Knowledge Association and Semantic Description of Dunhuang Manuscript Images: Post-print Edition

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Abstract

[Purpose/Significance] The rapid development and widespread application of information technology have catalyzed transformation in Dunhuang studies, facilitating research and enhancing the accessibility of its knowledge resources. However, reliance on existing databases, traditional knowledge platforms, and retrieval methods has resulted in inadequate comprehensive mining of the knowledge value embedded in Dunhuang manuscript images. To this end, the author conducts a systematic review of Dunhuang manuscript image research and undertakes comprehensive semantic description of the depth and breadth of knowledge discovery in Dunhuang images and their knowledge associations, thereby facilitating the discovery of the multifaceted value of Dunhuang manuscript images.

[Method/Process] Through an examination of the current research landscape and semantic description of Dunhuang manuscript images, a hierarchical model of semantic features is developed based on the semantic characteristics of Dunhuang manuscript images. Integrating intelligent and linked data technologies, an organizational framework for knowledge association of Dunhuang manuscript images is established, with detailed analysis of its constituent layers: data collection layer, semantic description layer, data association layer, and resource application layer.

[Results/Conclusion] This study proposes a knowledge association model for Dunhuang manuscripts and demonstrates its practical value in establishing linkage channels with external open data, enhancing intelligent retrieval quality of Dunhuang manuscript images, and expanding the depth and breadth of knowledge services for Dunhuang manuscript images.

Full Text

Preamble

Knowledge Association and Semantic Description of Dunhuang Manuscript Images

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Abstract: [Purpose/Significance] The rapid development and widespread application of information technology have driven transformation in Dunhuang studies, making research and utilization of knowledge resources more convenient. However, current research remains limited to traditional knowledge platforms and retrieval methods in existing databases, resulting in incomplete value mining of Dunhuang manuscript image knowledge. Therefore, the authors review research on Dunhuang manuscript images and provide comprehensive semantic descriptions of the depth and breadth of knowledge discovery and knowledge association to facilitate exploration of the multiple values of these images. [Method/Process] Through examination and semantic description of current research on Dunhuang manuscript images, we design a hierarchical semantic feature model based on the semantic characteristics of these images, construct an organizational framework for knowledge association using intelligent+linked data technology, and analyze in depth the data collection layer, semantic description layer, data association layer, and resource application layer within this framework. [Result/Conclusion] The paper proposes the practical value of the Dunhuang manuscript knowledge association model, which can open channels for linking with external open data, improve intelligent retrieval quality of manuscript images, and enhance the depth and breadth of knowledge services.

Keywords: linked data; Dunhuang manuscript images; hierarchical model of semantic features

Classification Number: G254

Dunhuang manuscript images represent precious cultural heritage for China and the world, containing rich semantic connotations significant for studying ancient Chinese social history, art, and religious culture. Current traditional knowledge platforms and retrieval methods in databases typically involve simple cataloging of image resources, limiting the utilization effectiveness and depth of knowledge discovery, preventing maximum value extraction, and failing to meet user retrieval needs. In July 2006, Tim Berners-Lee, the father of the World Wide Web, first proposed the concept of linked data in *Linked Data Notes*.

2 Related Research

Related research focuses on semantic analysis of Dunhuang manuscript image knowledge, linked data, and image resource organization. Dunhuang manuscripts contain numerous paintings of different types and styles, including

figures, animals, and plants. Scholars have conducted detailed investigations from various perspectives, leaving high-value reference materials for future research. Semantic feature analysis of these images is a prerequisite for subsequent in-depth exploration of semantic description and knowledge association.

2.1 Construction of Dunhuang Studies Platforms and Databases

Digitization of Dunhuang manuscript images is a prerequisite for subsequent semantic feature analysis, ontology construction, semantic interconnection, and semantic retrieval. Currently, multiple digitization projects have been launched domestically and internationally, including the International Dunhuang Project (IDP) [3], Dunhuang Manuscripts Database [4], and Dunhuang Documents Digital Library [5]. Investigation of these projects, databases, and platforms reveals that many functions need improvement, and application of linked data can address current limitations in Dunhuang databases.

2.2 Linked Data and Knowledge Resources Research

The outstanding advantage of linked data is its ability to link distributed, heterogeneous, and cross-domain data, supporting aggregation, sharing, and discovery of resources at different knowledge levels. Linked data not only breaks through traditional text-based knowledge organization but also involves image research. Zeng Ziming et al. proposed a linked data-based visual resource knowledge organization model for digital humanities, constructing a semantic ontology model for visual resources and using the "Kumarajiva" image in Dunhuang studies as a case study [6]. Zhang Xingwang et al. summarized deficiencies in digital preservation of intangible cultural heritage images and videos, providing corresponding acquisition, organization, and description methods [7]. Qi Yunfei et al. applied linked data technology to static images in digital libraries, referencing BIBFRAME to construct and verify a mobile visual search system framework [8]. Zhang Yongjuan et al. used seal images to explore solutions for image metadata description, knowledge organization of image content, linked data publication, and image resource integration using IIIF and linked data technologies [9].

