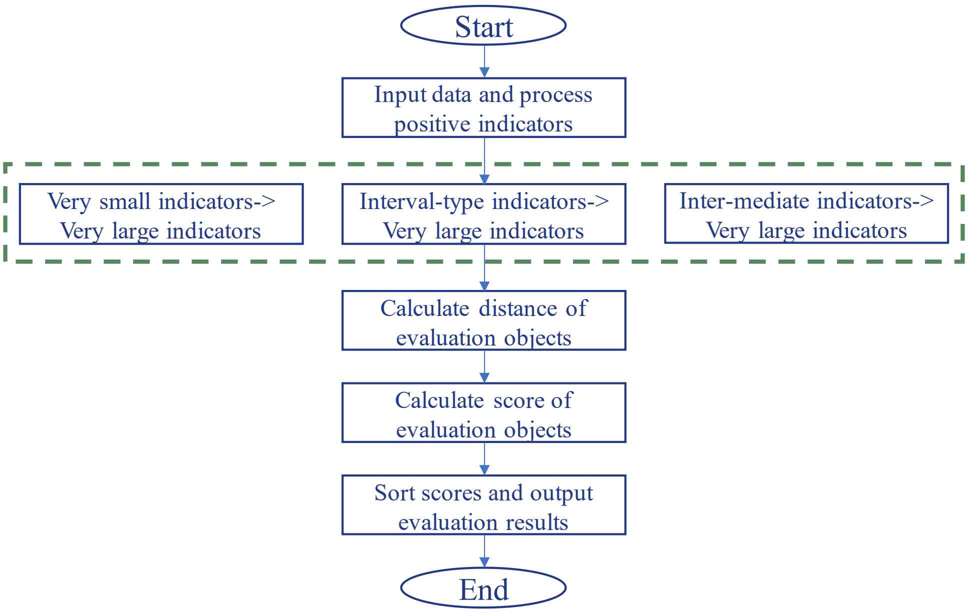

Figure 10. Principle of the TOPSIS method

Intelligent Clothing Design-AR Interactive Integration Evaluation Steps

Combining the subjective and objective assignment algorithms, this section proposes a TOPSIS algorithm-based assessment method for the interactive fusion of smart clothing design-AR, and the specific ideas are shown in Figure 11, which illustrates the evaluation steps for the interactive fusion of intelligent clothing design and AR.

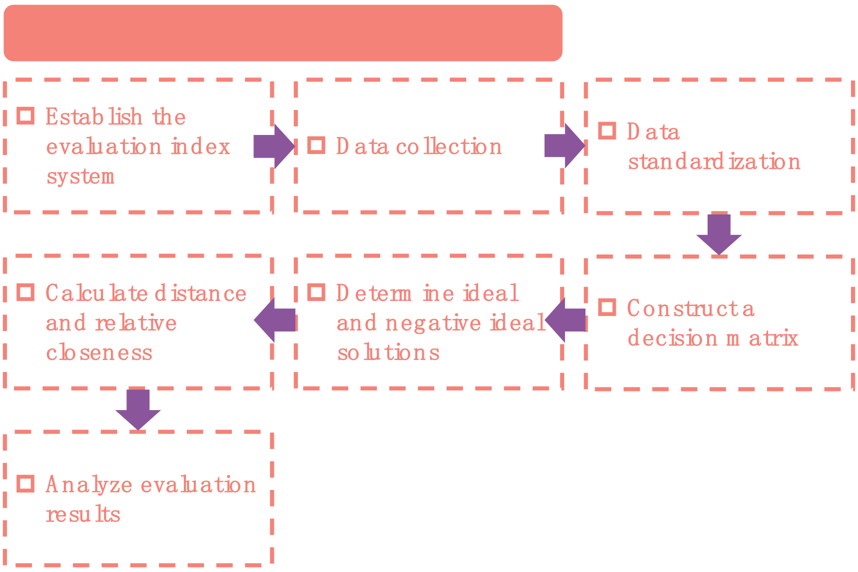

Figure 11. Intelligent Clothing Design-AR Interactive Fusion Evaluation

Step 1: Determine the assessment index system. According to the characteristics of intelligent clothing design-AR interactive integration, the evaluation index system includes both subjective and objective indices. Subjective indicators such as visitor satisfaction, cultural dissemination effect, etc., and objective indicators such as sensor performance, AR equipment performance, etc..

Step 2: Data collection. For subjective indicators, data are collected through a large-scale survey of tourists. For objective indicators, data collection is carried out using professional testing equipment and software, such as a high-precision thermometer to measure the actual accuracy of the smart clothing temperature sensor.

Step 3: Data standardisation. Different types and scales of data collected are standardised to make them comparable. Subjective scores are normalised, and objective technical indicators are converted into dimensionless values.

