The Framework of Modeling Buddhist Head in 3D with Semantic Information

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Abstract

Buddhist statues hold profound spiritual and cultural significance, yet their comprehensive analysis and identification remain largely reliant on manual annotation and expert scrutiny. Despite advancements in 3D modeling, the nuanced representation of these statues, essential for automated analysis, remains elusive. Integrating semantic information such as symbolic and cultural elements poses a further challenge. There currently exists no standardized method for modeling Buddhist heads in 3D with semantic information. This paper proposes a framework for the component-based analysis of Buddhist statues, particularly focusing on their heads, to bridge this gap. Drawing from diverse disciplines including archaeology, art history, and conservation, the framework leverages advancements in 3D reconstruction to provide a detailed depiction of intricate features. Building upon existing research outcomes, the framework facilitates the seamless integration of semantic information, capturing not only the physical attributes but also the cultural, historical, and spiritual dimensions of these sculptures. This approach aids in overcoming challenges in automated analysis and virtual restoration, providing a dynamic tool for exploration, preservation, and interpretation of cultural heritage. By enabling interdisciplinary synergy, the framework emerges as a dynamic tool for exploring, preserving, and interpreting the profound heritage of Buddhist art with unprecedented depth and clarity.

1. Introduction

The creation and dissemination of Buddhist statues are closely intertwined with both geographical locations and historical periods. Since the introduction of Buddhism to China during the late Western Han dynasty, its influence has endured for over a millennium, giving rise to a rich array of sculptural styles across different dynasties and regions. While many Buddhist statues are movable, numerous statues and temple structures have been preserved together, retaining spatial and temporal information within the statues.

Buddhist statues, entrenched within each niche, embody profound spiritual and cultural significance. Presently, the primary methods for their analysis and identification heavily rely on manual annotation and expert scrutiny. Despite strides in 3D modeling, the nuanced and modular representation of these sculptures remains elusive, hindering the potential for automated analysis.

The prospect of intelligent analysis, integrating semantic information such as symbolic, cultural, and interpretive elements, seems distant. While 3D modeling techniques are abundant, they often lack the required granularity and modularity essential for comprehensive artifact analysis. Consequently, the automation of cultural heritage analysis appears unattainable.

This paper aims to bridge this gap by advocating for the adoption of a framework that facilitates the component-based analysis of Buddhist statues. By leveraging advancements in 3D reconstruction, we aspire to provide a more detailed and nuanced depiction of the intricate features, particularly focusing on the heads of Buddhist statues.

Furthermore, this framework proposes the concept of Levels of Detail (LOD) for the 3D modelling of Buddhist statues to fulfil the different requirements of geometric details in different applications such as religious studies, archaeology, and cultural heritage preservation. Drawing inspiration from CityGML, a standard for representing 3D city models, this paper delineates a methodology that embraces the intricacies of Buddhist statue analysis through the lens of semantic modeling and LOD techniques.

2. The Modeling Framework

To facilitate cross-disciplinary applications spanning fields such as archaeology, art history, conservation, and beyond, the framework for 3D modeling of Buddhist heads intricately weaves together a diverse tapestry of knowledge gleaned from the humanities. The cultural landscape of Chinese grotto temples, notably dotting the ancient Silk Road, stands as a testament to immense archaeological and historical importance (Su, 2019; Chen, 2022). The Thousand Buddha Grottoes of Tuyoq in Xinjiang, originating from the Fifth Century, offer a poignant embodiment of Buddhist temple architecture, serving as a tangible link to the past (Tang et al., 2014). Chronological investigations, such as those meticulously conducted within the Dunhuang Mogao Grottoes, employ a fusion of radiocarbon dating and archaeological findings, weaving together strands of empirical evidence to construct a detailed temporal framework (Guo et al., 2018). Moreover, beyond mere physical structures, the nuanced study of iconography emerges as a pivotal component in conveying the essence of Buddhist traditions and doctrines. Through the discerning analysis of symbols and visual representations, scholars illuminate profound insights into the spiritual underpinnings of these ancient practices (Gong, 2009; Sentot et al., 2023).

In addition to semantics in the humanities, annotations related to disease identification and protection are also commonly employed in digital cultural heritage. Within the domain of semantic modeling, methodologies have been devised for evaluating damage and conducting structural analysis, leveraging technologies such as point clouds and building information modeling (Shu et al., 2022; Hamdan et al., 2021). Additionally, significant strides have been made in the realm of 3D reconstruction for virtual restoration of damaged artifacts (Chen et al., 2024).