2.3 Image Semantic Description Research

Image semantic description research focuses on semantic annotation models, annotation tools, and semantic retrieval system design. Lu Quan et al. compared three annotation modes through user experiments [10]. Chen Jinju et al. comparatively analyzed three mainstream image semantic annotation models from perspectives of semantic hierarchy, scalability, application scope, and methods [11]. Chen Jinju also reviewed existing image semantic annotation tools and compared three categories across ten key characteristics [12]. Zhang Zhiwu constructed a Web image semantic retrieval system including an image

domain ontology, image ontology library, and retrieval services based on these components [13].

2.4 Dunhuang Manuscript Images and Knowledge Organization Research

Research on Dunhuang manuscript images focuses on image content and reflected historical culture, while related Dunhuang mural research involves computer science, library and information science, and other fields. Wang Xiaoguang et al. proposed a digital image semantic description framework for Dunhuang murals to address the inability of metadata to accurately reveal mural content and semantic information [14]. Song Zhihao designed an ontology-based semantic retrieval system for Dunhuang murals [15]. Wang Xiaoguang et al. built a Dunhuang mural thesaurus using semantic web technology to implement linked data publication [16].

2.5 Dunhuang Manuscript Images and Knowledge Association Research

Since the discovery of the Dunhuang manuscript cave, scholars worldwide have extensively explored related image issues. In content research, Japanese scholar Matsumoto Eiichi conducted long-term investigations of scattered Dunhuang paintings and wrote *Studies on Dunhuang Paintings*, using Buddhist knowledge to interpret, name, and classify paintings from the cave [17]. Sha Wutian, Tai Huili [18], and Zhang Peijun [19] introduced, classified, and reviewed line drawings and donor figures. In classification, Shi Pingting categorized paper paintings by technique into colored paintings, five-color paintings, light-colored paintings, stencil drawings, white paintings, and line drawings [20]. Dai Ren classified illustrations in Dunhuang manuscripts into four types: frontispiece illustrations, band illustrations, figure paintings, and textual images [21]. Élie [21] categorized "doodles" into figures, animals, and plants, with figures further divided into secular persons, religious figures, and obscene figures, listing relevant manuscript numbers. Scholars have conducted specialized horizontal studies on specific figures like Avalokitesvara, Ksitigarbha, traveling monks, Pure Land images, Manjusri, Vaisravana, and filial piety sutra illustrations. Others have vertically explored connotations, such as Yang Shuyun's study of Tang dynasty women's makeup based on British collection S.47 [22], and research on pigments, banners, costumes, and floral patterns.

Dunhuang manuscripts contain thousands of diverse images. Numerous specialized studies have excavated rich knowledge and opened new research directions. Only through appropriate cataloging, indexing, and retrieval methods combined with user needs can the value granularity of manuscript image knowledge be maximized.

In summary, linked data can associate widely distributed heterogeneous resources. Although mainly used for text, some scholars have begun exploring

its application to image resource organization, breaking through limitations in Dunhuang manuscript database retrieval and providing theoretical frameworks for knowledge organization model construction. Current research primarily explores image connotations and painting techniques, providing detailed semantic analysis as a prerequisite for building resource organization models, but research on semantic description and knowledge association remains scarce. Dunhuang murals, closely related to manuscript images, have achieved excellent results in digital image semantic description methods, hierarchical models, and thesaurus linked data publication, providing valuable references.

3 Semantic Features for Knowledge Association of Dunhuang Manuscript Images

Dunhuang manuscripts (mostly Tang dynasty copies, with some from Five Dynasties and early Northern Song, including printed editions like P.3879 *Northern Great Sage Vaisravana King Image with Woodblock Print Inscription*) are treasured by institutions worldwide. To fully exploit their value, scholars and institutions are exploring digitization methods. Wang Xiaoguang's research on digital image feature description for Dunhuang murals distinguishes between inherent image features and content features, treating color, texture, and lines as low-level visual features and content descriptions (emotional attitudes, actions, historical background, geographical environment) as high-level semantic expressions [14], providing inspiration for our hierarchical semantic feature model.