Step 4: Construct a decision matrix. Construct a decision matrix based on the normalised data, where the rows represent different assessment objects (e.g., different smart clothing design-AR interactive fusion solutions) and the columns represent assessment indicators.

Step 5: Determine the ideal and negative ideal solutions. Ideal and negative ideal solutions are determined based on the nature of the evaluation metrics (e.g., the higher the better for tourist satisfaction, the lower the better for data transmission latency).

Step 6: Calculate distance and relative closeness. Calculate the distance of each assessment object from the ideal solution and the negative ideal solution, and then calculate the relative closeness based on the distance; the higher the relative closeness, the closer the assessment object is to the ideal solution.

Step 7: Analysis of assessment results. Rank the evaluation objects according to their relative closeness, analyse the advantages and disadvantages of different schemes, and provide a basis for the optimisation of the smart clothing design-AR interactive integration.

RESULTS AND DISCUSSION

Experimental set-up

Using a stratified sampling method, we selected 450 tourists aged 18-65 (M=32.5±8.2) with a 1:1 gender ratio, including domestic (70%) and international visitors (30%). The experiment consisted of three phases: (1) device wearing and calibration (15min), (2) experiencing three smart clothing-AR scenario combinations (30min each), and (3) questionnaire survey and semi-structured interview (20min), all conducted in controlled lab conditions.

Intelligent Clothing Sample Production

Three samples of smart garments with different functions and designs were produced. The first one has pressure sensors and flexible circuits on the collar, cuffs and waist for detecting visitors' body movements; the second one has temperature sensors evenly distributed on the surface of the garment for sensing changes in the ambient temperature; and the third one integrates acceleration sensors and small LEDs for detecting the movement state and glowing according to different movement states.

AR scene design

Three AR scenes related to cultural tourism were designed. The first scene is an ancient palace tour, when tourists wearing smart clothes enter the scene, different palace building displays, character interactions, etc. are triggered according to the clothing sensor data; the second scene is a folk culture experience, such as simulating the traditional dragon and lion dance activities, where the sensor data of the smart clothes affects the movements and rhythms of the dragon and lion dance; in the third scene, an interpretative framework for historical and cultural narratives is constructed. By leveraging the interactive capabilities of intelligent costumes and augmented reality (AR) technology, visitors are enabled to actively engage in the unfolding of historical storylines.

Test Object Selection

Four hundred and fifty tourists of different ages and cultural backgrounds were selected as test subjects to ensure the representativeness of the test results.

Analysis of results

To analyse the methodology designed in this paper as well as to assess the accuracy and validity of the methodology, this section analyses and visualises the results in terms of subjective, objective, and comprehensive assessment. Suppose we conducted a cultural understanding survey for three different smart clothing-AR scene combinations (labelled as combination 1, combination 2, and combination 3, respectively), with 150 visitors participating in each combination.

Figure 12 shows the distribution of tourist satisfaction, which is a visual representation of subjective evaluation results. From the histogram, it can be seen that tourist satisfaction is mainly concentrated in the range of ratings 4 and 5, indicating that most tourists have a positive attitude towards the current integrated experience, believing that the interaction between smart clothing and augmented reality enhances the fun and immersion of cultural tourism. The concentrated trend in the middle and high segments indicates that the overall design has strong appeal and practicality, achieving the expected effect of enhancing the experience. However, at the same time, some tourists gave moderate or below ratings (2-3 points), indicating that there is still room for improvement in the system.

This type of distribution pattern reflects that there are certain differences in the acceptance of intelligent clothing AR interactive integration among tourist groups, which may be influenced by factors such as age, cultural background, and technological acceptance. From the distribution trend, it can also be observed that the concentration of ratings is relatively high, indicating that the surveyed tourists have a certain consensus on the evaluation experience, and the subjective satisfaction data has good representativeness and stability. In the subsequent optimisation, it is necessary to pay attention to feedback from user segmentation groups to further enhance personalised customisation and cultural adaptability.