In the field of cultural heritage semantic modeling (Yang and Hou, 2023; Yang et al., 2024; Wang and Hou, 2023; CityGML 3.0, 2020; Padfield et al., 2019; Imran and Masud, 2021; Biljecki et al., 2018; Gkadolou et al., 2020) serve as foundational pillars, furnishing invaluable features and application requisites for the seamless integration of semantic information. By infusing depth and interpretive value into the modeling process, these insights enable a nuanced representation that transcends mere visual depiction. Thus, the framework not only captures the physical attributes of the sculptures but also encapsulates the cultural, historical, and spiritual dimensions embedded within them. Through this interdisciplinary synergy, the framework emerges as a dynamic tool, empowering scholars and practitioners alike to explore, preserve, and interpret the profound heritage of Buddhist art with unprecedented depth and clarity.

2.1 The Semantic and Topological Hierachies within Buddhist Heads

There exist various semantic and topological hierarchies concerning Buddhist statues (Li, 2003; Mogali et al., 2017). It is commonly believed that, in order to align with the concept of "divine authority bestowed upon kingship," which integrates politics and religion, emphasis was placed on depicting the relationship of inheritance between rulers of the Buddhist realm and secular realms, thus shaping idols to educate the masses. Consequently, Buddhist statues share many similarities with human figures in artistic representation.

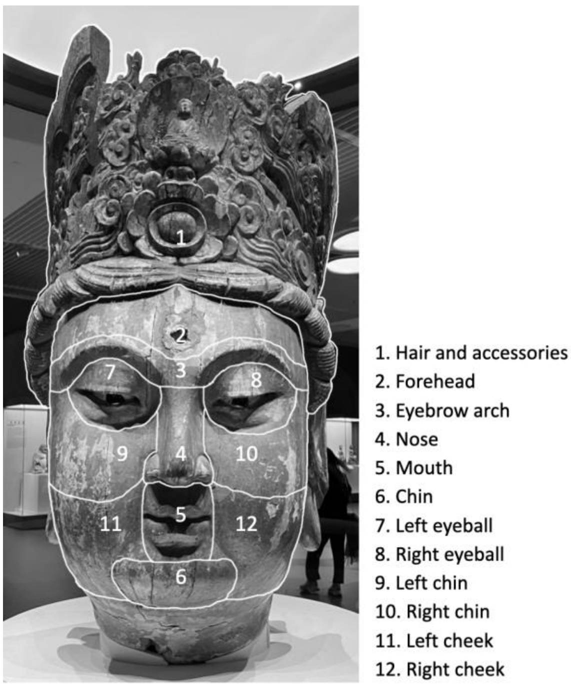

Figure 1. The components of a Buddhist head

This paper delineates the segmentation of Buddhist heads into 12 components, as illustrated in Figure 1. The semantic and topological hierarchy of Buddhist heads encapsulates a multitude of features and adornments, each imbued with profound significance in Buddhist iconography. Beyond this category lies a comprehensive hierarchy that extends to encompass a myriad of facial features and anatomical details, each imbued with its own symbolic and aesthetic significance within Buddhist iconography. Facial details, such as the arrangement of facial features, provide support for further analysis into the evolutionary patterns.

Common descriptions of facial details in Buddhist sculptures often stem from the field of fine arts (Li, 2020) and morphology. By integrating humanistic methodologies and insights, scholars dissect the study of sculptural iconography, thus enabling a more intricate delineation of the features adorning Buddhist sculptures. Such an approach not only enhances the understanding of the nuances within Buddhist iconography but also facilitates a deeper portrayal of its characteristics. By annotating digital models, researchers meticulously document and categorize facial features and adornments. This systematic approach enables the tracing of patterns, identification of regional variations, and discernment of stylistic influences across different historical periods. Figure 2. showcases a selection of Buddhist head components alongside their corresponding feature types.

