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3D LiDAR and multi-technology collaboration for preservation of built heritage in China: A review

Yuan Li [a,e], Long Zhao [a,e], Yiping Chen [b,*], Na Zhang [a,e], Hongchao Fan [c], Zhenxin Zhang [d]

[a] School of Architecture and Civil Engineering, Xiamen University, Xiamen, China
[b] School of Geospatial Engineering and Science, Sun Yat-sen University, Zhuhai, China
[c] Faculty of Engineering, Norwegian University of Science and Technology, Trondheim, Norway
[d] School of Architecture Urban Planning Construction Engineering, Polytechnic University of Milan, Mantova, Italy
[e] Xiamen Key Laboratory of Integrated Application of Intelligent Technology for Architectural Heritage Protection

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ABSTRACT

In recent years, the technical application of 3D LiDAR has gradually expanded to the field of built heritage. 3D scanning, high-precision measurement, and reconstruction have enriched the methods of built heritage preservation and significantly improved the quality of heritage preservation in China. 3D LiDAR has broken through the limitations of a single technology application and played a greater role in the field of heritage preservation on different scales. Through the collaboration of multi-technology, such as 3D printing, digital mapping, internet of things, machine learning, intelligent sensors, close-range photogrammetry, infrared detection, stress wave tomography, material analysis, XR technology, reverse engineering, etc., 3D LiDAR shows its technological advantages on exploring the remote real-time monitoring and digitization of the built heritage, geological and environmental data collection, prediction of sedimentation, deformation monitoring, weather monitoring,system life cycle health detection, digital reproduction of built heritage for developing scientific problems and engineering practices such as building contour recognition, information feature matching, structural reinforcement and damaged component replacement. In addition, through the docking with GIS, HBIM, XR, and CIM, it provides fine digital models and high-precision data benchmarks which contribute to the heritage visual reproduction; and through the docking with 3Ds Max, SketchUp, and other modeling software, it has contributed to the renewal design of the built heritage, space optimization, and the scientificity and rationality of the heritage value evaluation. However, past technology applications also highlighted many problems such as limited recorded information, a large amount of data, high difficulty in collaboration, non-standardized and fragmented data, and difficulty in data mining and comprehensive utilization. There are still deficiencies in building a built heritage data backplane, and the development of a dynamic, three-dimensional, intelligent and refined heritage monitoring system, and further research is needed on these issues. This study reviews the previous academic progress and application of 3D LiDAR in the reconstruction of built heritage and multi-technology collaboration in the process of preservation, clarifies the current research hotspots and methods, the frontier issues of concern, and also clarifies the specific problems and challenges in the future.

1. Introduction

Built heritage mainly covers three parts: architectural heritage, urban heritage, and landscape heritage, which have both material and social properties (Li, 2019). Built heritage constitutes the uniqueness and identity of a place, it is a non-renewable resource and can be vulnerable to change (Phillips, 2015; Organ, 2019; Tan, et al., 2020; Azmi, et al., 2021). As the physical carrier of regional space history, it plays a significant role in the continuation of the urban context, local characteristics, and collective memory (Wang et al., 2016; Vaz de Freitas, et al, 2022). In recent years, built heritage has faced many problems and challenges, such as deformation caused by environmental degradation, erosion, and collapse caused by natural disasters, excessive human intervention in the process of preservation and development, and inappropriate replacement of materials and colors in the process of restoration (Coombes, et al., 2021). A series of problems emerged, such

* Corresponding author.
E-mail address: chenyp79@mail.sysu.edu.cn (Y. Chen).

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as the disappearance of real historical and cultural information and the reduction of the historical value of heritage. In China, under the guidance of many principles such as authenticity, integrity, identifiability, readability, and sustainability, the practice of built heritage preservation is committed to the goal of maximum preservation and minimum intervention, while new technologies development and application play a key role in this process.

3D LiDAR has been an active research area in the photogrammetry, computer vision, and computer graphics communities, and it is concerned with several fields of the urban environment, cultural heritage, environmental monitoring, mapping, and modeling (Wang, 2013; Di Stefano et al., 2021). As a new mapping technology, 3D LiDAR is widely used in the field of built heritage preservation. It considers the advantages of high data acquisition efficiency and an accurate point cloud model, presenting a fine hierarchical structure at the level of modeling details of the built heritage (El-Hakim et al., 2004; Guo et al., 2020). At present, this technology has been widely used in high-precision 3D modeling of cultural heritage sites, digital mapping, heritage display, building ontology preservation, repair, structure precision measurement, archiving, digital basic database construction, industrial reverse engineering, virtual reality, and other fields. However, the preservation of the built heritage has the characteristics of multidisciplinary, multi-scale, complexity. A single type of application is difficult to meet the heritage preservation integration, all-round, multi-level, and structured requirements. 3D LiDAR-based technology collaborative methods become more adapted to the different types, scales, and structures of built heritage and important research direction. 3D LiDAR and multi-technology cooperation refer to the practice of taking 3D LiDAR as the main technology and combining 3S technology, 3D virtual reality, 3D printing, big data, and other technical means to carry out cooperation in the preservation process. The technology combination has flexibility and extensibility in realizing digital preservation of built heritage, display interaction, virtual restoration and reconstruction, authenticity, integrity, suitability, sustainable heritage environment optimization, and many other aspects. Based on the above discussion, it is necessary to review the 3D LiDAR and multi-technology cooperation in the field of built heritage preservation.

This literature review critically reviews the papers in Chinese from the time span of 2012 to 2022, summarizing the academic research and specific practice of 3D LiDAR and multi-technology collaboration in the preservation of built heritage. The contribution of this literature review is as follows: (1) this paper sheds the light on the current application of 3D LiDAR, including the problem-solving exploration, and the paradigm of collaboration with other technologies, which helps to establish a systematic understanding of the application of 3D LiDAR technology in the field of built heritage preservation. (2) through the analysis of many cases on built heritage preservation, this paper summarized the research progress of 3D LiDAR in collaboration with multiple technologies and presented the technical difficulties. (3) through the literature review, this paper highlighted the technical and methodological limitations, moreover, provided the future possibilities of technological application.

