

Knowledge Graph-Driven Semantic Association Analysis of Traditional Cultural Symbols and Intelligent Design of Cultural and Creative Products

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ABSTRACT In light of the rapid progress made in the digital transformation of cultural resources and intelligence in cultural creativity industries, there are issues with traditional cultural creativity design, including insufficient research into cultural semantics, low precision in matching elements in the design process, and poor effectiveness in solution discovery. To solve this issue, the use of knowledge graphs and semantic computing techniques to model cultural semantics and semantic relationships is proposed to develop an intelligent design system based on semantic association modeling. This paper proposes the structural representation of cultural symbols and models various types of semantic relationships and uses the graph embedding technique to enable vector representation of symbolic semantics and path reasoning to explore implicit semantic relationships. On this basis, the “cultural semantics-design element” mapping strategy is formed by mapping the semantics to color, pattern, and materials of the design, as well as multielement optimization under semantic constraints. Moreover, a mechanism for human-computer collaboration optimization and dynamic graph updating is established in order to ensure continuous iteration and precise control over the design solution. It can be seen that the above-mentioned method performs outstandingly well when it comes to cultural creativity design-related work: semantic matching precision is raised from 0.72 to 0.89; design consistency is improved from 0.75 to 0.86; while user acceptability is increased from 0.70 to 0.84. These metrics have been further improved during the process of optimization through iterations to 0.91, 0.89, and 0.88 respectively, illustrating that the method has successfully helped enhance the semantic precision of culture expressions and consistency in the whole design results.

INDEX TERMS knowledge graph, cultural symbols, semantic association, intelligent design, design element mapping

I. INTRODUCTION

UNDER the background of rapid development of digital technology and constant upgrades in the cultural and creative industry, traditional cultural resources are increasingly undergoing a process of transition into digitalization and industrialization, making the design of cultural and creative products increasingly become an important means of inheriting and innovating cultural content. On the other hand, existing cultural and creative designs are based on personal experiences of the designer and therefore result in difficulties like inadequate semantic analysis, inaccurate representation of cultural concepts, and inadequate consistency of the design in terms of symbol choice, semantic expression, and combination of elements. In addition, conventional techniques fail to structure multi-source cultural data and systematically model semantic connections between differ-

ent symbols. With regard to rapid development of intelligent design nowadays, how to ensure effective expression of cultural semantics and automated design has become one of the major bottlenecks to be solved immediately.

To resolve the above mentioned problems, this paper presents knowledge graph and semantic computing technology approaches for constructing a semantic association analysis and intelligent generation framework for the design of cultural and creative products. Through structural representation and modeling of traditional culture symbols and multi-type construction of semantic relationships, the process of semantic representation learning is realized by using graph embedding techniques, and then possible connections are explored using semantic reasoning methods. With this basis, the mapping between cultural semantics and design elements is formed, and the element combination

approach under semantic constraints is designed to realize the intelligent generation of designs. Moreover, the human-machine collaborative optimization method and dynamic graph update method are presented to improve the personalized features of the generated designs. The purpose of this paper is to present a theoretical methodology and technical approach reference for intelligent design of cultural and creative products.

II. RELATED WORK

In recent years, researches about multimodal cultural expression, data analysis and AI-assisted design has been deeply conducted, which provides significant theoretical and practical supports for digital transformation of cultural resource and innovative cultural products. To fill the gap of lack of large-scale empirical studies in multimodal discourse studies, Wang et al. designed multimodal content analysis method. By using structured coding and quantitative analysis model, they tested its validity by using urban short videos as example in the study of urban image building [1]. In view of literature analysis of traditional villages based on LDA theme model, Ge extracted four key themes and built a data-driven protection framework to coordinate the development of historical protection and revitalization [2]. With respect to construction and verification of traditional Chinese culture innovative value grading and evaluation system, Ji et al. achieved standardizing innovative value evaluation system of traditional culture in cultural and creative design through scale design and empirical research [3]. Jia et al. studied the mechanism and challenges of using generative AI to empower cultural creativity innovation for traditional handicrafts symbols. They believed that although the method enhanced the efficiency and transformed the industry, there were challenges like cultural superficiality. Moreover, they put forward the way of optimizing from aspects of technology, symbol, and ecology [4]. The study of Jiang and Ouyang utilized the bamboo materials from Xuefeng Mountain in designing cultural tourism and creative products through the empowerment of technology and integration of culture, advocating for promoting the coordination of nature, culture, and tourism in experience and sustainable design [5]. Therefore, to sum up, existing studies have achieved some results in analyzing cultural resources with digital means and designing creative products, but further exploration can be done regarding the intelligent semantic deep association modeling and generation mechanism. It is, therefore, necessary to employ the techniques such as knowledge graph to systematically analyze and intelligently represent the semantic structure of traditional culture symbols to enhance cultural design creativity.