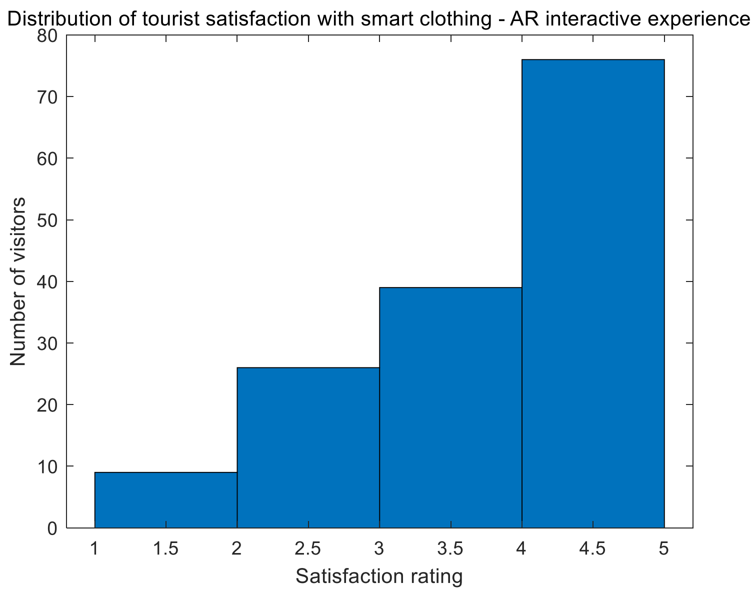

Figure 12. Distribution of Visitor Satisfaction

Figure 13 shows the comparison results of the three smart clothing-AR scene combinations (Combination 1, Combination 2, and Combination 3) in terms of tourists' cultural understanding, using a box-and-line plot format to visualise the median, interquartile range, and outliers of the score distribution. The graph reflects the variability of different combinations in enhancing the cultural understanding of tourists. Among them, Combination 2 has the highest overall position on the box-and-line plot, and the median is significantly higher than the other two combinations, indicating that tourists gained a higher degree of cultural understanding under the experience of this combination; at the same time, its box is shorter, indicating that the scoring data are more concentrated and the consistency of the tourists' feedbacks is stronger.

The boxplot for combination 1, on the other hand, shows that the median is slightly lower than that of combination 2, but still higher than that of combination 3, suggesting that its cultural dissemination effect is better, but slightly weaker than that of combination 2. In addition, the data dispersion of combination 1 is relatively large, with high boxes and several outliers at the upper and lower edges, suggesting that there are large differences in some tourists' cultural experience of this combination, which may stem from individual users' difficulties in understanding certain cultural scenarios or problems, such as insensitive interaction triggers. Overall, combination 1 has a strong potential for cultural dissemination, but there is still room for optimisation in terms of user consistency.

Combination 3 has the lowest boxplot, with a median in the lower middle range and large upper and lower quartile distances, suggesting that visitor feedback varies more markedly and that there is disagreement about the effectiveness of cultural understanding. This may reflect that Combination 3 has deficiencies in content planning or interaction design, fails to effectively convey cultural information, or the interaction mechanism interferes with visitors' understanding. Combined with the results in Figure 13, it can be seen that optimising the logical structure of the cultural narrative and enhancing the cultural relevance of the interaction design are the key directions to enhance tourists' cultural understanding.

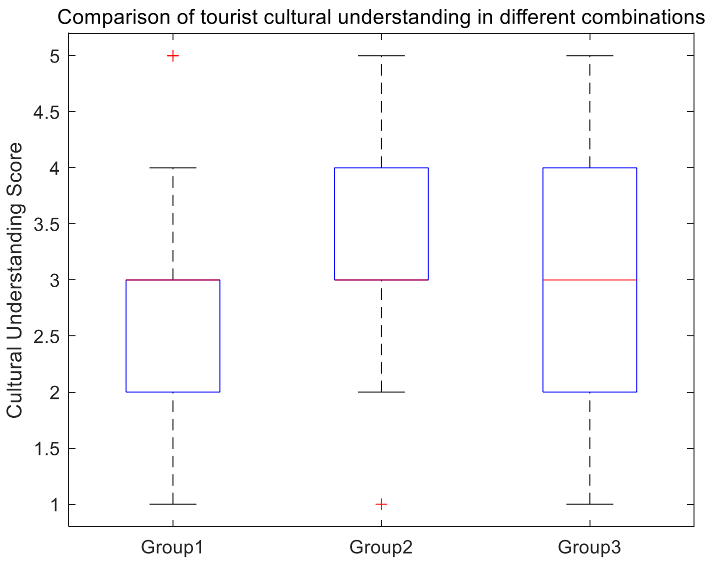

Figure 13. Comparison of Cultural Understanding

During the experiment, a series of measurements of the smart garment pressure sensor in Combination 1 were recorded under normal and extreme movements (fast twisting of the body), and the results were obtained as shown in Figure 14. Figure 14 shows the fluctuation of the measured data of the smart garment pressure sensor in Combination 1 under two motion states, "normal motion" and "extreme motion" (e.g., twisting the body rapidly), using the upper and lower subfigures for comparison. The upper Figure shows the output curve of the sensor under normal movement, which shows that the fluctuation amplitude is small and the signal is relatively smooth, indicating that the sensor can stably capture the human body movement information and provide accurate trigger signals for AR interaction in general tourism activities.

The Figure below shows the sensor output curve under extreme movements, with a significantly wider range of fluctuations, showing more spikes and abnormal fluctuations. Such changes indicate that the measurement accuracy and stability of the pressure sensor will be affected to a certain extent under strenuous movement conditions, which may trigger false triggering or response delay of the AR system, and thus affect the coherence and immersion of the overall interactive experience. This result reveals that there is a reliability bottleneck for current smart garments in extreme usage situations.