2. Data sources and study methods

To identify relevant studies, the authoritative citation databases based on the CNKI (China National Knowledge Infrastructure) academic platforms such as the Core journal directory of Peking University (PKU), CSSCI database (Significant Journal of Humanities and Social Sciences in Chinese), and CSCD database (Significant Journal of Science and Technology in Chinese) were adopted. This literature review mainly considers built heritage-related papers, focusing on the academic studies and practices of the 3D LiDAR and multi-technology cooperation in the field of built heritage preservation in China. The time is taken from 2012 to 2022, namely, take the recent 10 years as a periodic summing-up work. The papers collected in the above-mentioned databases are of high academic value and have good authority and reliability. The research data acquisition process is as follows: Firstly, based on the CNKI academic platform, this study selects high-quality papers from the Core journal directory of Peking University, CSSCI, and CSCD databases based on the search item, the first search term is “laser scanning”, moreover, “heritage”, “3D LiDAR”, and “preservation” were used as the second search term. Secondly, according to the research topic of this literature review, the retrieved Chinese literature was manually screened and classified. Finally, 265 papers were selected as the basic data for this review.

Based on clarifying the technical application background and current situation, the study makes an overall literature review of the selected Chinese papers. The specific research steps are as follows: First, use the bibliometric method and the statistical functions of CNKI to analyze the interannual distribution of bibliographic data. The distribution of academic journals, the distribution of disciplines, the distribution of researchers and their institutions, research hotspots, research issues, and research methods distribution are descriptive statistics, aiming to comprehensively present and clarify the progress of existing research in 3D LiDAR combined with built heritage preservation in China; Second, use the citation space method, the bibliometric visualization tool VOSviewer is used to sort out the hotspots, technical methods, and analyze the research density of Chinese papers; Third, conduct a comprehensive review of the multidisciplinary application of 3D LiDAR, the hotspots and methods of 3D LiDAR and multi-technology collaboration from multi-scale; Finally, based on the summarization, analysis, and comparison of the selected papers to give a discussion of the future challenge and future technological application, and the reference is drawn for the follow-up research.

3. Quantitative analysis of the statistical characteristics of the selected papers

3.1. Interannual distribution of papers

From the annual distribution of documents after 2012, the literature on 3D LiDAR and built heritage preservation collected by the Core journal directory of Peking University, CSSCI, and CSCD began to increase (Fig. 1), and then basically showed a trend of small increase year by year. After 2016–2017, the literature began to increase significantly; After 2017, it showed a trend of gradual decline, but the number of literature remained around 33–41 papers, which to some extent indicates that academic attention on the combination of 3D LiDAR and built heritage preservation has not decreased in recent years, and relevant research results have maintained a steady growth momentum.

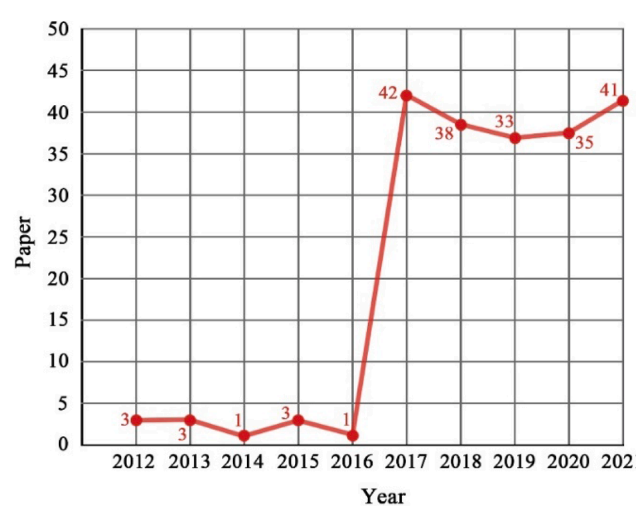

Fig. 1. Number and trend of publications in the Core journal directory of Peking University, CSSCI, and CSCD.

3.2. Distribution of journals and disciplines

From the perspective of source publications (Table 1), the top 10 journals in the number of Chinese papers published mainly focus on the five most representative disciplines of surveying and mapping, laser, cultural preservation, remote sensing, and architecture to carry out relevant research on built heritage preservation. Among the significant journals, *Bulletin of Surveying and Mapping* and *Laser Journal* occupy the first two places in terms of the number of published papers, focusing on the practical application of built heritage preservation, and covering more types of heritage at macro and *meso* scales. However, the paper published in cultural preservation and architecture journals focuses on the digital preservation of heritage sites at a mesoscale and microscale, and the number of articles published is far behind that of surveying, mapping, and laser journals. the advantages of this discipline need to be further released in subsequent studies. overall, the papers published in these journals cover the multi-disciplinary and multi-scale characteristics of built heritage preservation and are based on the discussion of multiple data sources, multi-technology combinations, key technologies, and technology applications, reflecting the trend of technological collaboration and disciplinary integration of research.

4. Hotspots and methods of 3D LiDAR for built heritage preservation

The preservation of built heritage possesses the traits of complexity, multi-scale, and multi-discipline. First of all, each field of study has unique viewpoints and methods for tackling particular issues. In terms of 3D LiDAR and multi-technology collaboration, the differences in the built heritage at macro, *meso*, and micro scales need to fill the needs of heritage preservation at different sizes. Thirdly, the authenticity and integrity of the preservation process, as well as the materiality and sociality of the architectural heritage, set extremely high standards and demands for the use of 3D LiDAR. Due to the aforementioned traits, 3D LiDAR and multi-technology collaboration have emerged as crucial tools for resolving multi-disciplinary, multi-scale, and complicated problems. The existing research shows a wealth of technology application and investigation through its inter-annual variance in research hotspots and methodologies, the tendency of technology selection, and emphasis on application density.

Table 1
Representative journals of the Core journal directory of Peking University, CSSCI, And CSCD Databases concerning the keywords of “3D LiDAR” and “heritage.”

	Journal	Number of Papers	Proportion	Publisher	Indexed database
1	Bulletin of surveying and mapping	46	23 %	SinoMaps Press	PKU/ CSCD
2	Laser Journal	38	19 %	Chongqing Optical Machinery Research Institute	PKU
3	Science of Surveying and Mapping	10	5 %	Chinese Academy of Surveying and Mapping	PKU/ CSCD
4	Acta Geodaetica et Cartographica Sinica	8	4 %	Chinese Society for Geodesy Photogrammetry and Cartography	PKU/ CSCD/EI
5	Engineering of Surveying and Mapping	7	3.5 %	Heilongjiang Institute of Technology; Chinese Society for Geodesy Photogrammetry and Cartography	CSCD Expanded
6	Sciences of Preservation and Archaeology	6	3 %	Shanghai Museum	PKU
7	National Remote Sensing Bulletin	6	3 %	Aerospace Information Research Institute, Chinese Academy of Sciences	PKU/ CSCD/EI
8	Dunhuang Research	5	2.5 %	Dunhuang Academy	PKU/ CSSCI
9	Laser & Infrared	4	2 %	North China Research Institute of Electro-Optics	PKU/ CSCD Expanded
10	Architectural Journal	3	1.5 %	Architectural Society of China	PKU/ CSSCI