III. RESEARCH METHODS AND TECHNICAL APPROACHES

A. KNOWLEDGE GRAPH-DRIVEN SEMANTIC ASSOCIATION MODELING METHOD

1) Classification and Modeling Mechanism of Semantic Relationships of Cultural Symbols

In order to construct an organized representation for the semantic relationships among traditional culture symbols, this paper extracts the symbols as nodes (V) and the semantic relationships as a set of typed edges (E) and represents them through a knowledge graph using triples. Here, the types of the semantic relationships can be roughly categorized into three main types: symbolic relations, contextual relations, and combinational relations.

Based on this, a unified graphical model is constructed as follows:

$$G = (V, E, R), \quad E \subseteq V \times R \times V \quad (1)$$

In order to improve the capability of identifying the semantic relation, a weighting method according to the cooccurrence rate and the semantic similarity was proposed. The weight value is calculated through a weighted fusion of textual and visual features: $\omega_{total} = \alpha \cdot sim_{test}(v_i, v_j) + (1 - \alpha) \cdot sim_{image}(f_i, f_j)$, where α is the modality balancing coefficient. Textual similarity is derived from word embedding vectors, while image similarity is extracted via a Pre-trained Convolutional Neural Network (CNN) to ensure cross-modal semantic alignment, which leads to the expression of the semantic strength in a quantitative form. Through this modeling method, the cultural symbols were converted from vague definitions to network structures with constraints.

2) Semantic Representation Learning Method Based on Graph Embedding

In order to solve the problem of directly calculating the semantics of cultural symbols, the graph embedding technique is adopted. The symbol nodes and relations are converted into vectors with lower dimension, and relation translation is carried out on the triple structure to keep its structural consistency, which finally realizes vectorized representation of the semantic relation.

The key constraint relationship between the two is:

$$\mathbf{h} + \mathbf{r} \approx \mathbf{t} \quad (2)$$

In training, the optimization of the distribution of embedding vector is achieved through a margin-based ranking loss function, which minimizes the score of positive triples while maximizing the distance from corrupted negative samples, following standard TransE paradigms. Through such a representation of symbols, we can determine the semantic similarity between symbols based on their vector angles or distances, and achieve a transition from “symbol matching” to “semantic matching”.

3) Semantic Association Reasoning and Implicit Relation Mining Methods

Following semantic representation learning, further exploration is conducted in order to discover possible semantic

relations using path reasoning and rule-based constraints. In the first step, a multi-hop relation path is converted into relation sequence form to capture path semantics by vector superposition, hence achieving indirect node association.

The key decision function for path reasoning is:

$$f(h, P, t) = - \| \mathbf{h} + \mathbf{r}_P - \mathbf{t} \| \quad (3)$$

With the help of this score above dynamically adjusted thresholds (τ), which are determined by the Maximum Likelihood Estimation (MLE) on the validation dataset to balance precision and recall, there will be a possibility to determine whether there is a semantic relationship between the nodes. By doing so, a rule constraint approach is adopted to extract common occurrence relationships of high frequencies and obtain stable semantics rules for reasoning, which ensures the validity of the reasoning results by means of confidence levels.

Under the joint effect of path reasoning and rule constraints, the implicit relationship in the knowledge graph can be expanded effectively and provide support for cultural creation in terms of symbol combinations.

B. SEMANTIC MAPPING AND GENERATION METHODS FOR CULTURAL AND CREATIVE DESIGN

1) Construction of a mapping mechanism from cultural semantics to design elements

In order to translate the meaning of cultural semantics into actual design form, a mapping relationship needs to be established between “semantic label and design elements”. The semantics of cultural symbols—defined here as structured semiotic units containing both visual form and cultural meaning—are translated into semantic vectors (s), while the design elements such as color, pattern, and materials are defined as element vectors (e). Through a mapping function, the projection from semantic vector space to design vector space is realized.