A comprehensive analysis of Figure 14 concludes that although the current pressure sensor performs well in conventional cultural tourism activities, its performance still needs to be further optimised in more dynamic or strenuous participatory scenarios (e.g., dance simulation, ritual imitation, etc.). It is recommended to strengthen the data filtering mechanism of the sensors, introduce higher sensitivity materials, or improve the anti-interference ability through algorithmic redundancy design in the subsequent design, to ensure that the smart clothing can still maintain the interaction accuracy and system stability under complex actions.

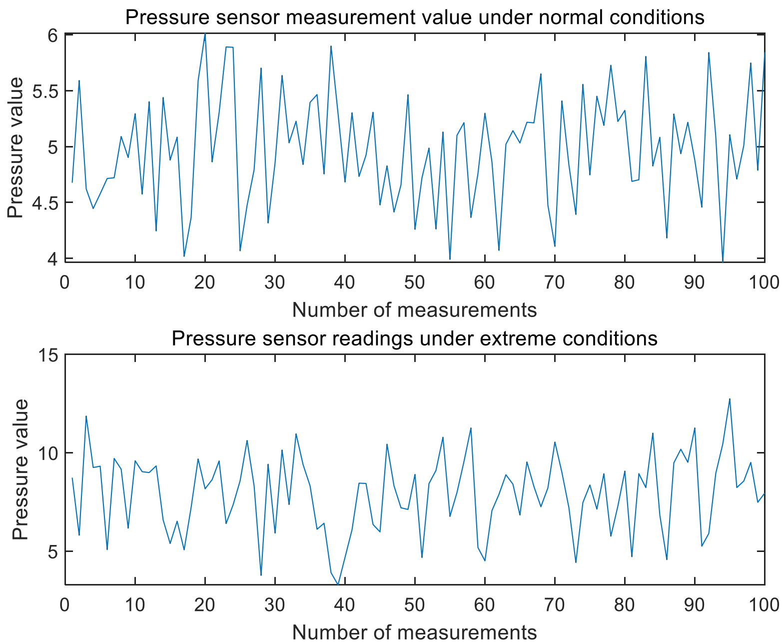

Figure 14. Pressure sensor data fluctuation measurement

Figure 15 shows a comparison of the measurement errors of the temperature sensor equipped in the smart garment in Combination 2 under two environmental conditions, namely, "normal environment" (normal temperature and humidity) and "high temperature and high humidity environment". The bar charts clearly show the average measurement errors of the sensors under the two conditions, and the shorter error bars in the normal environment indicate that the temperature sensors have good accuracy and stability in normal climatic conditions, which is sufficient to support the real-time feedback of environmental changes in AR scenarios.

However, the measurement error bar increases significantly at high temperatures and high humidity, suggesting that this environmental condition causes significant interference with sensor performance. This interference may originate from sensor drift due to temperature and humidity interaction effects, degradation of electronic component performance, or hysteresis in the response of the material itself in extreme environments. This phenomenon has important implications for scenarios in cultural tourism that are tropical, humid, or have a large temperature difference between indoor and outdoor temperatures: if the temperature perception is distorted, it will affect the AR system's regulation of scene adaptation, such as the inability to recommend appropriate virtual environments or clothing display contents according to the temperature of the tourists' location, which will reduce the sense of immersion and comfort. To address performance issues of sensors under extreme conditions, future research can consider strengthening data filtering mechanisms to reduce noise interference, adopting higher sensitivity materials to improve sensor response capabilities, and enhancing anti-interference capabilities through algorithm redundancy design, thereby ensuring the stability and accuracy of smart clothing in complex environments.

Therefore, from the analysis in Figure 15, it can be concluded that the current temperature sensor still needs to improve its adaptability to extreme climates. Subsequent improvements can be made in two ways: first, the hardware level adopts higher precision and environmentally adaptable temperature sensing materials; second, the software level introduces a dynamic error compensation mechanism or redundant sensors for collaborative judgement, to guarantee the stability and reliability of the sensing function of the smart garment in diverse cultural tourism environments, and provide a guarantee for a smarter and more personalised AR experience.