5. Research hotspots of 3D LiDAR in the field of built heritage preservation

In Chinese publications from 2012 to 2021, research hotspots for 3D LiDAR in the field of built heritage preservation are displayed in Fig. 2 and Table 2. Digital mapping, point clouds, Lidar, monitoring of deformation, geological hazards, repair and reconstruction, 3D modeling, technological fusion, virtual reality, information display, etc. are some of the hotspots for research. It is worth noting that on the technical side, the combination of 3D LiDAR with a wider range of disciplines and their technologies provides more problem-solving solutions for built heritage preservation; on the outcome side, the research seeks a more multidimensional orientation based on heritage preservation, including spatial optimization, database construction, innovation in image processing techniques and human experience. The research focus is shifting from single technology application to multi-discipline and multi-technology integration, and the research content is not merely recording the current situation. In addition to laser technology & equipment research and built heritage research, interdisciplinary research with archaeology and anthropology is also a new trend in recent years (Wei et al., 2013).

The keywords extracted from the Chinese literature in Table 2 can be summarised as (1) types of built heritage; (2) distribution of built heritage; (3) conservation practices of built heritage; (4) technological innovations and applications of built heritage, and (5) data processing of built heritage, etc. These keywords, combined with 3D LiDAR, present the current conservation practices and technological innovations of the academic community at different scales and types of heritage sites and in the framework of different combinations of technological tools in a multi-technological collaboration. In addition, Table 2 shows that 3D LiDAR and multi-technology collaboration have been applied to different scales and types of built heritage, but there is variability in the combination of technical tools, and in the process of preservation practice, some scholars have also tried to seek breakthroughs in reconstruction, monitoring, digital representation and simulation, machine identification, boundary extraction, and 3D printing. More notably, the research focus of 3D LiDAR and multi-technology collaboration in Chinese publications are shifting from technology applications to big data, artificial intelligence, cognition, and emotion.

5.1. 3D LiDAR methods used in built heritage preservation

The key technical approaches used in the Chinese study for the period of 2012 to 2022 (Fig. 4) are 3D LiDAR, UAV, 3S technology, XR technology, 3D printing technology, and artificial intelligence technology. Additionally, the technical collaboration in software mostly utilizes the modeling and drawing programs Revit/BIM, 3Ds Max, CAD, and Agisoft PhotoScan and involves algorithms, close-range photography, tilt photogrammetry, virtual presentation, measurable real image, etc. In terms of technological application, it has been discovered that the model of 3D LiDAR and multi-technology collaboration is more adaptable in

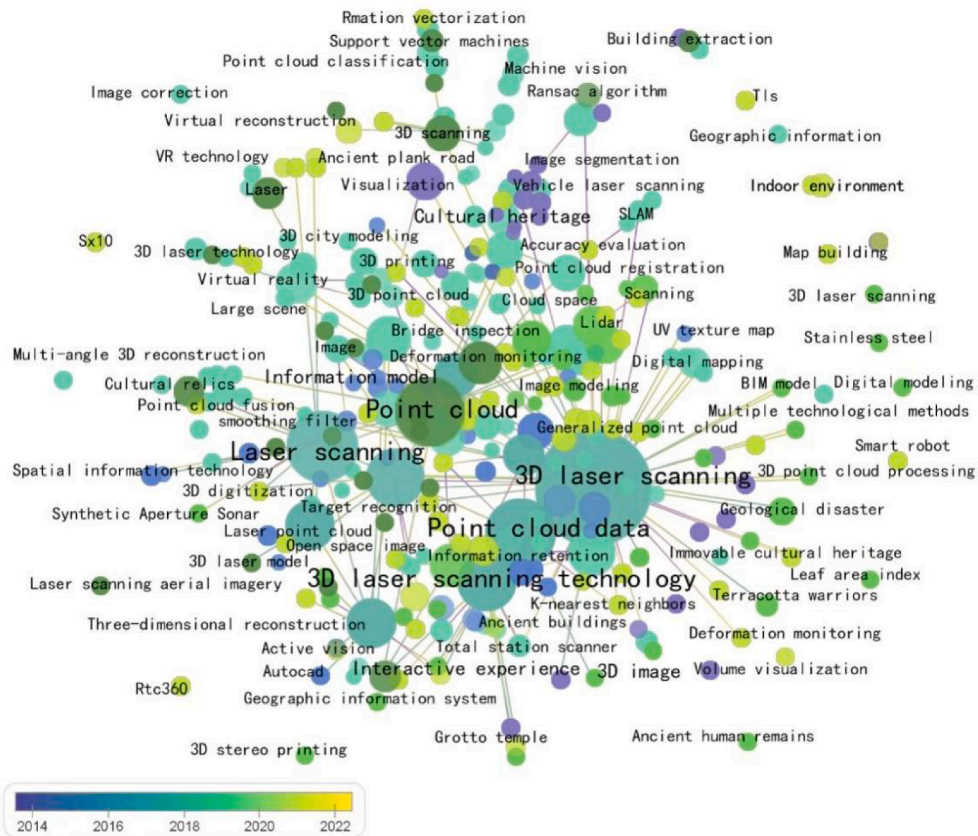

Fig. 2. Research hotspots of publications in Chinese and their yearly variations.

solving professional difficulties and can provide more targeted research plans; the model of 3D LiDAR and multi-technology collaboration is also more adaptable in terms of data management. In terms of interdisciplinary, complicated, and comprehensive research themes that can also be coordinated through 3D LiDAR and multiple technologies, it can better match with the data storage and management functions of BIM/HBIM and GIS/HGIS and play a supportive role in the research process. The model provides an in-depth discussion for research, on the development path, the model of 3D LiDAR and multi-technology collaboration has started to be tightly integrated with the environmental behavior science and psycho-behavioral science of built heritage sites.

In Chinese publications, there are relatively extensive studies on the use of mobile communication systems, thermal imaging cameras, and 3D laser scanning in the preservation of constructed heritage, which is frequently employed in preservation projects. Some academic conferences and forums on spatial information technology on cultural heritage preservation in China have already displayed mature technology applications; in addition, the English paper that combines MATLAB and 3D laser scanning in the research on built heritage preservation is worthy of further discussion. Additionally, more research needs to be done regarding the degree of multidisciplinary integration. In general, the technical application of Chinese papers displayed through the VOS viewer knowledge graph has maintained a roughly synchronized state in the past 10 years.