The mapping can be understood as a function learning problem that maps semantic vectors space into design elements space, which can be expressed as:

$$\mathbf{e} = f(\mathbf{s}) = \mathbf{W}\mathbf{s} + \mathbf{b} \quad (4)$$

where ($\mathbf{W}$) is the mapping weight matrix, and ($\mathbf{b}$) is the bias term. In real-time implementation, however, the mapping process is not a single factor-based solution, but a mixed approach involving rules and data-driven solutions: first, by using expert knowledge, rule sets are created so as to associate semantically-related terms such as “auspicious” with color and shape; Secondly, the system leverages semantic associations to ensure that conceptually similar terms yield consistent design feature outputs, thereby enhancing the robustness of the mapping mechanism.

Moreover, to ensure the reliability of the mapping, multi-element constraint conditions are employed to ensure that

the three factors (color, pattern, and material) are all semantically related, hence avoiding any semantic error in the design process.

2) Design Element Combination Strategy Based on Semantic Constraints

When the semantics have been mapped to the individual design elements, it is important to discuss how multi-element combination can be handled. Due to the holistic nature of cultural and creative product design, it is required that the design elements meet the requirement of being semantically consistent and formally coordinated with respect to culture.

The design scheme is represented as a set of elements ($E = e_1, e_2, \dots, e_n$). The rationality of the combination is evaluated by a semantic consistency function. Its core is to maximize the semantic coordination between elements within the combination, while satisfying the graph relationship constraints.

The combinatorial optimization objective can be expressed as:

$$\max \sum_{i \neq j} \text{sim}(e_i, e_j) \cdot C_{ij} \quad (5)$$

Wherein, ($\text{sim}(e_i, e_j)$) represents the semantic similarity between elements, and (C_{ij}) represents the constraint weights derived from the knowledge graph relationships (such as whether co-occurrence is allowed, or whether semantic conflicts exist).

Based on this, the optimal combination is selected from the candidate elements through a constraint screening and scoring ranking mechanism, so that the generated scheme has consistency in cultural semantics and coordination in design expression.

3) Semantic-driven generation method for cultural and creative product solutions

With semantic mapping and element combination in mind, an effective method for designing cultural and creative products is put forward. First of all, semantic inputs made by users will be mapped to design schemes automatically after going through semantic analysis, element matching, and optimal combination. The whole procedure for design can thus be briefly expressed as a function.

Specifically, semantic inputs will first be mapped to semantic vectors, and related symbol nodes are selected from the knowledge base. Then a number of design elements are produced through mapping. Ultimately, the optimal design scheme can be produced based on the combination strategy. The design process is therefore described as follows:

$$D = g(S) = \arg \max_E ; F(E | S) \quad (6)$$

Where (S) represents the input semantic set, (E) represents the combination of design elements, and ($F(\cdot)$) is the comprehensive scoring function, which comprehensively

considers semantic matching degree and combination coordination.

In order to make the results generated even more applicable, user preference parameters can be used to optimize the scoring function and help the system dynamically balance between “cultural harmony” and “individual expression”.

With the methods stated above, a feedback cycle generation model from understanding semantics to design output is established, thus making the whole process intelligent and controllable.

C. KNOWLEDGE GRAPH-DRIVEN INTELLIGENT DESIGN IMPLEMENTATION MECHANISM

1) System Architecture Design for Cultural and Creative Design

For facilitating the general workflow of semantic modeling and design generation, the system architecture is designed based on four-layered hierarchy, namely, the data layer, knowledge layer, reasoning layer, and application layer. The data layer manages the access and preprocessing of multi-source data of cultural symbols. The knowledge layer takes charge of knowledge graph storage and management. The reasoning layer performs semantic reasoning and design element generation. And the application layer offers users the function of design interaction and display.

When the system runs, data transfers among layers through interfaces. Its general workflow can be regarded as a process of mapping from input data to design output, where the semantics of inputs are mapped to design outputs through knowledge reasoning and generation components. It can be mathematically expressed as:

$$D = \mathcal{F}(X; G, \Theta) \quad (7)$$

Where (X) represents the input data (semantics or user requirements), (G) represents the knowledge graph, (D)(Θ) represents the system parameters (including mapping rules and model parameters), and (D) represents the output design scheme.

2) Design Optimization Mechanism for Human-Machine Collaboration

Taking the automatic design solution as the basis, a dynamic user participation approach is adopted to optimize the design results interactively through feedback. In detail, the user preference factors can be expressed by the vector $\mathbf{u}$ and incorporated into the design evaluation formula so that the generation method can be adjusted adaptively according to user choices. To ensure real-time feasibility under complex reasoning, the system utilizes high-performance vector indexing (such as FAISS) and edge-computing acceleration. Experimental tests on a standard workstation (NVIDIA RTX 4090, 64GB RAM) demonstrate an average inference latency of less than 150ms per design iteration, meeting the interactive requirements of human-machine collaboration.

