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Comparison of 3D Reconstruction Tools for Public Participation in Architectural Heritage Conservation

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ABSTRACT

Traditionally, heritage conservation has been chiefly led by government, with an emphasis on protecting well-known architectural treasures. However, a substantial portion of architectural heritage consists of lesser-known and remote architectures, often neglected, inadequately preserved and documented. As depicted in the memorable quote from the movie CoCo, "Death is not the end of life, forgetting is the end of life". This sentiment is also highly suitable to be used in lesser-known architectural heritage. They still exist worldwide, harboring history, culture, art, and narratives amidst the dust of time. But they have been largely forgotten by the world and left in obscurity. Consequently, there is an urgent need to establish a bottom-up approach that actively involves the public in the preservation of lesser-known heritage sites.

The process of capturing the 3D geometries and surface textures of architectural heritage represents an easily comprehensible undertaking for the public. Three-dimension (3D) reconstruction method is a good way to document the 3D information of architectural heritage. Numerous 3D reconstruction tools are available, making it imperative to identify one that stands out for its accessibility and user-friendliness, particularly for the public. Hakka Tulou, Zhenchenglou, is selected as a case in this study. 4 tools, including Metashape, Pix4D, DJI Terra, and CU-Recon, are used to reconstruct this heritage building. A survey is conducted to figure out the satisfaction level of the reconstruction outcomes by the four tools. The reconstruction results are compared in four aspects, including clearness, accuracy, integrity, authenticity. This study introduces a new way for public participation in architectural heritage conservation and provides deep insights into the documentation of architectural heritage.

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1. Introduction

Architectural heritage serves as a cornerstone of regional identity, bridging historical legacies with contemporary contexts, thereby encapsulating local cultures comprehensively. It plays a pivotal role in preserving the historical narrative of a region and fostering a sense of connection among its inhabitants [1]. Architectural heritage, as an irreplaceable asset, contributes significantly to the advancement of civilization and embodies the historical essence of nations. Acknowledged as crucial for sustainable progress, architectural legacy embodies diverse cultural, economic, and scientific significance. Vital for safeguarding the enduring presence and pertinence of indigenous cultures amid sustainable development, the recording and preservation of architectural heritage are paramount [2]. Nonetheless, an array of perils, encompassing structural degradation, environmental alterations, contamination, unsustainable building methods, and conflicts, present substantial hurdles to architectural heritage's sustainability, precipitating its decline and conceivable forfeiture. Consequently, embracing strategies fostering the sustainable safeguarding and utilization of architectural legacy becomes imperative.

Traditionally, governmental entities have predominantly spearheaded heritage conservation endeavors, primarily concentrating on safeguarding renowned architectural landmarks [3]. Lesser-known architectural heritage received less attention. Scattered across the globe, these structures enshrine rich histories, cultural significance, artistic merit, and tales entwined with the sands of time. Yet, they remain largely overlooked by the global community, languishing in anonymity [4–8]. Hence, there exists an urgent imperative to embrace a grassroots approach that actively involves the populace in the conservation of obscure heritage sites.

Rendering the 3D shapes and surface textures of architectural heritage emerges as an attainable pursuit for the general populace. This recording process aids in digitizing heritage assets, fostering wider distribution, increased awareness, and improved conservation endeavors. The outlined data capture methods chiefly involve fundamental digital 3D portrayal of heritage edifices. This digital 3D model serves as a pivotal instrument for pinpointing possible hazards and guiding efficient conservation tactics. Thus, the implementation of a model 3D reconstruction technique for heritage structures is imperative.

Gathering data to reconstruct building models commonly employs two main tools: optical images and laser data, both aimed at capturing vital spatial data and texture details [9]. Laser data renowned for its precision, is primarily employed with ground laser scanners, making it ideal for intricately reconstructing individual structures in 3D. Nevertheless, its limited scanning range renders it inadequate for large-scale historical buildings. Moreover, LT presents logistical hurdles due to its hefty price tag, weight, and need for specialized expertise.

Conversely, OP technology is predominantly integrated into drone platforms, providing cost-effective and portable solutions. OP enjoys widespread adoption across diverse architectural sectors due to these advantages [10]. The core process of OP entails utilizing cameras to capture a series of photos, followed by the generation of 3D data through corresponding reconstruction algorithms. Multi-view stereo (MVS) plays a pivotal role in this process, extracting the 3D geometry from a series of images taken from different positions and angles. However, the reconstruction of architectural heritage necessitates high levels of clarity, accuracy, and comprehensiveness. Hence, a comparison of various reconstruction approaches is essential to discern the efficacy of these methods.