5.2. The technical application density of 3D LiDAR in the field of built heritage preservation

In Chinese literature from 2012 to 2022, point cloud data, digitization, 3D modeling, 3D virtual reality, close-range photogrammetry, 3D modeling, virtual visualization, 3D printing, and other technical applications related to the preservation of built heritage are concentrated. The density of technology applications in the Chinese literature is concentrated in laser applications, scanning, close-up photogrammetry, and 3D modeling, while the rest of the technology applications are more evenly distributed around 3D laser scanning.

Through the aforementioned technical methods and their annual changes and technical application density (Fig. 5), it can be found that the Chinese studies have the following characteristics in terms of technical methods: First, from focusing on the ontology of architectural sites and ontology-environment complexes (Wan et al., 2020) to the coordinated observation of air-land-space integration, the internet of things, display interaction, perception and computing involving the preservation of built heritage; Second, from a single technology application to a comprehensive research of multi-technology integration, such as the combination of 3D LiDAR and 3Ds Max, 3D printing technology, and XR technology, applied to virtual scene construction, public archaeology, virtual restoration and reconstruction (Geng et al., 2021); The combination of laser scanning and 3S technology, HBIM and heritage big data is applied to the construction of heritage data platform and the monitoring and management of heritage sites; the combination of 3D LiDAR and artificial intelligence technology is used to explore semantic segmentation, image matching, feature extraction, image processing, etc.

Overall, the Chinese paper focuses on 3D scanning systems, 3D reconstruction, 3D modeling, information display, digital mapping, and close-range photogrammetry; in terms of methods; the technical collaboration of Chinese paper in software is mainly GIS, Revit/BIM, and 3D modeling software, and involves computer programming algorithms, 3D virtual scenes, close-up photography, oblique photogrammetry, virtual display, measurable live images, etc. In the past 10 years of Chinese papers, “high-precision modeling”, “digital surveying and mapping”, “virtual simulation”, “information display” etc. are the research hotspots in the field of built heritage preservation. The combination of “big data”, “artificial intelligence”, “machine learning”,

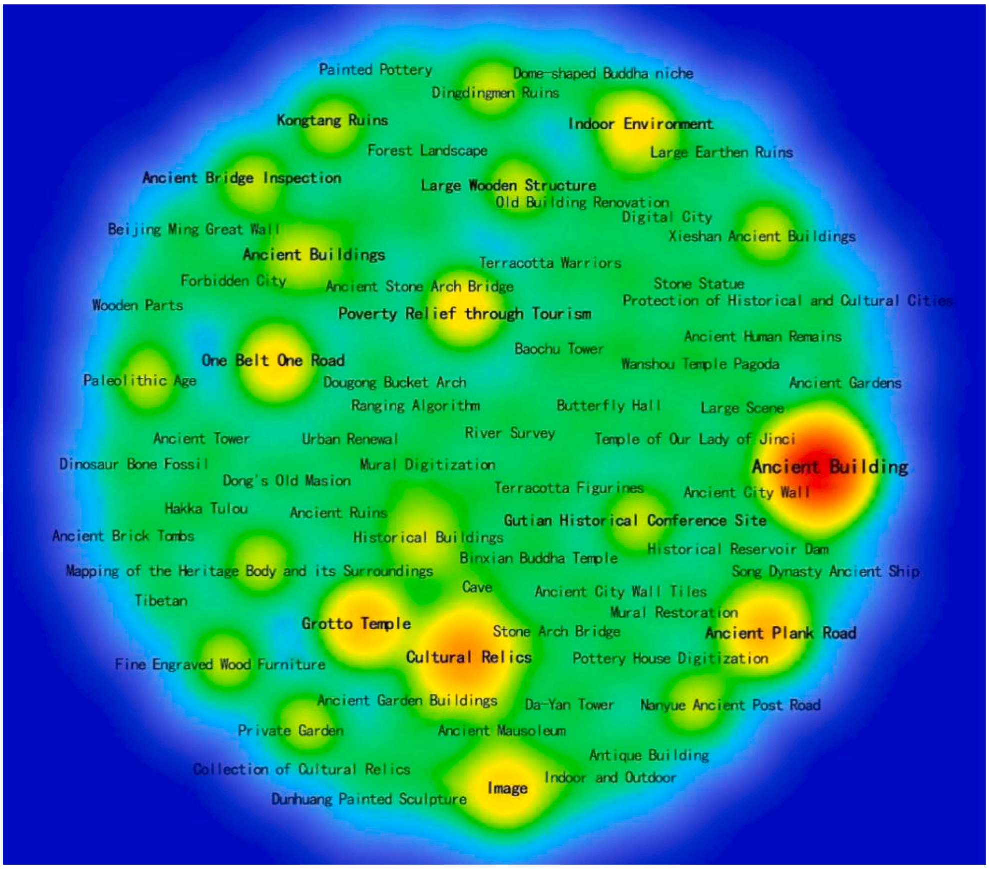

Fig. 3. Publications in Chinese that focus on the types and distribution of built heritage.

"deep learning", "mathematical model" and "information system" can be seen as the current focuses in this field.

6. Application of 3D LiDAR and Multi-Technology collaborative in the preservation of built heritage

6.1. Digital application on built heritage preservation with Multi-Scale, Multi-Purpose, and Multi-Technology docking

After more than 20 years of development, 3D LiDAR hardware has made great progress in stability, accuracy, and ease of operation, especially in airborne, vehicle-mounted, and ground 3D LiDAR. Based on the collected Chinese papers, this study selects representative papers to present the application and current technological progress in order to clarify the multi-purpose and multi-technology docking of 3D LiDAR at a multi-scale.

On the macro scale, Hu Yaofeng, et al. (2016) carried out research on key technologies for the census of immovable cultural heritage based on 3S technology and studied the census standards for immovable cultural heritage, the "three lines" of cultural relics, and mobile terminal equipment. Basic analysis systematically discusses the application of 3S new technologies in the census, such as 3D LiDAR technology, measurable scene image technology, and mobile GIS, and verifies the superiority of 3S technology in the census through a successful case; Liang Shuang, et al. (2016) researched the key surveying and mapping techniques for the Qin and Shu ancient road heritage; Wang Bing, et al. (2017) combined 3D LiDAR and close-range photogrammetry to construct an internal and external information database of the Great Wall of Ming Dynasty, which improved data acquisition capabilities; Huo Pengpeng, et al. (2020) used a variety of data sources in the 3D reconstruction method of the Ming Great Wall in Beijing, used Contextcapture Center software for data processing to construct Mesh 3D models, and used medium and long-range 3D laser scanners. The elevation information of the Great Wall is determined from the point cloud, and the Great Wall and its appendages are modeled in turn in 3Ds Max software and exported in a common format to ensure its universality.