In the design scheme evaluation function formulated from the perspective of semantic matching and combination rationality, user preference factors are considered to correct the evaluation result. Its mathematical expression is:

$$F'(E) = \lambda_1 F_{sem}(E) + \lambda_2 F_{comb}(E) + \lambda_3 F_{user}(E, \mathbf{u}) \quad (8)$$

Where (F_{sem}) represents semantic matching degree, (F_{comb}) represents combination coordination degree, (F_{user}) represents user preference adaptation degree, (λ_i) and is the weight coefficient.

3) Feedback-based map update and evolution mechanism

In order to guarantee the longevity and flexibility of the knowledge system, it is essential to create a dynamic updating approach that relies on user actions and design outputs. In particular, user selections, modifications, and evaluations are taken into consideration as implicit feedback and employed for correcting the attributes of nodes and the weights of connections within the knowledge graph.

While updating the knowledge graph, the weights of relations will be gradually altered based on feedback signals, with frequent acceptance leading to an increase in weight while inappropriate pairs being assigned lower weights. This can be represented by:

$$w_{ij}^{(t+1)} = w_{ij}^{(t)} + \eta \cdot \Delta_{ij} \quad (9)$$

Wherein, (w_{ij}) represents the weight of the relationship between nodes, (η) and is the learning rate, (Δ_{ij}) which is determined by user feedback (such as selection or rejection).

On the other hand, by applying periodic reconstruction and relationship filtering techniques, low-confidence relationships are removed, whereas high-confidence paths are reinforced, thus realizing the evolutionary adaptation of the knowledge graph architecture. Such an approach allows the system to learn from users' experiences and design templates continuously, resulting in improved performance of semantic reasoning and design generation.

IV. APPLICATION AND RESULT ANALYSIS OF INTELLIGENT DESIGN FOR CULTURAL AND CREATIVE PRODUCTS

A. DATA ORGANIZATION AND SEMANTIC INPUT CONSTRUCTION

The test dataset is created by randomly sampling traditional cultural symbols such as lucky symbols, decorations of artifacts, and cultural images, then standardizing the annotations of the semantics. The semantic inputs were presented in terms of label compositions, consisting of cultural semantics like “auspicious” and “blessing,” situational features such as “festival” and “gift,” and style considerations including “simple” and “traditional.”

For actual design and generation purposes, semantic labels need to be transformed into input vectors, while candidates can be retrieved from a knowledge graph. In order

to stabilize the input, multi-label semantics will be merged using weights, which will allow for the dominance of core semantics. To prevent overfitting and ensure data reliability, a 10-fold cross-validation method was applied during the training and evaluation phases. The dataset was partitioned into ten subsets, ensuring that the reported precision and acceptance metrics represent the average performance across diverse symbol combinations.

B. PROCESS OF GENERATING CULTURAL AND CREATIVE DESIGN SCHEMES

Semantic input triggers node matching and expansion in the knowledge graph to select out cultural symbols with high semantic correlation; subsequently, design element candidates, such as color scheme, pattern combination, and material recommendation, will be produced accordingly through the semantic mapping process.

At the element combination phase, the system sorts and screens out alternative elements based on their semantic correlation and relational constraints to form several optional design proposals. Under different semantic inputs, the outputs exhibit marked variations in terms of style manifestation. For instance, if “prayer + festival” serves as semantic input, the design will be inclined toward the adoption of high saturation and warm hues along with symmetrical patterns, whereas “simplicity + cultural heritage” will lead to the use of low saturation colors and abstract graphics. Finally, the output is delivered in the format of “combination of design elements + application illustration”, and could be implemented to facilitate the visual design of cultural and creative product carriers (e.g., office supplies, apparel, or souvenir).

C. EVALUATION AND COMPARATIVE ANALYSIS OF DESIGN RESULTS

In order to test the validity of the results, the design results produced were tested based on three aspects: semantic matching degree, design consistency, and user acceptance. The semantic matching degree is mainly about the correlation between the design results and the input semantic information; the design consistency is mainly about the uniformity of the combination of elements; and the user acceptance is mainly evaluated subjectively.

The comparative study was conducted to compare the design results obtained using the knowledge graph-based method and those obtained using the conventional design method based on experience. The research indicates that the semantic modeling design results are more effective in terms of semantic transparency and stylistic consistency and can eliminate the distortion caused by the experiential bias during the design process.