Herein, this study uses four 3D reconstruction approaches to reconstruct one heritage building, Hakka Tulou to evaluate the effectiveness of these approaches. The paper is structured as follows: Section 2 shows a literature review on the digitalize the heritage buildings. In section 3, 4 different 3D reconstruction approaches are introduced for the following 3D modeling of the heritage. Then, A case study is provided to introduce the Hakka Tulou. Results and conclusions are showed in Section 5 and Section 6.

2. Literature review

In the past two decades, there has been a growing interest in utilizing technology for the digital preservation of cultural heritage.

Kadi et al. [11] introduced a 3D reconstruction methodology grounded in prior knowledge, aimed at generating novel tools to organize acquired data digitally. Integrating these tools into a parametric framework would enhance the reliability of three-dimensional interactive representations and facilitate future reuse. Beyond serving as a mere case study, the example elucidates our approach, intended to be applicable across various contexts, enabling model generation from minimal data while circumventing the need for case-by-case solutions.

Jia et al. [12] harnessed the capabilities of 3D laser scanning technology alongside point cloud information processing to meticulously analyze the distinct characteristics of Chinese garden elements. Through this integrated approach, precise classification of landscape information pertaining to Chinese classical royal gardens was achieved, culminating in the development of comprehensive 3D digital information models for these gardens. The classified point cloud information, encapsulating various garden elements, serves as a foundational resource for diverse applications such as heritage conservation, monitoring management, and informatization initiatives related to garden elements. Notably, this study extends beyond individual elements to encompass the entirety of Chinese royal garden components, both built and natural. This holistic approach encompasses structures, secondary buildings, garden features, as well as natural topography and vegetation. Special emphasis was placed on the meticulous collection and processing of classical garden terrain environments and rockery spaces, aiming to enhance the cohesion among multisource information data. Ultimately, the refined correlation among these datasets contributes to heightened accuracy and management efficiency in garden spatial information. Moreover, the insights gleaned from this research hold promising implications for the future conservation and management of Chinese landscape cultural heritage, offering expanded avenues for practical applications in this domain.

Kompoti et al. [13] conducted preliminary documentation of the medieval Palaiokastro castle, employing cutting-edge technologies such as terrestrial laser scanner (TLS) and unmanned aerial vehicles (UAVs). They adopted a holistic approach, integrating TLS and UAV photogrammetry to swiftly capture a comprehensive view of the entire gate area, minimizing potential occlusions. TLS was deployed to capture facades, while UAVs were utilized to capture overhead views of the castle gate. Recent advancements in post-processing algorithms have facilitated the merging of TLS and UAV models, resulting in highly precise 3D models of the entire gate structure. The fusion of UAV photogrammetry with terrestrial laser scanner data generated various valuable outputs, including textured 3D models, orthophotos, 2D floor plans, elevations, and sections. These diverse outputs are crucial for achieving thorough and accurate geometric documentation of the Southwest gate of Palaiokastro Castle, significantly aiding in effective data management and the identification of different construction phases of the South Gate.

Kallas et al. [14] outlined the utilization and importance of 3D image-based modeling, emphasizing its timely benefits for disaster response and improving decision-making processes in emergency scenarios. The documentation resulted in swift yet accurate 3D models of the historic buildings impacted by the Beirut explosion, despite the intricate structural features of the post-blast setting. Following data processing, cultural heritage specialists and engineers received valuable documentation delineating structural weaknesses, damages, and accessibility concerns. This facilitated remote evaluation of the buildings and accelerated the implementation of emergency measures.

Dimitriou et al. [15] aimed to devise an innovative computational design methodology centered around the 3D modeling of historical structures, aiming to produce an accurate as-built model of a designated listed building. This initiative entailed utilizing parametric clustering and schematic modeling techniques rooted in computational methodologies to generate 3D surfaces and shapes corresponding to various elements of the building. The intricacy of form, especially regarding the specific architectural component under examination, presented significant hurdles in the 3D modeling process. To materialize the research, the Holy Church of Agios Georgios Tropaiophoros in the village of Dali, situated in the Nicosia district of Cyprus, was chosen as a case study. The outcomes derived from this tailored methodology were meticulously assessed and subsequently integrated into the development of an Augmented Reality (AR) platform. AR technology, acknowledged for its burgeoning potential in enhancing the perception and navigation of architectural heritage, was employed to further augment the usability of the generated models.

3. Methodology

This study evaluates the effectiveness of five different 3D reconstruction approaches on modeling heritage buildings. The five 3D reconstruction approaches are LCM-MVSNet, Colmap, Metashape, Pix4D, and DJI Terra.