On the mesoscale, Xie Jinpeng, *et al.* (2015) combined 3D LiDAR technology with AutoCAD, 3D Max, and SketchUp to build a digital 3D model for the preservation of Kaiping Diaolou, serving 3D image reconstruction of the Diaolou building. Wang Chenyang, et al. (2016) explored a fast and high-precision modeling method for built heritage by combining 3D LiDAR, archival data, and SketchUp; The same method was applied to the point cloud registration and in terms of modeling methods, Cui Xiaolei, *et al.* (2021) used 3D LiDAR to 3D digitize ancient buildings, including three major processes: image point cloud data acquisition, point cloud data processing, and 3D model creation. Among them, the building point cloud data is scanned and collected by the Trimble TX5 3D laser scanner, and then the data is processed by the Trimble Real Works software that is matched with it, and then the ancient buildings are constructed in 3D through modeling software such as 3Ds Max and SketchUp; In 2017, to find out the occurrence and development of the disease of the Three Pagodas of Chongsheng Temple, accurately assess the preservation status of cultural relics, and improve the digital management level of cultural heritage, with the support of Yunnan Provincial Bureau of Cultural Relics, Dali City Cultural Relics Preservation and Management Institute cooperated with Shanghai Jianwei Libao Engineering Technology Co., ltd. has launched the Internet of Things remote real-time monitoring and digitization project for the Three Pagodas of Chongsheng Temple. The preservation status and risks faced by the Three Pagodas of the Holy Temple were monitored in real-time, a real-time early warning system for cultural relics safety was established, and a cultural relic monitoring and digital management platform was constructed. Yu Peiyong, et al. (2018),

Table 2
Research categories and hotspots in the Chinese publications.

	Research Category	Research Hotspots
1	Types of Built Heritage	Spatial archaeology, Field Archaeology, Cultural relics, Preservation of historical and cultural cities, Historical and cultural blocks, Ancient buildings, Classical private gardens, Industrial heritage preservation, Large wooden structures, Wooden components of ancient buildings, Immovable cultural heritage, Indoor environment, Building facades, Large-scale earth sites, Carved furniture and handicrafts, Ancient city walls, Ancient city wall bricks, Ancient building sites, Ancient mausoleums, Large-scale heritage site scenes, Ancient road ruins.
2	Distribution of Built Heritage (As is shown in Fig. 3)	Ancient pagodas in the Guanzhong area, Ancient stone arch bridges, The Shixia Great Wall, The residence of the emperors of the Qing Dynasty Imperial Palace, Ancient Buddhist halls, Kaiping watchtowers, Painted pottery, Rock paintings, Murals, Cave temples, Ancient plank roads, Ancient Shu Road, The Jinci Temple, Historic site of the Gutian meeting, Suzhou Suiyuan Garden, Wanshou Temple Pagoda, Nanyue Ancient Post Road, Big Wild Goose Pagoda, Song Dynasty Ships, Hakka Tulou Buildings, Dougong bracket system, Caves, Xieshan Ancient Buildings, Reservoir Dams, Buddhist Statues, Zhengzhou City God Temple, Pottery Figures, Baochu Pagoda, Terracotta Warriors and Horses, Beijing Ming Great Wall, Dome-shaped Buddhist niches, Kongtang ruins, Binxian Buddha Temple, Forbidden City, Paleolithic heritage site, Stone tool analysis, Stone statues, Dong's residence, Mogao Grottoes, Dingdingmen site, Dunhuang painted sculptures.
3	Practice of Built Heritage Preservation	Digital preservation of cultural relics, Digital archaeology, Archaeological surveying and mapping, Open-air images, Large-space positioning, geographic distribution, Scanning, Classification, Extraction, Preservation and repair of ancient buildings, Reconstruction, Development and evolution, Fire, Weathering monitoring, Deformation monitoring, Geological disasters (wind sand, earthquakes, landslide, typhoon), Garden information model, 3D real scene, Fine surveying and mapping, Remote sensing archaeology, Information system construction, Tilt monitoring, Health monitoring, Optical measurement, Indoor full element model, Local geometric features, Building topographic map, Building façade (surveying and mapping, extraction), Ontology map of cultural relics, Landscape evaluation, Disaster-damaged buildings, Lighting design, Disease detection, Stability assessment, Defect measurement, Space optimization (detail facade reconstruction, Old city reconstruction, Old building reconstruction, Antique buildings, Spatial relationship, Eco-tourism, Land consolidation), Tourism poverty alleviation, Safety evaluation, Difference analysis.
4	Technological Innovation and Application	The 3D scanning system, 3D reconstruction, 3D modeling, Information display, 3D model making, Digital mapping, Close-range photogrammetry, Intensity correction, Point cloud stitching, Point cloud segmentation, Registration, Feature extraction, Semantic segmentation, Terrain mapping, Rapid manufacturing, 3D printing, Emergency mapping, Reverse modeling, Deep learning, Virtual reality, Interactive display and experience, Machine vision, Extreme learning, Visual sensing, Recognition research, Computational imaging, CT scanning, Artificial neural network, Reality fusion, Intelligent mining machine, Visual simulation, Boundary extraction, Active vision, Passive vision.
5	Data Processing	Technology fusion and integration, Data (mining, division, stitching, fusion), Fusion modeling, Database, Archaeological big data, UAV, Close-range photogrammetry, Imagery, Remote sensing, LiDAR, Augmented reality, Virtual reality, GIS, BIM, 3Dmax, VR, Visualization.

relying on the restoration and preservation project of Zhu De's former residence, used close-range photogrammetry technology and 3D laser technology to build a fine 3D model, digitally preserved the former residence of the great man, and elaborated on the ancient architecture based on 3D LiDAR technology. The refined digital modeling process provides an example for further cultural heritage modeling research; Similar to this method, Guo Jiangning, Chen Nianqing, Sun Hao, *et al.* (2020) performed fusion modeling based on terrestrial 3D LiDAR technology and aerial photography to reconstruct high-precision complete 3D models of ancient buildings. Wan Fei, *et al.* (2021) explored a fine 3D model of the ancient post road in Nanyue Based on the VR scene construction, which provides new ideas for the digital preservation of historical buildings.