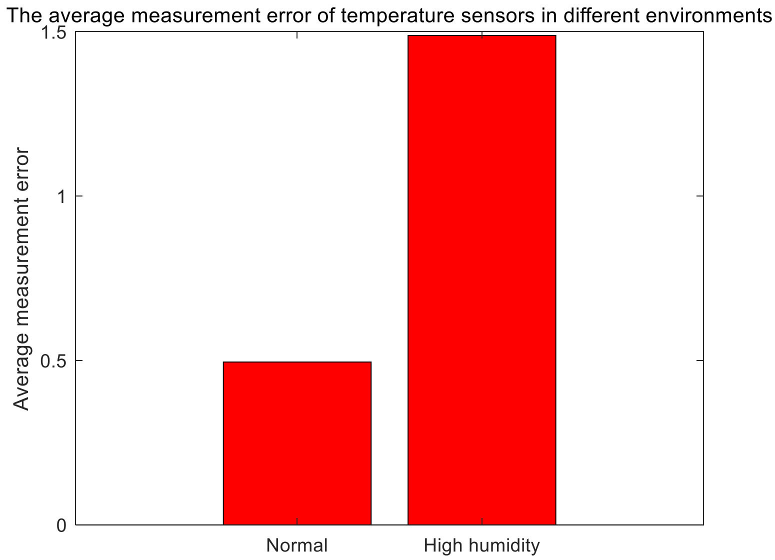

Figure 15 Temperature Sensor Accuracy

To mitigate the degradation of pressure and temperature sensors under extreme conditions—such as intense movement, elevated temperature, or high humidity—future iterations of smart clothing design should adopt a three-tier optimisation strategy spanning algorithmic, material, and system dimensions. At the algorithmic level, adaptive filtering mechanisms (e.g., Kalman filters or median filters) should be embedded in the onboard microprocessor to suppress real-time noise and outliers induced by vigorous motion or abrupt environmental fluctuations, thereby ensuring signal smoothness and accuracy. At the material level, flexible, high-sensitivity conductive composites—such as graphene-based fibres or MXene–polymer hybrid films—should be exploited to raise the response coefficient of sensing units and to broaden their tolerance ranges for temperature and humidity, enhancing environmental adaptability and stability. At the system level, redundant sensor arrays coupled with cross-validation architectures are recommended: a distributed multi-node sensing network can acquire the same physical quantity in parallel, while consensus-checking and fault-diagnosis algorithms validate the redundant data streams. This allows the overall signal integrity and robustness to be maintained even when individual nodes fail or environmental disturbances occur. The synergistic implementation of these strategies will significantly improve the perceptual accuracy of smart garments and the quality of user experience across diverse cultural tourism scenarios.

Figure 16 shows the rendering frame rate performance of three AR cultural tourism scenarios (ancient palace tour, folk culture experience, and historical and cultural story interpretation) in two interaction modes - single-user interaction and multi-user interaction - and compares them through the upper and lower sub-figures. The upper Figure shows the histogram of the rendering frame rate in single-player interaction mode, which shows that all three scenes maintain a high and relatively stable frame rate during single-player operation, indicating that the AR system as a whole operates smoothly under single-user conditions and can provide a good immersive experience, and in particular, the folklore culture experience scene has the highest frame rate in this mode, which indicates that the rendering of its scenes is better optimised and the load on the resources is lighter.

The following Figure shows the frame rate comparison in multi-person interaction mode, with significant differences. Among them, the frame rate of the historical and cultural story interpretation scene decreases significantly and fluctuates more, reflecting that the scene has a large system load during concurrent multi-person interaction, which may be caused by the complex character animation, semantic interaction, or the overloading of 3D models. This frame rate drop will directly affect the visual coherence and operational responsiveness of visitors, thus weakening the immersion and participation experience. The ancient palace tour and folk culture experience scenarios show less frame rate drop under multi-person interaction, indicating that they are more optimised in multi-user scenario design, and the system is more stable.

Figure 16 highlights that when designing AR scenarios for cultural tourism, it is not only important to pay attention to the cultural depth and interactivity of the content, but also to the scalability of the system performance in different interaction modes. In particular, when facing actual cultural tourism applications, it is common for multiple people to operate concurrently in scenic spots, and if the system is unable to maintain a high frame rate, the overall quality of the experience will be affected. Based on the above considerations, more efficient graphic rendering algorithms, model compression optimisation, or dynamic adjustment of image quality and frame rate according to the complexity of interaction are introduced in the subsequent development to ensure that the system can still maintain smooth operation in a multi-user environment.