2.1 LCM-MVSNet

LCM-MVSNet is an innovative deep learning-based method designed for dense 3D reconstruction from 2D images. Developed in the field of computer vision, MVSNet addresses the challenge of reconstructing accurate and detailed 3D models from a set of input images captured from different viewpoints. Unlike traditional multi-view stereo methods, which rely on handcrafted features and heuristics, MVSNet leverages convolutional neural networks (CNNs) to learn representations directly from the input images. At its core, LCM-MVSNet consists of several interconnected neural network modules that jointly perform tasks such as depth estimation, view selection, and fusion to generate a dense 3D point cloud. By leveraging the power of deep learning, MVSNet can handle complex scenes with varying lighting conditions, occlusions, and texture patterns, producing high-quality reconstructions with fine details.

2.2 Metashape

Metashape represents a state-of-the-art software solution, boasting an engine core that pushes the boundaries of photogrammetry to its utmost capabilities. Designed to cater to specific industry needs, the system leverages machine learning techniques for post-processing and analysis tasks, ensuring the delivery of precise results. The software accommodates the processing of images captured by RGB or multispectral cameras, including multi-camera systems, transforming them into valuable spatial information in various formats such as photogrammetric point clouds, textured polygonal models, georeferenced true orthomosaics, and DSMs/DTMs. Moreover, it enables the co-processing of images with LiDAR points, harnessing the benefits of both data sources. Advanced post-processing functionalities further enhance the models by eliminating shadows and texture artifacts, computing vegetation indices, and extracting information for farming equipment action maps, among other tasks.

2.3 Pix4D

Pix4D is a leading provider of photogrammetry software solutions that revolutionize the way professionals collect, process, and analyze aerial imagery. With a commitment to innovation and cutting-edge technology, Pix4D empowers users across industries such as agriculture, construction, surveying, and public safety to transform raw aerial imagery into actionable insights and valuable geospatial data. At its core, Pix4D's suite of software products leverages the power of photogrammetry to generate highly accurate 3D models, point clouds, orthomosaics, and digital surface models (DSMs) from standard images captured by drones, aircraft, or other aerial platforms. By harnessing the principles of computer vision and machine learning, Pix4D software is able to process vast amounts of imagery quickly and efficiently, enabling users to extract valuable information about terrain, structures, vegetation, and more.

One of the key strengths of Pix4D lies in its user-friendly interface and intuitive workflow, making it accessible to both seasoned professionals and newcomers to the field of photogrammetry. Whether it's monitoring crop health, assessing construction progress, conducting environmental surveys, or creating 3D maps for urban planning, Pix4D provides the tools and capabilities needed to unlock the full potential of aerial imagery data. With a global user base spanning over 180 countries and partnerships with industry leaders, Pix4D continues to push the boundaries of what's possible in aerial mapping and geospatial analysis. By combining advanced technology with user-centric design, Pix4D remains at the forefront of innovation in the field of photogrammetry, helping users make better-informed decisions and achieve superior results in their projects.

2.4 DJI Terra

DJI Terra represents cutting-edge 3D model reconstruction software, centered on the principle of photogrammetry. With its robust capabilities, it facilitates the precise and efficient reconstruction of both 2D and 3D imagery, harnessing the power of DJI LiDAR data processing. Specifically tailored for DJI Enterprise drones and their accompanying payloads, DJI Terra seamlessly integrates to provide a comprehensive application suite. This suite serves diverse industries including land surveying, power transmission, emergency services, construction, transportation, and agriculture. Notably, DJI Terra offers flexibility in generating 3D models at varying resolutions—high, medium, and low—ensuring adaptability to specific project requirements. Leveraging AI technology, the software automatically optimizes water surfaces within the models. Moreover, it facilitates the export of models in industry-standard formats, catering to a wide array of applications such as surveying and mapping, accident reconstruction, power grid assessment, and construction project monitoring.

2.5 Colmap

COLMAP, an acronym for "Structure-from-Motion and Multi-View Stereo," is a versatile and widely-used software tool renowned for its capabilities in reconstructing three-dimensional models from two-dimensional images. Developed by a team of researchers at the University of British Columbia, COLMAP offers an efficient and robust solution for various computer vision tasks, particularly in the domain of visual reconstruction and scene understanding. Leveraging state-of-the-art algorithms and techniques in structure-from-motion and multi-view stereo, COLMAP enables users to generate accurate and detailed 3D reconstructions from collections of images captured from different viewpoints.

The core functionality of COLMAP revolves around its ability to process a set of unordered images and extract their corresponding camera poses and sparse 3D point clouds. By analyzing the visual features and geometric relationships between images, COLMAP reconstructs the underlying scene geometry and camera parameters, facilitating the creation of dense 3D reconstructions through multi-view stereo techniques. This enables users to visualize and analyze complex real-world scenes in a digital environment with unprecedented detail and accuracy.