On the microscopic scale, Fang Wei, *et al.* (2015) corrected the murals through the laser point cloud intensity during the digital preservation of murals, which solved the problem of few feature points and uneven distribution in intensity image extraction; Zhao Rong (2016), Lv Wenxu, *et al.* (2016) of the Institute of Archaeology of the Dunhuang Academy used 3D LiDAR to collect images of Buddhist shrines and painted sculptures in Dunhuang Grottoes, serving the efficient and accurate requirements of archaeological mapping; He Yan, *et al.* (2016) proposed the detection technology of ancient relief damaged area by laser beam scanning, and proved its advantages in the clarity and error control of scanned images; Hu Bengang, *et al.* (2016) used 3D laser point cloud data through reverse engineering. Carry out 3D modeling of physical cultural heritage, with the help of reverse engineering software such as PolyWorks, Geomagic, etc., automatically identify the physical cultural heritage features in 3D laser point cloud data, and automatically fit regular geometric elements to build a refined 3D model. The model has high accuracy and can be reaching the sub-millimeter level or above, fully meeting the accuracy requirements of cultural relic restoration; Wang Lele (2021) and Gao Yang (2021) explored the method of virtual restoration of damaged areas of cultural relics based on high-precision 3D LiDAR models; the team of Dr. Professor Cao Yongkang of Shanghai Jiaotong University combined laser scanning measurement, infrared detection, stress wave tomography, Methods such as material analysis are applied in the preservation process of ancient bridges in Shanghai, and the monitoring of ancient bridges, disease detection, structural reinforcement and replacement of damaged components are realized through the application of various technologies. Similar practices at the micro-scale are also used in high-precision real texture 3D modeling of built heritage (Qi et al., 2021), 3D reconstruction of irregular cultural relics (Xi et al., 2020), etc.

In addition to the above studies, Chinese scholars have also carried out research at different scales based on 3D LiDAR and multi-technology collaboration: 3D digital representation of Suzhou Tiger Hill Pagoda (Zhang et al., 2012), Jingjiang Royal Mausoleum (Zhou et al., 2015), Shichahai Lake Surrounding Mapping (Gao et al., 2021) and other heritage sites preservation research. Among scholars in other countries, Ortiz-Coder, et al. (2020) proposed a method for 3D reconstruction of heritage scenes using video measurement-based equipment, which is based on two cameras with different characteristics and adopts visual simultaneous localization and the combination of cartography (SLAM) and photogrammetry, VSLAM works with a series of filtering algorithms for the best selection of images and guarantees that users will not lose

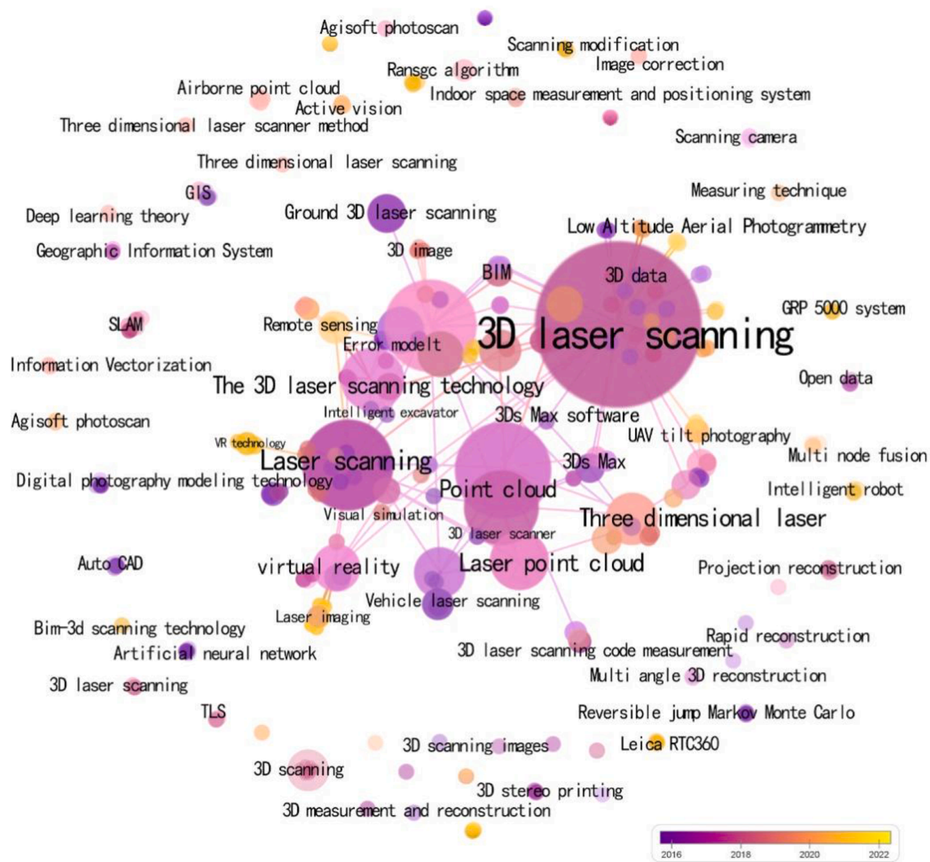

Fig. 4. Technical methods adopted in existing publications in Chinese and their annual changes.

track during real-time data acquisition. Through case studies, evaluations, and comparisons, it was found that the method is 17 times faster than laser scanners in capturing data, and the post-processing of the system is fully automatic but takes more time than laser scanners in post-processing.

However, current research and preservation techniques have also brought to light a number of issues, including the dearth of recording information, the difficulty of collaboration, the non-standardization and fragmentation of data, the difficulty of data mining, and the difficulty of comprehensive utilization. There are still deficiencies in dynamic, three-dimensional, and refined aspects, which need to be further explored, such as, continuing to deepen the use of convolutional neural networks (CNN) for the image-based reconstruction of high-precision 3D heritage buildings and the overall environment; strengthening the detailed characteristics of built heritage and the refinement of structural reconstruction; technology development of dynamic scene reconstruction of built heritage at different scales; innovative algorithms for the reconstruction and evaluation of built heritage at different scales.

6.2. Comprehensive application of built heritage preservation from multiple Perspectives, Integration, and High-Precision docking

3D LiDAR technology and multi-technology collaboration continue to produce breakthroughs in different research issues, on the one hand, multi-view, high-precision, and point cloud annotation meet the requirements of surveying and mapping accuracy and information accuracy for different types of built heritage. Technology enables researchers to quickly and accurately capture and reconstruct the geometry and color of built heritage; on the other hand, it has high comprehensive efficiency and low cost, improves the efficiency of modeling and digital storage, and breaks through the limitations of single technology applications. The docking of HBIM, VR, and CIM provides fine digital models, high-precision data benchmarks, and basic materials, which are highly targeted in the preservation of built heritage.