TABLE 1. Changes in design effectiveness during human-machine collaborative optimization

Interaction rounds	Semantic matching degree	Design Coordination	User acceptance
Round 1	0.86	0.83	0.8
Round 2	0.88	0.85	0.83
Round 3	0.9	0.87	0.86
Round 4	0.91	0.89	0.88

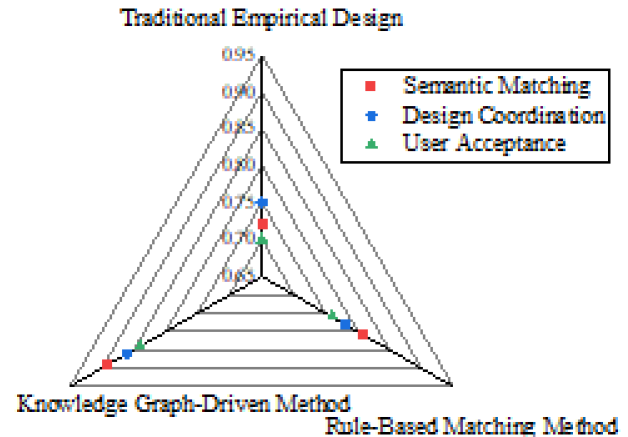


FIGURE 1. Comparison of evaluation results of creative design using different methods

Note: The rating range is 0–1, with higher values indicating better results.

As shown in fig 1, there are great differences in the evaluation criteria of cultural and creative design outcomes depending on design methods. The traditional experiential approach had obtained scores of 0.72, 0.75, and 0.70 for semantic matching, design harmony, and user acceptance, which were rather poor. Therefore, we can conclude that it was too dependent on personal experience, and its weakness was cultural semantic expression and consistency in combining elements. On the contrary, the knowledge graph method was superior to others according to all the indicators listed above, getting scores of 0.89, 0.86, and 0.84 for semantic matching, design harmony, and user acceptance correspondingly. This resulted in the increase of performance by about 23.6%, 14.7%, and 20.0% as compared with traditional experiential approaches. It proves that with the help of the described approach and using knowledge graphs, designers may enhance the effectiveness of semantic connections between cultural symbols and achieve higher levels of consistency in their combinations.

As one can see from Table 1, there are large disparities in terms of the evaluation criteria of the results of cultural and creative designs due to the design methods used. In particular, traditional experiences scored at 0.72, 0.75, and 0.70 when it came to such categories as semantic match, design harmonization, and user acceptance. These numbers prove that there was a great lack of consistency in the described method since its reliance on personal experience was evident. At the same time, knowledge graph proved to be better than other methods in terms of the aforemen-

tioned aspects, obtaining scores of 0.89, 0.86, and 0.84 correspondingly. This allowed increasing the efficiency of the method in comparison with others by 23.6%, 14.7%, and 20%. As one can see, knowledge graphs helped improve the efficiency of semantic relationships and combination of symbols.

V. CONCLUSION

The current paper mainly discusses semantic expression and applications of traditional cultural symbols in the field of cultural and creative designs by utilizing a new approach for intelligent designs driven by knowledge graph-based semantic association modeling. Through modeling semantic relations between cultural symbols in structure and expressing such semantic relations through vectors, coupled with semantic mapping techniques and element combination approaches, automatic design generation of cultural semantic expression is enabled. At the same time, mechanisms of human-machine collaborative optimization and dynamic graph update techniques are employed to further enhance the accuracy of semantic matching and personalization capabilities of generated designs. Some related application experiments have verified that the proposed approach can effectively resolve some issues like semantic ambiguity and improper element combination associated with traditional design processes. This demonstrates a great improvement in semantic matching efficiency, design coordination, and user acceptance, thereby revealing the practical value of applying knowledge graphs in the intelligentization of cultural and creative design practices. It should be noted that the above methods still have some deficiencies regarding semantic annotation accuracy and multimodal data fusion techniques; some complicated cultural context features still cannot be well represented. Future research could further introduce deep generative models and cross-modal learning methods to improve the depth of semantic understanding and the diversity and innovation of design generation.

AUTHOR CONTRIBUTIONS

Limin Yuan designed, collected and analyzed the data, and drafted the manuscript. Limin Yuan conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Limin Yuan participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

CONFLICTS OF INTEREST

The author declares no conflict of interest.

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