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Integration of Modern Technologies in the Conservation of Cultural Heritage Buildings

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Abstract

We owe it to future generations to ensure that heritage buildings remain standing and preserved as they are for everyone to see, including those future generations. IoT technology is efficiently utilized in contemporary systems for real-time data gathering and continuous monitoring of the environment and modern Cultural Heritage (m-CH) structures within Building Information Modeling (BIM) systems. These are further supported by Cloud computing, which aids in the accurate restoration of historic buildings, real-time data monitoring, and predicting maintenance needs, ensuring their longevity for future generations. It also discusses the role AI plays a crucial role in managing heritage building conservation, detecting structural issues, and responding effectively to prevent further harm, ensuring the preservation of architectural wonders for future generations. For this reason, this review assigns importance to the abilities of these modern technologies for preserving the CH buildings and responses to practical concerns and ethical consequences of applying; the review still targets the researchers and stakeholders who are concerned about using the power of technology to protect and maintain the CH buildings.

Discipline: Multidisciplinary (Computer Sciences & Architectural Engineering).

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1 Introduction

Heritage buildings represent a nation's culture and history, acting as sources of national pride (Mohamed et al, 2023; Qadir et al, 2022). It is important to preserve these structures for future generations to learn their original characteristics and to give examples of green architecture (HMOOD, 2022; Wilkinson, 2022). By incorporating spectacular features and teamwork, heritage buildings can be preserved with long durability and environmental respect (Sema et al, 2022).

Through a synergy of IoT, cloud computing & AI technologies, heritage buildings can be monitored and restored, using non-parametric 3D modeling and digital twins for prediction (Pansoni et al, 2023; Angeloni et al, 2023). However, more research is needed for ethical issues and preserve important features while respecting social impact in historical contexts, despite the ongoing development of AI and ML applications (Vuoto et al,2023; Prados-Peña et al,2023).

IoT devices and sensors enable predictive maintenance in heritage structures by continuously monitoring environmental conditions (Pansoni et al, 2023; Villa et al, 2021). This proactive approach identifies potential issues like humidity rise, mold formation, and moisture-related problems before they become critical (Papitsi et al,2023). This proactive strategy ensures that strategies are implemented before mold, structural problems, and other deterioration occur (Kalis et al, 2023; D'Orazio et al, 2023; Saban et al, 2022).

Exploring the possibilities of utilizing benign cloud computing can be used to preserve historic structures, ensuring sustainable restoration, real-time maintenance, and real-time monitoring (Mohamed et al, 2022). AI tools can be used for intelligent preventive maintenance systems, assessing sensor data, and identifying issues early (Pech et al, 2021). These systems track factors like temperature, humidity, and structure configuration, preventing further deterioration and ensuring future generations benefit from preserved architectural values (Giannini et al, 2022). Pre-emptive conservation allows for immediate conservation intervention (Abate et al, 2023).

This work discusses advanced technologies like the IoT, cloud computing, and AI that can greatly change the protection of historic buildings, focusing the need to explore new directions and issues related to these technologies.

2 Contemporary Technologies for Monitoring and Conservation of the Heritage Buildings

The IoT and other contemporary technologies are becoming indispensable to day-to-day living, helping people, businesses, and governments everywhere (Marchello et al, 2023). With the IoT ready to revolutionize life once again, it improves efficiency and connectivity. IoT connectivity is tapped into by smart city initiatives to boost output, reduce operating costs, and enhance operational effectiveness. However, issues like privacy and safety continue to exist, necessitating a variety of approaches (Kumar et al, 2019). IoT has enormous promise to create safer, smarter, and more efficient cities despite these obstacles (Nižetić et al, 2020).