From the perspective of preservation, Zhang Xu, et al. (2013) used 3D LiDAR combined with CAD and 3D printing to explore the technical methods of reverse engineering restoration of cultural relics. Hong Kong scholar Siu Susanna Lai Kuen (2021) discussed the technical methods for the restoration of built heritage damaged by natural disasters, to ensure complete and faithful restoration. To solve the problem of digital preservation of built heritage, Li Minzhen, *et al.* (2015) adopted 3D LiDAR to reconstruct the historical buildings along the Huangpu River in Shanghai in a refined manner, and the models are managed by components, to organize massive information and facilitate subsequent statistics and use. In response to the monitoring and management of built heritage, Zhou Wei, et al. (2012) used laser scanning technology to monitor the deformation of large-scale ancient buildings in the Foxiang Pavilion of the Summer Palace.

From an evaluation perspective, Yin Yongsheng, et al. (2020) combined 3D LiDAR with deep learning to directly learn and extract the built heritage features from image data through deep learning based on constructing 3D virtual models and processing photo data; Multi-technology types researched 3D digital modeling technology for maintaining infrastructure, especially the use of point cloud data, thinking about the transformation from infrastructure resilience management to structural maintenance, from 3D model to structural analysis, system cost, and a series of challenging issues such as massive data processing, the research has reference significance for the preservation practice of the built heritage of the historical urban area in terms of technical coordination, flexible management, and structural maintenance.

From the perspective of heritage management, scholars and practitioners of heritage preservation choose to use 3D digital surveying and mapping technologies such as close-range photogrammetry, 3D laser scanning, and multi-technology comprehensive surveying and

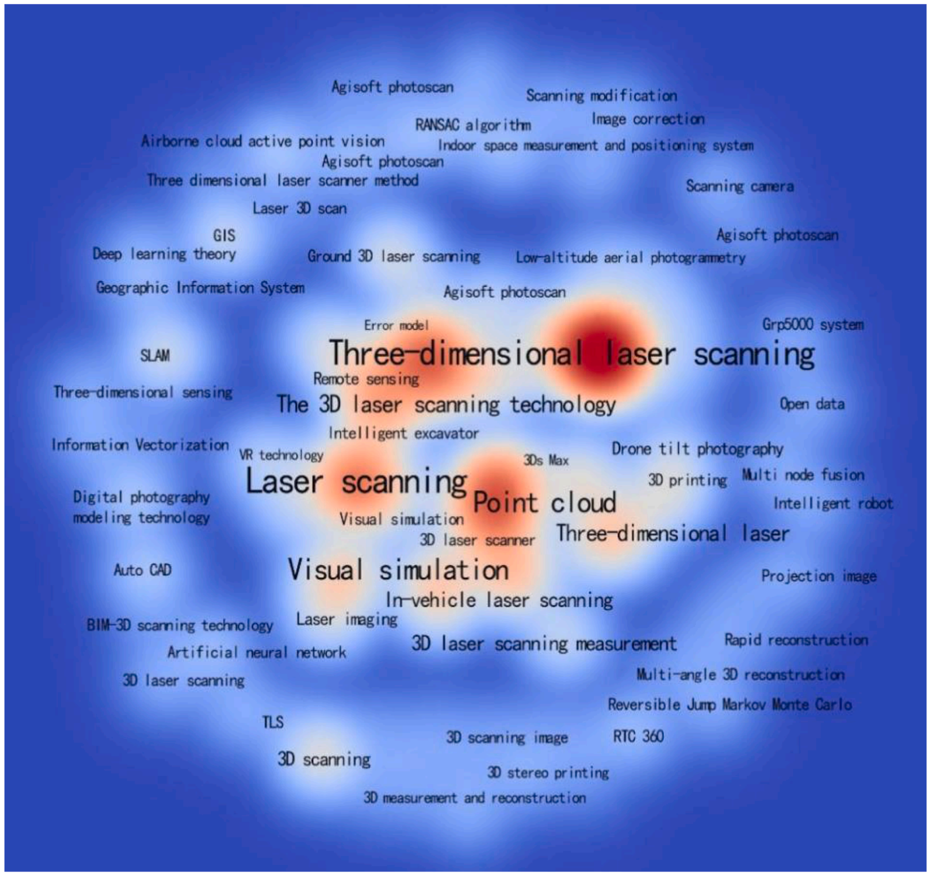

Fig. 5. Technology application density of papers in Chinese.

mapping in combination with 3D information management technologies such as 3D geographic information system and information model to serve the fine, digital and dynamic management of built heritage. Such as Liang Huilin, et al. (2020) employed three-dimensional digital mapping and information technology to collect, process, store, manage, maintain, update and analyze data, serving the preservation, management and sustainable use of garden heritage in China; Zhang Zhi, et al. (2021) discussed the construction of the information technology method framework for the preservation and utilization of the Great Wall cultural heritage, and advocated using the digital twin theory to design experimental research and comparative analysis to summarize the technical methods for data collection of different types of Great Wall cultural heritage, such as multi-source remote sensing technology (aerospace remote sensing, unmanned aerial vehicle remote sensing, multi-source ground detection), Internet of Things technology (dynamic collection, real-time communication, two-way interaction), GIS (Web GIS/Cloud GIS/Smart GIS), information simulation technology (GIM/LIM/BIM), virtual reality technology (VR/AR/MR), covering macro, *meso* and micro scales, 2D, 3D and 4D dimensions, and different components of physical entities, serve as the basic technical support for the intelligent preservation of the Great Wall cultural heritage, which is both a method of built heritage preservation and a means of heritage information management.

From the lens of heritage perception, Dr. Professor Li Yuan (2020, 2021, 2022) from Xiamen University and Xiamen Key Laboratory of Integrated Application of Intelligent Technology for Architectural Heritage Protection focuses on the value perception study of multi-dimensional built heritage, including old urban quarters, historic streets, historic urban landscapes, and historic buildings based on the collaboration of 3D LiDAR, UAV tilts photography, BIM, machine learning, virtual simulation, questionnaire, structural equation modeling (SEM), human performance experiments, and artificial intelligence algorithm. In his study, through the quantitative analysis of built heritage combined with environmental psychology and human spatial behavior characteristics, his research evaluated the preference, cognition, and satisfaction of humans with the historical environmental information of heritage sites, and the feasible optimization strategies were proposed through a range of quantitative evaluation results.

Along with the aforementioned four facets, existing research based on 3D LiDAR and multi-technology collaborative research on building contour identification, building settlement prediction, deformation monitoring, weathering monitoring, system life cycle health detection, building classification, building erection, rapid surface extraction, 3D dynamic image reconstruction, information feature matching research, non-destructive analysis technology research, data management, and visualization research, data acquisition, and structure storage optimization and other technologies have expanded the comprehensive application scope of built heritage preservation. Existing research and applications provide the basis for the following three technological innovations: (1) innovate the multi-modal image fusion 3D reconstruction technology, and effectively guide the precise restoration of micro-scale built heritage details or internal structures through visual information; (2) reconstruct the multi-scale adaptive built heritage environment based on robots and multi-modal fusion perception systems; (3) on different scales, continue to carry out the technical connection between rapid 3D reconstruction and real-time reconstruction based on the combination of 3D LiDAR and digital twin technology.