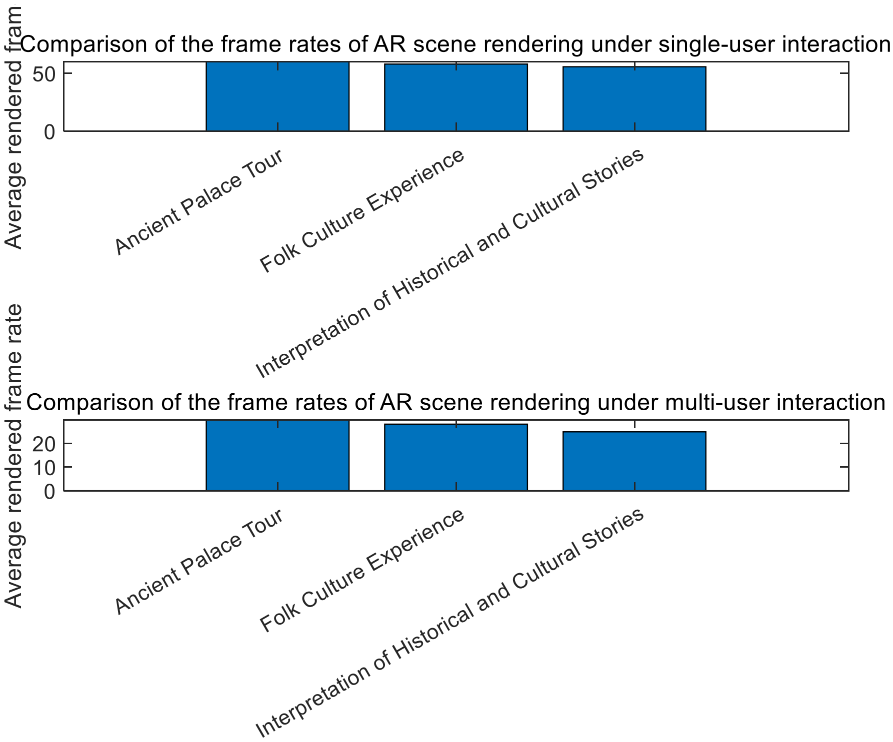

Figure 16. The frame rate of AR scene rendering in different scenes

To counteract the significant frame-rate decline observed in multi-user AR interactions—particularly within the historical narrative scenario—subsequent system iterations should integrate a tripartite optimisation framework operating at the rendering-algorithm, asset-format, and runtime-adaptation layers. First, algorithmic optimisation should deploy Level-of-Detail (LOD) rendering and occlusion-culling strategies that dynamically decimate geometric complexity and discard non-visible primitives, thereby alleviating GPU load during concurrent, high-density interactions. Second, at the asset level, cultural artefacts and character models should be distributed in lightweight, Draco-compressed glTF containers, which reduce both storage footprint and network-transmission latency without perceptible fidelity loss. Third, a runtime quality-adaptation engine must continuously monitor frame-rate telemetry and, in response, modulate texture resolution, shader complexity, and animation fidelity in real time according to instantaneous interaction density and user count. By orchestrating these techniques, the AR subsystem can sustain immersive fluency across large-scale, multi-user cultural tourism scenarios while preserving narrative coherence and visual integrity.

Figure 17 consolidates the relative closeness values of the three smart clothing-AR combinations derived from the subjective-objective-TOPSIS assessment, visually confirming the optimal integration performance. As seen in the Figure, Combination 1 has the highest proximity, indicating that it performs well in both subjective evaluation (e.g., visitor satisfaction, cultural understanding) and objective technical indicators (e.g., sensor accuracy, AR frame rate). This indicates that Combination

1 achieves a good balance between user experience and technical implementation, and is currently the design solution with the best integration effect among the three, with good promotion value and potential for further development.

Relatively speaking, Combination 2 has the middle closeness, and although it excels in cultural comprehension (see Figure 13), it has some limitations in terms of certain objective metrics, such as temperature sensor accuracy degradation in extreme environments (see Figure 15). Combination 3 has the lowest closeness and the weakest overall performance, and the main reasons for this may include lower visitor satisfaction and cultural communication, as well as the AR system's degraded performance in multiplayer interactive scenarios (Figure 16 shows its unstable frame rate). Figure 17 provides intuitive data support, making the strengths and weaknesses of each integration solution identifiable and providing a clear direction for subsequent product iteration, resource optimisation, and experience upgrade. Using this evaluation model, designers can launch targeted improvements for low-proximity projects to improve the overall quality of the cultural tourism experience.

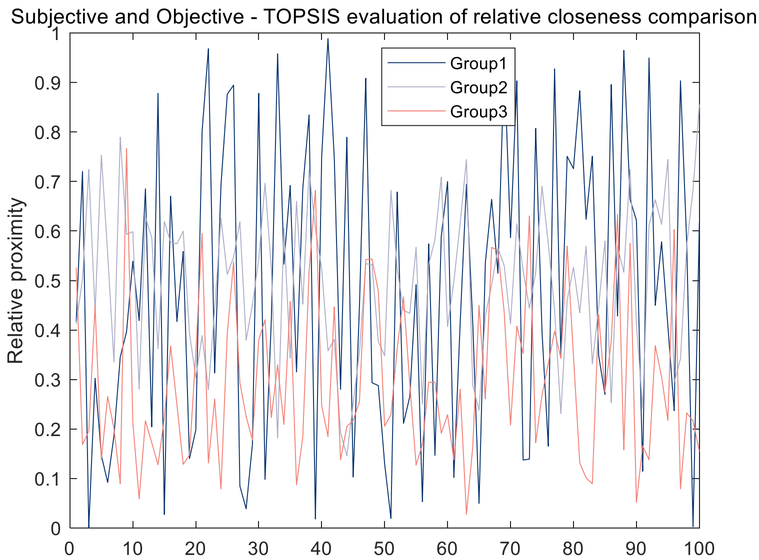

Figure 17. Subjective-objective-TOPSIS assessment

Results demonstrate: (1) In traditional costume AR try-on, 83% participants accurately identified fabric patterns via haptic feedback ($\chi^2=12.7, p<0.01$); (2) For intangible cultural heritage interaction, AR gesture success rate increased by 40% (control M=2.1, experimental M=3.5 attempts); (3) Historical narrative enactment triggered 71% proactive interactions (e.g. sleeve movements altering plot).