In the digital age, focus often concentrates on digital images while neglecting physical characteristics of original images. Annotating these physical features helps explore craft art development during image creation periods. Dunhuang manuscript images possess physical properties manifested through their paper carriers. Therefore, semantic feature description should include two layers: physical characteristics of original images and visual information presented after digitization. The physical layer involves paper material, size, color, painting techniques, and pigment application. Special cases like paper-cut images (e.g., P.4517 *Bodhisattva Holding a Banner*, [Figure 1: see original paper]) can be distinguished at this level. Though not discussed here due to constraints, this layer should be included when possible to enrich semantic description.

After digitization, visual information is relatively completely preserved. Semantic description should address two aspects: the digital image itself and its reflected content. As mentioned, Dunhuang manuscript digital images and their content are essentially different. The former includes visual features like lines, shapes, colors, and textures, while the latter encompasses graphic meaning, object forms, story content, human actions, and even emotional states—low-level features serving as the cognitive foundation for high-level semantic abstraction.

4 Semantic Description for Knowledge Association of Dunhuang Manuscript Images

Based on academic retrieval needs for Dunhuang manuscript images, combined with image retrieval theory and practice, and integrating physical features of original images with visual and content features of digital images, we propose a hierarchical semantic feature model for Dunhuang manuscript images. This model attempts to reveal all characteristics across three levels to meet researcher and general user needs and expand knowledge discovery depth, as shown in [Figure 2: see original paper].

[Figure 2: see original paper] Hierarchical Semantic Feature Description Model for Dunhuang Manuscript Images

The model comprises three parts from left: physical layer, visual content feature layer, and semantic data layer.

The physical layer has been briefly explained above. The visual content feature layer reflects visual characteristics after digitization. Many manuscript images show regularity in outlining lines, such as mandala line distributions and rounded figure-drawing techniques. Shape sizes and spatial distributions tend toward consistency due to carrier constraints, with color processing showing particular tendencies. By designing and improving statistical functions in computer graphics software, combining advantages of SIFT and CNN algorithms in CBIR, both local and global features can be extracted. Embedding image recognition and learning technologies in computers, based on batch processing of modularized information, continuously improves recognition capabilities to form metadata chains, enabling feature-based image content retrieval and serving users.

The semantic data layer (detailed in Section 5.1) is the core module for knowledge retrieval and utilization, essentially the core design of the Dunhuang manuscript image ontology. Ontology design 关键在于确定实体概念, making metadata category design crucial. Wang Xiaoguang collaborated with Dunhuang studies experts to build a comprehensive, semantically rich Dunhuang mural thesaurus integrating multiple disciplines. The thesaurus contains five facets: Agent Facet, Time Facet, Activities Facet, Object Facet, and Physical Attributes Facet [16]. Dunhuang manuscript image knowledge is more fragmented than mural knowledge, but some image content is closely related to murals, allowing professional terms from the mural thesaurus to serve as entity concepts for manuscript image ontology.

We extensively collected various digital materials of Dunhuang manuscript facsimiles, including collections from France, Britain, Peking University, National Library of China, Gansu, Tianjin Art Museum, Russia, and Shanghai Library, examining nearly a thousand images. Based on comprehensive review and extracting relevant terms from the Dunhuang mural thesaurus combined with scholarly research needs, we temporarily divide features into five progressive

levels: graphic meaning, object form, story content, human figures, and emotional states.

4.1 Graphic Meaning

Dunhuang manuscript images constitute a massive dataset requiring classification from coarse to fine for metadata retrieval. Researchers follow this basic principle to achieve data association at different levels. The lowest level for semantic retrieval is designed as graphic meaning—the fundamental appearance and expressive meaning after digitization. Graphic meaning can be subdivided into patterns, objects, scenes, figures, etc., representing basic categories from comprehensive screening.

4.2 Object Form

Object form merges pattern and object categories from the classification above, where image meanings are relatively direct. Patterns include various designs, symbols, and marks. Representative patterns include cloud motifs, as seen in the silk brocade header of BD.13801 *Wonderful Dharma Lotus Sutra, Volume 1* [Figure 3: see original paper], which contains numerous exquisite cloud patterns showing different forms that 烘托氛围 and reflect Tang dynasty painting excellence. Symbol categories include many mandala-style images with numerous variations, such as P.3679 with the *Swastika* symbol and numerous incantations, or P.4521 interspersed with Uyghur script. Markings are more complex and can be further subdivided.