7. The built heritage preservation based on 3D LiDAR and Multi-Technology Collaboration: Future challenge and future technological application

Innovative 3D digitization and geomatics approaches have emerged over the past few decades as non-invasive technologies in the field of cultural heritage, primarily to meet the demands of documentation, management, and protection (Di Stefano et al., 2021). The 3D LiDAR with its unique technical advantages plays an increasingly important role in the practice of digital recording, assessment, intervention, reparation, restoration, monitoring, optimization, improvement, etc. To go further, the future challenge and future technological application on built heritage preservation based on 3D LiDAR and multi-technology collaboration focus on four parts:

(1) 3D LiDAR interfaces with digital recording and artificial intelligence in the field of built heritage preservation and integrates with multiple sources of heterogeneous data, leading to the digitization and virtualization of the whole element (Lu et al., 2021), real-time and visualization of the full state, and provides visualized, analyzable, computable, and three-dimensional work paths and specific technologies that bridge the differences in the depth and mode of work requirements. For example, image recognition, feature extraction, linguistic analysis, algorithms, simulation analysis (control data and change of conditions, inversion of change processes), identification of risk points at different scales (fire, flood, mountain seepage, weathering, constructive damage, human damage, improper restoration) and sensitivity, vulnerability prediction (combining close-up photogrammetry, hyperspectral imaging techniques, thermal imaging of walls, ultrasonic techniques to map building painting and frescoes, telemetry of concrete surface defects, structural material properties, and toughness, structural damage, settlement, deformation, stains, and mould; combined with GNSS and high-sensitivity remote sensing analysis to achieve large-scale architectural heritage disaster information collection and collaborative observation, to enhance the disaster prevention and response capability of architectural heritage conservation), etc. Facing the needs of built heritage preservation in three-dimensional health monitoring and management, risk prediction, preservation planning, design and construction, operation optimization, interactive feedback from the heritage Internet of Things, comprehensive spatial analysis, and scientific decision-making, serving the dynamic conservation of multi-scale architectural heritage space and intelligent governance of heritage sites.

(2) based on the preservation of the physical space of the built heritage, it turns to the perception calculation of the intangible level of the built heritage. Through multi-technology collaboration, while preserving the built heritage, it explores the relationship among the built heritage, its value, and people, so that information, systems, and models can be interconnected with social behavior and spatial environment, develop from one-way heritage information collection, analysis, and release to multi-dimensional information interaction, strengthen human-landscape interaction, and quantitatively express cognition, emotion, memory, preference, attachment, etc., and serve for the long-term goal of people-centered adaptive reuse and development, it will feed back into the preservation of the physical space of architectural heritage while improving the experience of local communities and tourists.

(3) 3D laser scanning and multi-technology synergy will be more useful in the direction of informatization, digitization, and wisdom of architectural heritage conservation, with potential applications in integrating cultural and historical information of architectural heritage, developing new tools to store and share all relevant metadata, building an open and shared cultural heritage information model (CHIM), heritage big data platform, 3D visualization platform (3DGIS), regional heritage management information platform, 5G + AR remote visualization expert system, and Heritage Intelligent System (HIS) for historical heritage conservation. Through the construction of the platform, long-period, multi-scale, multi-dimensional information collection, spatio-temporal data mining and analysis, monitoring and evaluation, and management applications are realized to serve a high-quality, refined, integrated, and collaborative paradigm of comprehensive architectural heritage conservation practices. For example, by combining digital virtual restoration design and 3D printing technology, we can simulate traditional craft forms to repair and restore the structural components, skin texture, and key features of architectural heritage to achieve the continuation of the authenticity and integrity of heritage.

(4) The interface between 3D laser scanning and intelligent media technology is also a noteworthy development and trend. Combining digital elevation models based on 3D laser scanning, model presentation films with 5G, augmented reality (AR), virtual reality (VR), mixed reality (MR), big data mining and knowledge discovery to create immersive, intelligent and interactive experiences in the following ways: First, it is applied to simulate different scenarios of economic, social and environmental development, responding to different needs of architectural heritage conservation and all aspects of multi-situational simulation; second, it is applied to the use of digital museum displays (digital reproduction) and cultural exhibitions under the perspective of experience economy, for example, the overall effect formed by combining with 3D dome technology and NPC interaction to improve the interpretation and display dissemination of built heritage; Third, bringing more experiential autonomy and cultural production possibilities in the context of cultural tourism integration, moving from information services to knowledge services, realising heritage education from a cultural empowerment perspective, metaverse-based time travel, story maps and digital product development, cultural IP development and transformation, etc.

8. Conclusion

This literature review focuses on the use of 3D LiDAR in the field of built heritage preservation of various scenarios through a multidisciplinary lens. It provides a thorough survey on 3D LiDAR and multi-technology collaboration that contains the hotspots and methods, their application, future challenge, and future technological application in built heritage sites.

Reviewing the cases of 3D LiDAR and multi-technology collaboration in the existing study, it can be found that the technology presents a diversified trend in the application, and the combination with other technology types can also provide effective feedback through the analysis of specific problems. It is important to note that the practice of integrating with digital twins, artificial intelligence, multi-source heterogeneous data, and data platform construction is not included in the existing research cases of 3D LiDAR and multi-technology collaboration, and the practice of combining big data and machine learning is still in its infancy. Few studies have also focused on how individual behavior and perception experiences (whether virtual or real) relate to 3D LiDAR and multi-technology collaboration, which emphasizes the limitations and shortcomings of these two fields in the age of artificial intelligence, big data, and the metaverse.

In the future, 3D LiDAR and multi-technology collaboration will be more in-depth to guarantee a sustainable and promising preservation outcome. Although the current practice of built heritage protection is constantly based on 3D LiDAR to solve more problems of built heritage preservation, there is no doubt that the comprehensive changes brought about by the above new technologies will be an important thrust for the further development of 3D LiDAR and multi-technology collaboration over time.

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CRediT authorship contribution statement

Yuan Li: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Funding acquisition. **Long Zhao:** Conceptualization, Methodology, Writing – review & editing. **Yiping Chen:** Methodology, Writing – review & editing. **Na Zhang:** Validation. **Hongchao Fan:** . **Zhenxin Zhang:** Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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