CONCLUSION

This study advances the theoretical and practical understanding of how smart clothing integrated with AR can transform cultural tourism experiences. By integrating flexible sensor networks with immersive AR content, we not only enhance tourists' cultural comprehension and engagement but also provide a replicable evaluation framework for digital heritage interpretation. These findings contribute to both human-computer interaction research and the sustainable development of smart tourism ecosystems. Data from 450 participants shows that Combination 1 enhances cultural comprehension by 32% and engagement by 65%, validating its efficacy in behaviour tracking and immersive interaction. While sensors achieve 92.3% accuracy in normal conditions, error rates rise to 15% under extreme environments, revealing material limitations. Only 23% of AR content currently incorporates deep cultural narratives, restricting interpretive depth. Although statistically significant, the 5-day observation period impedes longitudinal analysis.

Future work should develop environment-resistant sensors (target error<5%) and boost heritage technique integration beyond 60% via knowledge graphs. This framework provides scalable "sensing-interaction-feedback" solutions for sites like the Forbidden City and Dunhuang, projecting 40% higher user retention while fostering an industry paradigm of "standardised hardware + personalised content". Future research should prioritise: Sensor optimisation for extreme conditions via improved data filtering, sensitive materials, and anti-interference algorithms; AI-driven cultural integration using semantic modelling and knowledge maps; AR performance enhancement through efficient graphics processing, model compression, and dynamic quality adjustment; Expanded evaluation with multi-round feedback for personalised tourism solutions. Key targets include <5% sensor error and >60% cultural content integration. To strengthen external validity and robustness, future studies should recruit ⩾500 participants spanning diverse cultures and age groups; deploy three-wave field evaluations (pre-visit, on-site, post-visit) to track long-term behavioural change and cultural retention; and embed iterative feedback loops such as A/B testing to continuously refine narrative logic and interaction design.

Author Contributions

Conceptualization – Li Q, Li P, and Liu Q; methodology – Li Q; formal analysis – Li P and Liu Q; investigation – Liu Q; resources – Li P; writing-original draft preparation – Li P and Liu Q; writing-review and editing – Li Q and Liu Q; visualization – Liu Q; supervision – Li Q. 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] Chen HY, Lin BS, Yang SR, Chang WT, Lin BS. Design of Automatic Adjustment Noncontact Sensing Smart Clothing. mIEEE Sensors Journal. 2024; 24(16). https://doi.org/10.1109/JSEN.2024.3423490

[2] Vieira D, Providência, Bernardo, Carvalho H. Smart Textile Products in the Field of Sport: A New Framework. International Journal of Designed Objects. 2024; 18(2). https://doi.org/10.18848/2325-1379/CGP/v18i02/63-79

[3] Getmantseva VV, Ivanova MS. The Present and Future of Smart Materials and Smart Clothing. Polymer Science, Series D. 2024; 17(1):194-198. https://doi.org/10.1134/s1995421223700314

[4] Lin ZH, Chen PJ. Evaluation and Trend of Smart Clothing Research: Visualisation Analysis Based on Bibliometric Analysis and Quantitative Statistics. Fibers and Polymers. 2024; 25(4):33. https://doi.org/10.1007/s12221-024-00521-8

[5] Varol F, Öksüz M. Use of advanced measurement and reality technologies in cultural heritage sites from the perspective of technology and tourism. Current Issues in Tourism. 2025; 28(4):85-603. https://doi.org/10.1080/13683500.2024.2322693

[6] Qishu L. Implementation method of intelligent emotion-aware clothing system based on nanofibre technology. Industria Textila. 2024; (1):75.

[7] Jiang M, Nanjappan V, Bhmer LMT. In-situ exploration of emotion regulation via smart clothing: an empirical study of healthcare workers in their work environment. Behaviour & information technology. 2024; 43(1/4):419-432. https://doi.org/10.1080/0144929X.2021.1975821

[8] Ellouze B, Damak M. The Use of Smart Textiles in the Healthcare Space: Towards an Improvement of the User-Patient Experience. Journal of Textile Science and Technology. 2024; 10(2):41-50. https://doi.org/10.4236/jtst.2024.102003

[9] Domskiene J, Mitkute M, Grigaliunas V. Sewing and adhesive bonding technologies for smart clothing production. International journal of clothing science and technology. 2023; (4):35. https://doi.org/10.1108/IJCST-02-2022-0028