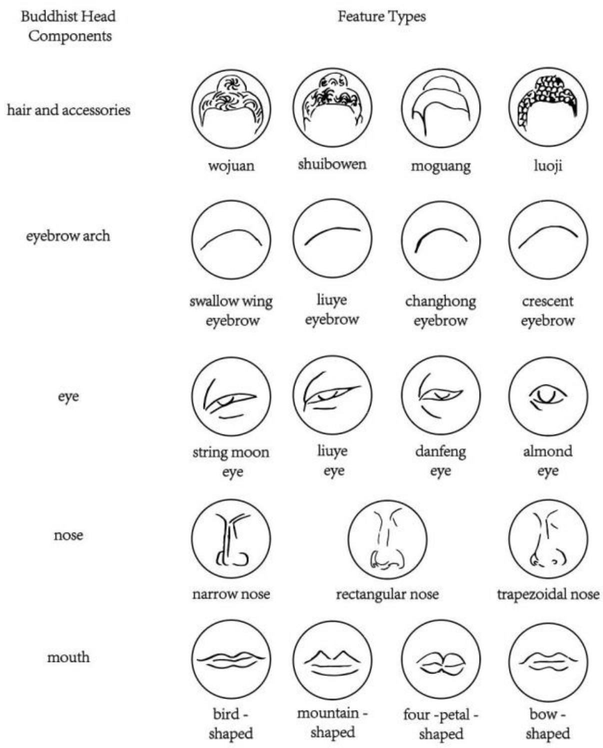

Figure 2. Annotated Descriptions of Facial Features

2.2 The CityGML ADE for Buddhist Head Modeling

CityGML, an international standard for semantic 3D city and topography models, is based on the GML3 standard of the Open Geospatial Consortium. It encompasses the geometrical, topological, and semantic aspects of 3D city models (Kolbe et al., 2005). CityGML serves as both a data model and an

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exchange format for storing digital 3D models of cities, providing a comprehensive representation of cities including various above-ground objects like buildings, bridges, and tunnels (Ledoux et al., 2019). The latest version, CityGML 3.0, introduces new features such as the space concept, enhanced data conversion capabilities, and improved links to other standards, enhancing its usability for a wider range of users and applications (Eriksson et al., 2020). CityGML has been utilized in various applications such as urban management, town planning, architectural design, environmental analysis, disaster management, facility management, and site surveying, showcasing its versatility and importance in the geospatial domain (İlal, 2022). Furthermore, CityGML has been integrated with other standards like the LandInfra standard to address challenges in the intersection of Building Information Modeling (BIM) and Geographic Information Systems (GIS), highlighting its role in bridging different domains and facilitating interoperability (Kumar et al., 2019). Moreover, CityGML has been instrumental in providing semantic structures for point clouds, enabling the integration of 3D point clouds with semantic 3D city models to offer detailed information beyond simple classification (Beil et al., 2021). CityGML stands as a crucial standard in the geospatial field, offering a robust framework for representing 3D city models with rich semantic information, facilitating a wide array of applications and enabling interoperability across different geospatial technologies.

Class Name	Attribute and Interpretation
AbstractBuddhistHead	name; Excavation time; Belonging to which grotto; Documentation Number; protection level; Material information; Craftsmanship; theme(Buddha, Bodhisatta and etc.); recorded in(books and etc.); Disease/Damage
Hair and Accessories	type (Ushnisha, crown and etc.)
Face	type (Squareness roundness and etc.)
Forehead	type (whether has Urna)
Eye	type (round, alomond and etc.)
Nose	type
Mouth	type, shape and expression
Midface	type, width and height
Chin	type
Cheek	type, width and height

Table1. The Terminology Table of CityGML Buddhist Head ADE

CityGML ADE (City Geography Markup Language Application Domain Extensions) is a specialized model that extends the capabilities of the CityGML standard to cater to specific application requirements (Kim et al., 2014). It serves as a powerful tool to address diverse application needs by introducing new functionalities and features beyond the core CityGML model. ADEs play a crucial role in enhancing CityGML by allowing for the inclusion of additional information such as energy calculations, utility networks, metadata, and building construction processes (Tufan et al., 2022; Boates et al., 2018; Labetski et al., 2018; Zhang et al., 2019). By extending CityGML through ADEs, users can incorporate detailed information at various scales.This approach provides insights for constructing a 3D Buddhist model with semantic information, which enables advanced spatial and temporal analysis, thus contributing to the exploration, preservation, and understanding of Buddhist cultural heritage.
The terminology table of CityGML Buddhist Head ADE lists a comprehensive array of classes, attributes, and interpretations specifically tailored for the detailed documentation and analysis of Buddhist head artifacts within urban modeling environments, presented as Table 1. This specialized extension categorizes various aspects of Buddhist heads, including abstract representations, hair and accessories, and specific features such as the forehead. Each class is accompanied by a set of attributes crucial for thorough documentation, including excavation time, material composition, thematic representations, and preservation status. This structured approach enables urban planners, archaeologists, historians, and cultural heritage professionals to effectively manage and analyze data related to Buddhist head artifacts, fostering greater understanding and appreciation of cultural heritage within environmental contexts.