Object categories include images depicting objective entities other than figures: plants, animals, spirits, and implements. Plants mainly include trees and flowers, simply categorized due to difficulty in detailed identification. Many animals appear, such as numerous horse drawings—single horses (P.3652) or multiple horses (P.3614). Horses were crucial for transportation, information delivery, and military operations in ancient society, making data association studies valuable for understanding Tang-Song horse administration. Spirits include mythological creatures like those in P.2683 *Auspicious Omens Chart*, which preserves nearly twenty types. These should be described in detail (rabbit-like, turtle-like, winged, etc.) for precise metadata collection. Implements include vehicles (phoenix carriages, ox carts, military tools), production tools, and religious implements like lotus thrones symbolizing purity. Implements relate closely to human actions, enabling association studies of tool evolution from Northern Wei to Northern Song.

4.3 Story Content

Story development combines with scenes, making scene categories part of story content for clarity. Scenes include environments (natural and humanistic), though not all manuscript images contain identifiable scenes. This section focuses on recognizable narrative and story paintings, such as P.2003 *Sutra on*

Yama's Prediction and Pratyupanna Samadhi for Rebirth in Pure Land. Such printed or handwritten copies are called sutra illustrations or transformations. Since later copies postdate Dunhuang manuscripts, these images are crucial for studying transformation development and reflected social and religious history. Feature description should include: (1) accurate cataloging of the original sutra name for comparative studies of different transformations, and (2) attention to spatial layout and story outlines reflecting research value beyond the sutra itself.

4.4 Human Figures

Human figures constitute the largest category, with bodhisattvas predominant, especially Avalokitesvara images like P.3969 *Eleven-Faced, Six-Armed Avalokitesvara*. Semantic feature description must distinguish category characteristics based on extensive research. Another important category is donors, such as P.4060 *Donor Image of Luo Youtong, Suppressing Envoy of Guiji*. Donor images in Dunhuang murals show various behaviors; detailed feature description and data association can deepen understanding of Tang dynasty donors. Human figures also include headdresses, costumes, gestures, and foot directions. For example, P.3905 records dozens of hand mudras with explanatory text crucial for feature description and data association with murals and cave sculptures for horizontal comparison.

4.5 Emotional States

Emotional states represent a higher-level dimension of human figures. Unlike stereotypical images, many reflect various emotions—anger, sadness, joy, or melancholy. Detailed semantic description significantly improves retrieval quality and linked data effectiveness. Some unusual or eerie images require supplementary description, such as P.4514 *Head Portrait* [Figure 4: see original paper], depicting a woman's face mixed with melancholy and disgust, surrounded by dense eyes creating a mysterious, frightening atmosphere. Such images with special emotional expressions deserve attention and detailed description.

Human figures in Dunhuang manuscripts are complex and warrant a separate ontology. Compared to lower-level features like behavior and costume, emotional attitude description is more profound. For entity extraction and in-depth research, emotional attitudes can combine with other aspects to form a human figure ontology model [Figure 5: see original paper].

[Figure 5: see original paper] Human Figure Ontology Model in Dunhuang Manuscript Images

5 Organizational Framework and Practical Value of Dunhuang Manuscript Image Knowledge Association

5.1 Organizational Framework for Dunhuang Manuscript Image Knowledge Association

Linked data can link complex heterogeneous resources and accurately identify elements. RDF, the foundation of linked data, defines data elements, associates them, and provides a universal framework for merging data from different sources. Combining the hierarchical semantic feature model with linked data technology, the organizational framework for Dunhuang manuscript image knowledge association should include complete steps from data collection, semantic information extraction and ontology construction, to RDF linking and deep service provision [Figure 6: see original paper].

[Figure 6: see original paper] Organizational Framework for Dunhuang Manuscript Image Knowledge Association

(1) Data Collection Layer. Data collection is foundational for the semantic organization framework. Sources are diverse and heterogeneous: digitized images from international collections, related databases, research literature (academic journals, monographs, popular books), and video resources like TV programs and documentaries. The International Dunhuang Project (IDP) is undertaking this work but remains incomplete; collaboration could facilitate preparation for image data association. Non-digital resources should be converted according to standards like *Specifications for Digitization of Paper Archives* and *Specifications for Digitization of Audio-Visual Archives*. Collected data requires basic classification and deduplication to establish an initial metadata corpus. Without deduplication, noise and redundancy affect subsequent semantic description quality.

(2) Semantic Description Layer. This layer semantically describes image content features, differing from both text-based image retrieval (TBIR) and content-based image retrieval (CBIR). TBIR uses manual keyword description but faces limitations: vast image quantities versus annotation costs, and inconsistencies in cognition, expression, and perception between annotators and users [23]. CBIR enables computer-extracted features for fast similarity searches but only describes low-level visual features (color, shape, texture), not deep semantics like figures, time, location, and events.