2.1 IoT Technology

IoT involves the integration of numerous smart devices with sensors, software, and network connectivity to collect and transmit data. (Leo, 2023). Due to advancements in technologies, the internet has become a tool of transformation in various sectors, such as in transport and smart city systems through ML and MCC (Salama et al, 2023). Most of the IoT facilitates seamless integration of computer-embedded systems like sensors and actuators in buildings, enhancing their utility and quality of life for people (Islam et al, 2024; Polepaka et al, 2023). Through IoT, automating routine tasks in various sectors presents growth opportunities in transport, healthcare, energy, manufacturing, education, digital marketing, agriculture, and business (El Abd, 2023).

From an educational perspective, IoT technology significantly enhances the use of electronic lectures in education, particularly during calamities like the Coronavirus outbreak (Salama et al, 2023). Regarding the IoT technology is revolutionizing agriculture by automating crop management, ensuring precise growth and harvesting dates, and reducing resource wastage (Al-Taai et al, 2023). How the IoT is transforming digital marketing: it is by redefining customer experience and introducing a new target marketing approach by collecting data from IoT devices (Al-Taai et al, 2023).

The IoT's vast number of platforms and devices lacks a single defined model, making deployment more challenging. Related research articles propose various architectures. The main architecture of the IoT, as shown in Figure 1, consists of three layers (application layer, network layer, and perception layer) (AlSheikh et al, 2021).