4. Case study

Hakka Tulou, also known as Hakka earthen buildings, are iconic architectural marvels found predominantly in the mountainous regions of southeastern China, specifically in the Fujian and Guangdong provinces. These structures are recognized for their unique blend of architectural ingenuity, historical significance, and cultural heritage, making them an integral part of China's rich architectural landscape. Tulou, a Chinese term meaning "earthen building," refers to large circular or square communal residences constructed from rammed earth, wood, and other locally sourced materials. They typically house multiple families or even entire clans, embodying the communal lifestyle and social cohesion of the Hakka people, an ethnic group with a distinct cultural identity. What sets Hakka Tulou apart is their impressive size, architectural complexity, and defensive features. Built over centuries, spanning from the 13th to the 20th century, these monumental structures showcase remarkable engineering prowess and resilience against natural elements and potential threats. They often feature thick earthen walls, fortified entrances, and strategically placed windows for ventilation and defense.

Zhenchenglou holds a prominent position among the historical structures of Fujian province, warranting urgent attention for preservation and documentation. However, its significant scale poses a considerable challenge for conventional LiDAR scanning methodologies. With a towering height exceeding 10 meters and a diameter approaching 60 meters, covering an expansive area of approximately 5000 square meters, Zhenchenglou presents a formidable task for ground-based scanning. Moreover, the surrounding terrain, characterized by intricate rice, tea, and tobacco fields, adds to the complexity. Adjacent to Qingchanglou, another Tulou located approximately 30 meters northwest of Zhenchenglou, the site's confined and obstructed street environments necessitate strategic placement of numerous LiDAR scanning stations to ensure comprehensive data collection of the building's 3D geometric properties and intricate details. However, such an approach would inevitably disrupt the daily activities of local residents, underscoring the need for alternative methods to mitigate such interference.

(a) (b)

Fig. 1. (a) Hakka Tulou (b) Zhenchenglou.

5. Results

The Zhenchenglou is reconstructed by LCM-MVSNet, Colmap, Metashape, Pix4D, and DJI Terra. The reconstruction process was executed utilizing an NVIDIA 3090ti GPU, with a total of 248 images employed as input data for the reconstruction tools. The outcomes of this reconstruction endeavor are depicted in Fig. 2. However, it is noteworthy that the software Colmap encountered difficulties in completing the reconstruction task due to its heightened memory requirements when processing the same quantity of photos. Consequently, the constraints of software Colmap led to an "out of memory" scenario in this particular instance. On the other hand, the reconstruction conducted using DJI Terra necessitated the prior selection of the reconstruction scope. As a result, the reconstruction outcomes from DJI Terra solely depict the structure of Zhenchenglou without incorporating the surrounding landscape. It is important to highlight that DJI Terra confronts limitations in achieving the reconstruction process in the absence of the Global Positioning System (GPS), as it relies on GPS data for image matching purposes. From the results, it can be found that LCM-MVSNet shows an outperformance on the heritage reconstruction.

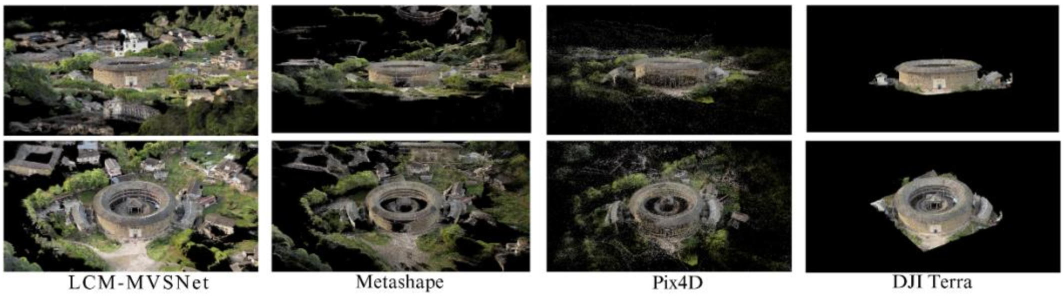

Fig. 2. Comparison of the 3D reconstruction quality of different tools.

6. Conclusions

This study used five reconstruction tools (LCM-MVSNet, Colmap, Metashape, Pix4D, and DJI Terra) to digitalize the heritage buildings and their effectiveness were evaluated. Zhenchenglou was selected as a case to be reconstructed. This study found that Colmap failed to reconstruct the heritage building. The reconstructed models of Metashape and Pix4D are not complete and show missing building components. The DJI terra can finish the reconstruction task, but it is also limited by GPS. LCM-MVSNet shows an outperformance on the reconstruction. The generated model is complete and clear. But it needs a high-performance computer. Overall, this study demonstrates the significant potential of heritage building digitalization.

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