To seamlessly integrate the CityGML Buddhist Head ADE into the existing CityGML data model, this diagram employs the standardized definitions of CityGML. Drawing inspiration primarily from the Building module within CityGML, each component within the Buddhist Head ADE diagram inherits information from the preceding hierarchical level, as shown in Figure 3. This design approach ensures consistency and compatibility with the established CityGML framework, allowing for the smooth incorporation of Buddhist head artifacts into geospatial modeling environments. By leveraging the structure and principles of CityGML, the Buddhist Head ADE facilitates the systematic documentation and analysis of these artifacts while maintaining interoperability with other urban data elements.

Modeling Buddhist head using CityGML enables the representation of corresponding semantic information across three geometric levels. This becomes imperative when dealing with point cloud data of extensive cultural heritage sites characterized by intricate surfaces. In handling vast datasets, such an approach facilitates superior data management and organization, significantly enhancing both interactive capabilities and scalability.

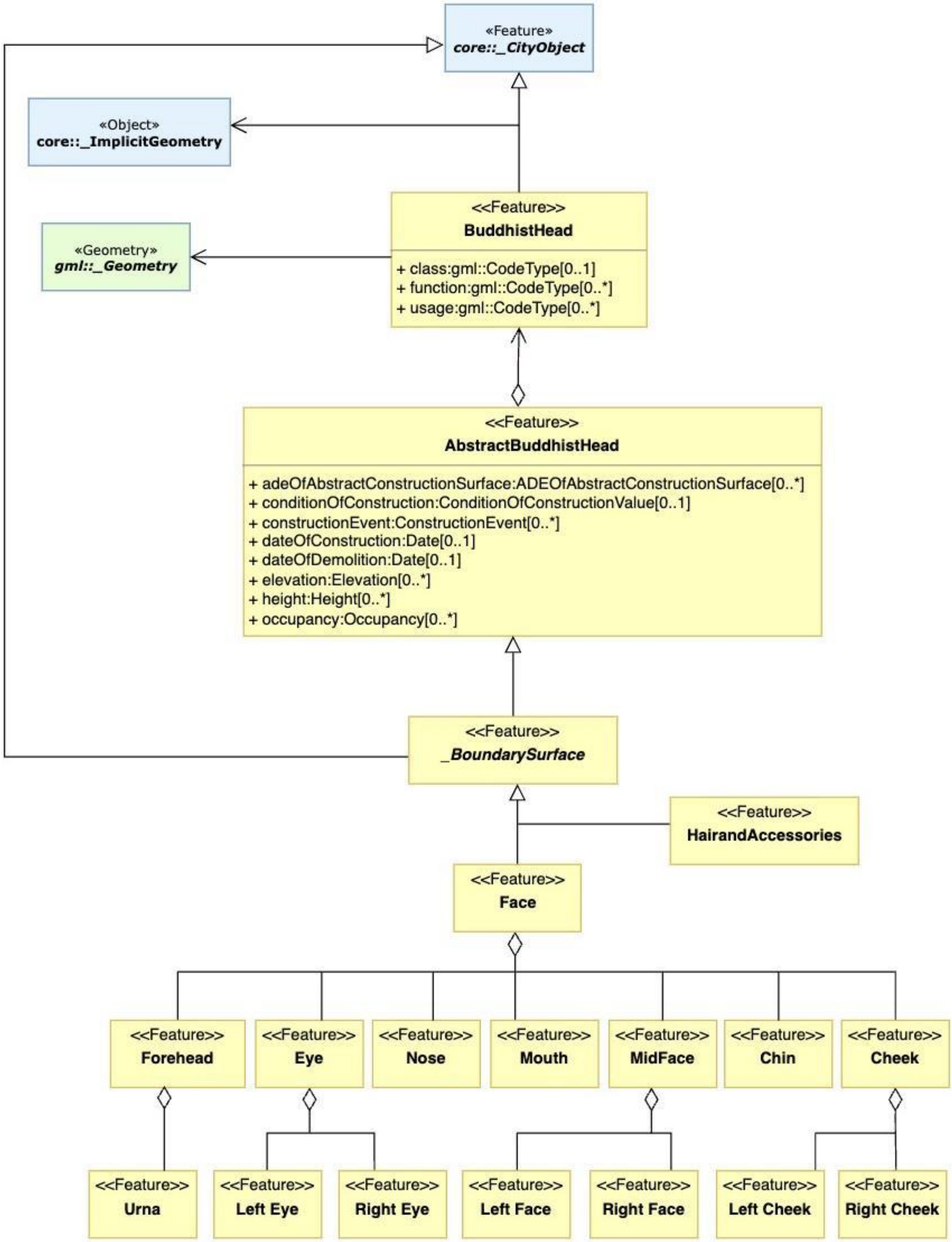

Figure 3. UML diagram of the Buddhist head

2.3 The Concept of LoD

The concept of levels of detail (LoD) in 3D modeling is essential for creating accurate and efficient representations of objects or environments. Various studies have contributed to defining and formalizing LoD in 3D city modeling (Fan and Meng, 2012;Biljecki et al., 2014). The levels of detail includes metrics such as geometric granularity, dimensionality, appearance, and spatio-semantic coherence (Ohori et al., 2015). It is crucial to consider the intended purpose of the 3D model and the desired levels of detail when selecting spatial data sources for modeling (Pluta and Krakowie, 2018).

The Buddhist head model is meticulously designed to offer a holistic portrayal of both thematic and spatial characteristics across three distinct tiers of intricacy, designated as LOD1 to LOD3, as illustrated in Figure 4.

At the foundational LOD1 level, the model employs a convex hull to encompass vital attributes including the statue's nomenclature, excavation timeline, grotto association, national security identifier, protection status, material constitution, craftsmanship intricacies, thematic classification, archival provenance, and evaluation of any detected ailments or damages. LOD1 essentially establishes the basic framework for understanding the statue's significance and condition.

Progressing to LOD2, the model advances its depiction by partitioning the hair and accessories as well as the facial region into discrete convex hulls, integrating descriptors such as the typology of hair and accessories and the morphological nuances of facial features. LOD2 enhances the understanding of the statue's aesthetic qualities and symbolic significance by focusing on finer details.