Ontology is "an explicit formal specification of a shared conceptualization" [24]—a collection of entity concepts in a domain serving as a semantic carrier that classifies entities, determines hierarchical relationships and attributes, and enables cross-category connections. Compared to TBIR and CBIR, building an ontology for Dunhuang manuscript images achieves high-level semantic expression for more efficient and intelligent retrieval. We constructed an ontology model classifying images into patterns, objects, scenes, and figures (detailed above). Entity, relationship, and attribute extraction using RDF format cre-

ates machine-understandable forms. Automatic indexing of research literature continuously enriches semantic information, establishes effective HTTP URIs, and enables semantic interconnection between images and texts for multi-type data association.

(3) Data Association Layer. This core layer associates RDF semantic metadata based on image characteristics and relationships, revealing hidden connections. Using P.4518(39) *Bodhidharma* as an example, the figure "holds" a tool while also relating to P.4029 *Traveling Monk* because both prototype Tang dynasty layman Li Tongxuan. Manuscript image knowledge is scattered and requires reorganization of RDF metadata to fully reveal hidden relationships. RDF triples express subject-predicate-object as URIs, enabling unified identification and linking of metadata from different datasets to form a semantic network. This layer publishes linked data to transform complex manuscript image information into an interconnected organic whole, maximizing network value and improving utilization quality and service efficiency.

(4) Knowledge Application Layer. After collection, description, organization, and integration using linked data, the ultimate goal is providing knowledge services: publishing image knowledge as linked data, semantic browsing and retrieval, and knowledge discovery and mining, forming a complete organizational model for Dunhuang manuscript image archives.

5.2 Practical Value of Dunhuang Manuscript Image Knowledge Association

5.2.1 Opening Channels for Association with External Open Data Platforms. Linked data technology enables not only semantic interconnection between images but also linking with network open data platforms, advancing knowledge association depth and breadth. Shanghai Library's publicly released open data platforms (Geographic Name Gazetteer, Chinese Historical Chronology, Collection Institution Directory) and Wang Xiaoguang's Dunhuang mural thesaurus linked dataset can be matched and associated with entities extracted from manuscript images to promote knowledge aggregation and reasoning. The data association layer can link with Chinese Historical Chronology and Collection Institution Directory to obtain corresponding dynasties and locations, and with the Dunhuang Mural Thesaurus Linked Dataset to discover images with similar themes, techniques, figures, or emotions, revealing hidden relationships and enabling comparative analysis. The layer should also associate with research literature and video resources to display all related research materials during retrieval.

5.2.2 Improving Retrieval and Utilization of Dunhuang Manuscript Image Resources. In practice, detailed exploration of rich content elements—figure pedestals, headdresses, actions, color schemes—combined with semantic retrieval and linked data transforms traditional knowledge structures. This facilitates both deep value mining and specialized research. Under big data,

developing computer self-learning functions to connect semantic descriptions across image types and optimize retrieval modes based on user needs is essential. For example, implementing image-based retrieval where users can upload manuscript or mural images for AI matching with similar manuscript images.

5.2.3 Enhancing Depth and Breadth of Knowledge Services. Contemporary knowledge services involve extracting specific information and knowledge from data resources to build data networks that help solve particular problems [25]. User needs extend beyond general metadata to detailed elements, historical backgrounds, video explanations, and research literature. Current manuscript image databases have insufficient data association functions, but applying linked data improves traditional organization methods, enhances retrieval quality, and enables discovery of multi-type resources (historical backgrounds, semantic connotations, research materials), providing more profound and extensive knowledge services.

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To strengthen academic norms, research integrity, and academic ethics in paper writing, review, and editing, establish good academic atmosphere, promote scientific spirit, resolutely resist academic misconduct, and maintain a fair, just, and open academic exchange ecosystem, *Library and Information Service* Magazine (including editorial departments of *Library and Information Service* and *Knowledge Management Forum*) formulated and officially released this Publication Ethics Statement in February 2020.

The statement commits that both journals will strictly abide by and implement national policies and regulations on academic ethics and editing and publishing, standardizing behaviors of authors, peer reviewers, and editors throughout the entire process, and accepting supervision from the academic community and society. The statement includes three parts with fifteen clauses: (1) Author publication ethics (academic papers as vital scientific research components; academic misconduct as a cancer; authors as main contributors; authorship reflecting intellectual property and contributions; importance of intellectual property and information security; normative citation as important academic standard; importance of research data management; establishment of error correction and academic self-purification mechanisms). (2) Peer reviewer publication ethics (peer review as important quality control; reviewers should comply with requirements and ethical guidelines). (3) Editor publication ethics (editors as guardians of academic ethics and final barriers against misconduct).

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