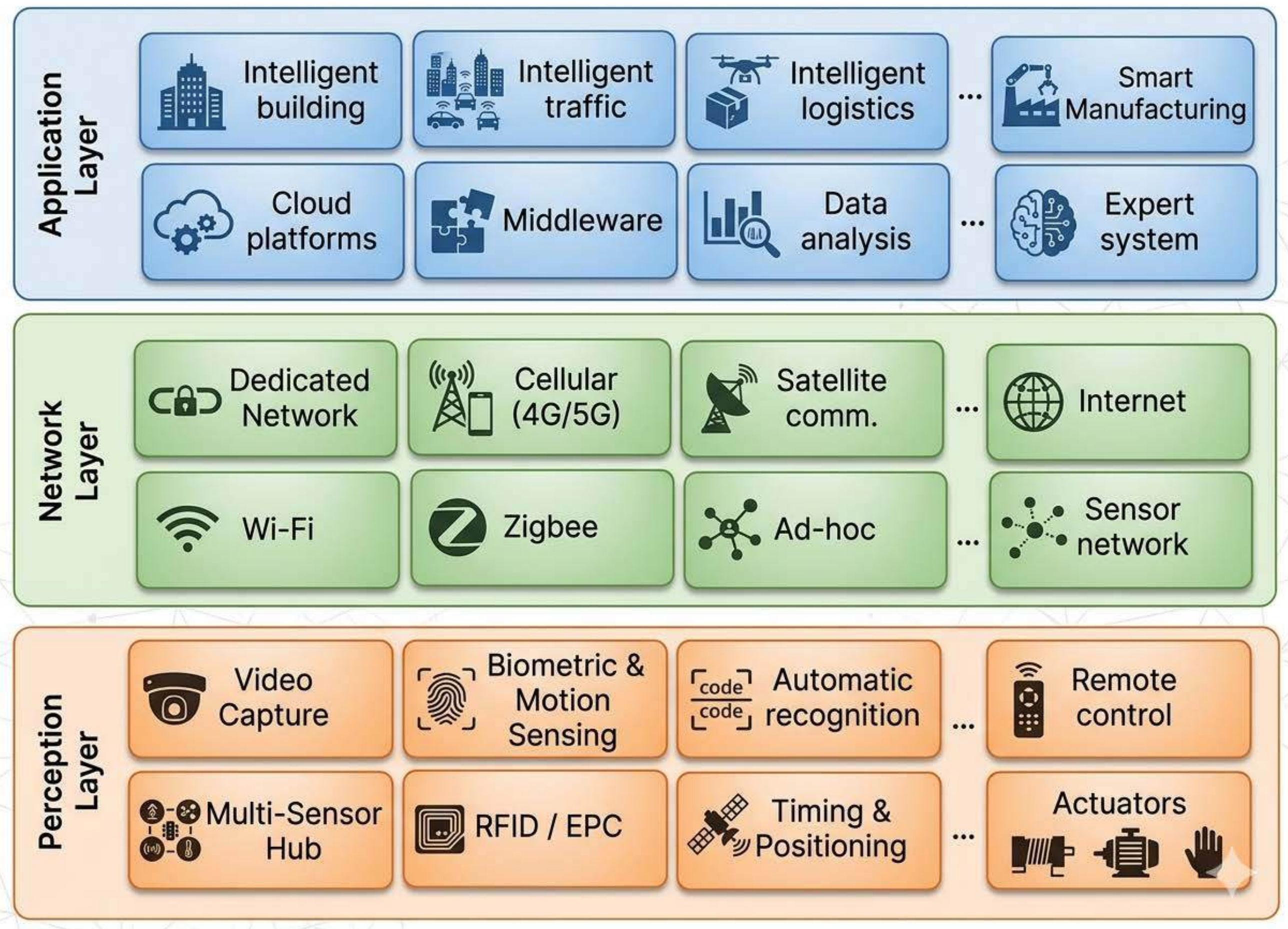

Figure 1: The IoT architecture (modified from AlSheikh et al, 2021).

2.2 Cloud Computing

Because there is a growing demand for cloud services from both individuals and institutions, cloud service providers need to match consumers' expectations (Jawhar, 2022). The services can be categorized into three types (see Figure 2) (Hameed et al, 2023):

a-Software as a Service (SaaS),
b-Platform as a Service (PaaS), and
c- Infrastructure as a Service (IaaS).

This distributed environment offers organizations high scalability, reliability, and cost-effectiveness compared to other types (Aminizadeh et al, 2024). Hailed for offering a secure environment, it comprises several computers linking centrally positioned servers to host applications and store data (Chadwick et al, 2020). These systems, with their vast computational resources and storage capabilities, can be effectively utilized to develop high-performance knowledge discovery systems (Iqbal et al, 2020). Cloud computing architecture includes virtualizing resources for diverse workloads, rapid instantiation of virtual or physical machines, and self-repairing programming paradigms(Santos et al, 2021). Therefore, the study has revealed cloud computing as an essential technique to address the complexity of different data associated with CH (Qasha, 2022). From the analysis, it is evident that the adoption of cloud services can positively impact the management and monitoring of heritage sites since this will increase the chances of evaluating the risks brought about by climate change and formulating strategies for dealing with this problem (Rashid, 2022).