Subsequently, at LOD3, the model attains a meticulous portrayal by scrutinizing facial feature proportions and categorizing intricate details, thereby facilitating a comprehensive comprehension of Buddhist statues at both macroscopic and microscopic levels. By scrutinizing facial feature proportions and categorizing intricate details, LOD3 enhances the comprehension of Buddhist statues at an advanced level of analysis.

This hierarchical modeling strategy facilitates interdisciplinary analysis by providing varying levels of detail tailored to different research needs. Additionally, it contributes to the preservation and scholarly understanding of Buddhist statues by offering a structured approach to studying these culturally significant artifacts, from their historical context to their artistic intricacies.

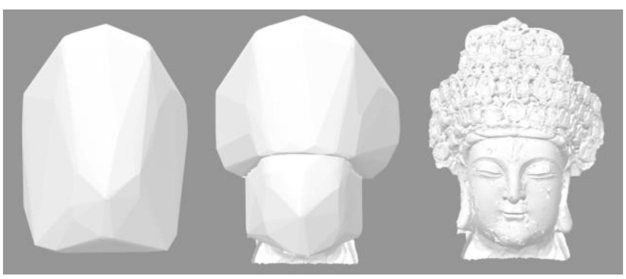

Figure 4. The Three Levels of Detail(LOD) in the 3D modeling

3. Conclusion

The framework proposed for modeling Buddhist heads in 3D with semantic information represents a significant leap forward in the field of cultural heritage preservation and analysis. By bridging the gap between traditional manual methods and modern technological advancements, this framework offers a comprehensive approach that caters to the diverse requirements of various disciplines, from religious studies to archaeology and beyond. Through the integration of semantic richness and the employment of LoDs strategies, the framework ensures the faithful preservation and detailed analysis of Buddhist sculptures, including immovable artifacts like Buddhist heads.

Expanding this framework to include the utilization of CityGML's standardized data model and exchange format brings forth numerous benefits for the preservation and dissemination of cultural heritage. CityGML's standard framework enhances the accessibility, interoperability, and scalability of 3D models of Buddhist heads, facilitating interdisciplinary collaboration and global research initiatives. Additionally, CityGML ensures the long-term preservation and future-proofing of these invaluable cultural artifacts, allowing for the inclusion of additional semantic information and LOD strategies as our understanding of Buddhist art evolves.

Furthermore, by incorporating iconography modeling to semantically annotate immovable cultural heritage, such as Buddhist statues, researchers can synthesize findings from disciplines such as iconography, archaeology, and historical geography to construct a symbolic network. This network, potentially termed the Buddhist Iconography Thesaurus, aims to provide a three-dimensional representation of symbolic elements.Consequently, there is potential for further integration with tools like BERT, CLIP and BLIP to achieve intelligent cultural heritage preservation and utilization.

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