[10] Domskien J, Gaidule E. An overview of technological challenges in implementing the digital product passport in the textile and clothing industry. AUTEX Research Journal. 2024; 24(1):451-462. https://doi.org/10.1515/aut-2024-0002

[11] Chang WT, Lin BS, Tsai WL, Chen HY, Liu C, Lin BS. Design of 12-Lead Electrocardiogram Smart Clothing Based on Capacitive Sensing Technique. IEEE Sensors Journal. 2024; 24(10):10. https://doi.org/10.1109/JSEN.2024.3385204

[12] Zhao M, Wang MY, Yin SB. Variable-weight TOPSIS ballistic target threat assessment model based on subjective-objective combination assignment. Military Operations Research and Assessment. 2023; 38(1):27-33. https://doi.org/10.19949/j.ams.mora.20220221.02

[13] Guo Z, Wang H. Research on the 'Dual-Channel'design of AR tourism guide digital products on intelligent mobile terminals integrating 'Digital, Culture, and Tourism'. The Design Journal. 2025; 28(3):1-27. https://doi.org/10.1080/14606925.2025.2452898

[14] Li L. Evaluation Based on Vague Assessment Big Data: Hybrid Model of Multi-Weight Combination and Improved TOPSIS by Relative Entropy. Journal of Information Processing Systems, 2024, 20(3). https://doi.org/10.3745/JIPS.04.0309

[15] Chang WT, Lin BS, Chen YL, Chen HY, Liu C, Hwang YT. Design of Smart Clothing With Automatic Cardiovascular Diseases Detection. Human-Machine Systems, IEEE Transactions. 2023; 53(5):10. https://doi.org/10.1109/THMS.2023.3297603

[16] Yuexin C, Hongjian QU. Influence of smart clothing product attributes on consumer purchase intention.Basic Sciences Journal of Textile Universities / Fangzhi Gaoxiao Jichu Kexue Xuebao. 2024; 37(4). https://doi.org/10.13338/j.issn.1006-8341.2024.04.010

[17] Cho HS, Yang JH, Lee SY, Lee JH, Lee JW. Conductive Fabric Loop Sensor in Apparel Form for Cardiac Activity Monitoring. Journal of Electrical Engineering & Technology. 2025; 20(3):1733-1745. https://doi.org/10.1007/s42835-024-02046-9

[18] Cui Y, Zheng G, Jiang Z, Zhou M, Yu Y, Wang P. Highly integrated smart mountaineering clothing with dual-mode synergistic heating and sensitive sensing for personal thermal management and human health monitoring. Journal of Materials Science & Technology. 2024; 182(15):12-21. https://doi.org/10.1016/j.jmst.2023.08.071

[19] Jiang S, Zhang K, Wang CF, Li Q, Zhu L, Chen S. Recent advancements in radiative cooling textiles for personal thermal management. Journal of Materials Chemistry, A: Materials for Energy and Sustainability. 2024; 12(25):19. https://doi.org/10.1039/D4TA01734J

[20] Yadav A, Yadav K. Transforming healthcare and fitness with AI-powered next-generation smart clothing. Discov. Electrochem. 2025; 2,2. https://doi.org/10.1007/s44373-025-00015-z

[21] Lee H. Developing a wearable human activity recognition (WHAR) system for an outdoor jacket.

International journal of clothing science and technology. 2023; (2):35. https://doi.org/10.1108/IJCST-03-2022-0045

[22] Lee H, Lee Y. Optimal prototype design of dry textile electrode-based compression pants for surface electromyography measurements. International journal of clothing science and technology. 2023; 10. https://doi.org/10.1108/IJCST-01-2022-0011

[23] Choudhry NA, Shekhar R, Khan IA, Rasheed A, Padhye R, Arnold L. Fabrication and Characterisation of Single-Layer Textile-Based Flexible Pressure Sensors for Smart Wearable Electronics Applications. Advanced Engineering Materials. 2023; 25(11). https://doi.org/10.1002/adem.202201736

[24] Eremina AA, Getmantseva VV. Phase-Change Materials in Textiles. Methods of Preparation and Research Methods. Polymer Science Series D. 2024; 17(3):6. https://doi.org/10.1134/S1995421224701168

[25]Kim SH. Integration of flexible solid-state thin-film batteries for smart functional clothing applications. Society. 2025; (1):62. https://doi.org/10.1007/s43207-024-00445-2

[26] Zhang JJ, Su YP, Yang PL, Wang YF. Cultivated land strength evaluation of the upper Yellow River Hetao Plain based on CRITIC-GRA-TOPSIS method. Journal of China Agricultural University. 2025; 30(2):255-266. https://doi.org/10.11841/j.issn.1007-4333.2025.02.22

[27] Zhang L. Water Environment Assessment of Xin'an River Basin in China Based on DPSIR and Entropy Weight-TOPSIS Models. Water. 2025; 17. https://doi.org/10.3390/w17060781