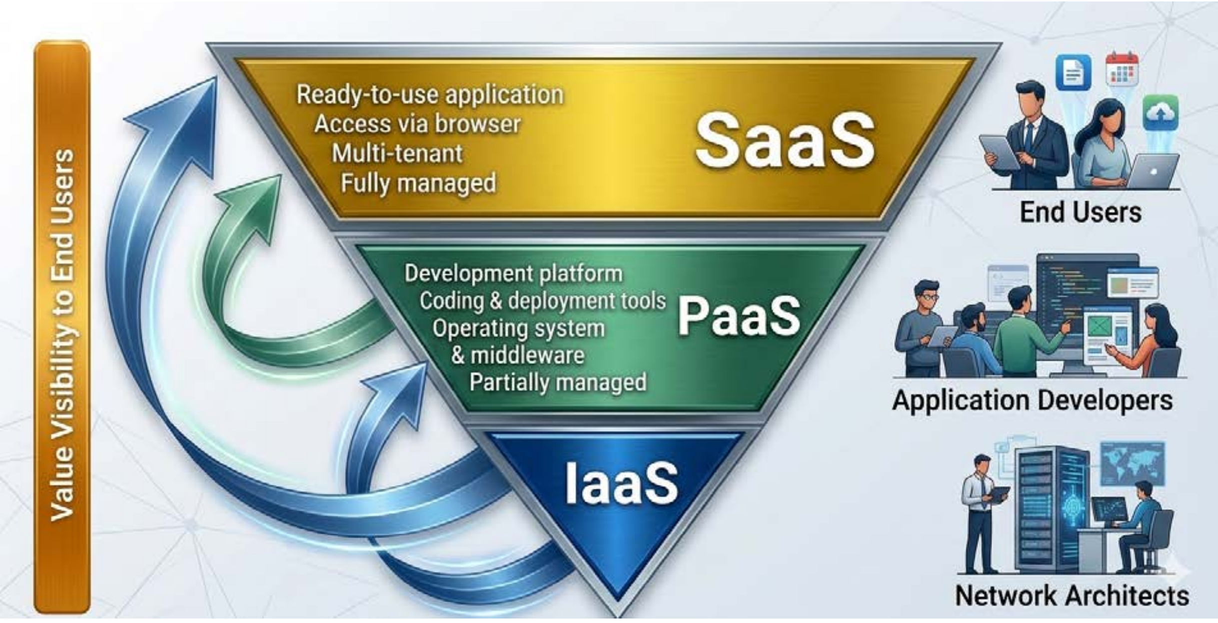

Figure 2: The structure of Cloud Computing (Modified from Hameed et al, 2023).

2.3 Artificial Intelligence (AI)

AI's new and active branch aims to make machines as intelligent as humans, solving problems using learning and logic. (Cheng, 2023). The use of data analysis and algorithms in fields like robotics, machine learning, and data analysis is crucial for improving performance across various industries (Cheng, 2023). AI enhances productivity in healthcare, education, and services by finding efficient solutions, providing better decision-making methods, and introducing flexible applications (Nasseef et al, 2022).

Further, AI aids in identifying patterns in images and sounds, predicting outcomes, understanding voice commands, operating machines, and recording human performances in games and movies (Chelsea, 2023). These methods include machine learning, artificial neural networks (ANN), natural language processing, computer vision, and cognitive abilities for decision support, skills execution, information interaction, picture interpretation, and problem solving (Saker, 2022).

Therefore, modern technologies can significantly aid in overseeing and conserving architectural monuments, preserving historical constructions, and promoting sustainable management, thus recommending their use in this review.

3 The State of the Art for Using Contemporary Technologies for Heritage Buildings

Today's Innovative technology enhances public preservation of heritage buildings, allowing effective control and assessment to prevent degradation (Rossi, Bournas,2023). Comprehensive historical data assessment aids in designing progressive technologies and strengthening CH programs (Lu, 2023).

3.1 IoT in Heritage Building Preservation

Heritage building preservation is very important and has several benefits that could transform conservation efforts. This way, IoT technologies can enhance control over heritage sites, improve preservation efforts, enhance security, and provide enhanced visitor experiences (Lerario, 2020). The IoT concept is gaining attention as scholars and researchers discover new frameworks and solutions that could revolutionize the preservation world. For instance, majoring in the central body of the Monserrate Palace (Machete et al, 2023), it discusses the specific object of the CH area in the framework of the Cultural Landscape of Sintra in Portugal; it is one of the brightest sights of the area. This study generated an H-BIM model using Autodesk Revit software and 3MURI software for structure analysis. An IoT sensor, MeM, was placed on the central tower to measure vibrational behavior. Data from the sensor was integrated into the Heritage BIM (H-BIM) model, creating a digital replica of the structure. The aim is to improve understanding and cost-efficiency in maintenance and repair.

Mitro et al (2022) proposed a distributed smart sensor network, called "smart tags," designed for the HYPERION project in four pilot cities of CH. These wireless IoT appliances permanently monitor environmental conditions around Tier 1 CH buildings, enhancing climate change impact assessment models and quantifying risk. The network addresses the issue of identifying and measuring climate change impacts on historical structures, demonstrating its versatility in environmental observation near historical structures (Mitro et al, 2022).

However, Colace et al (2021) explored the potential of IoT in protecting CH buildings, which have been dilapidated over time. The study focuses on providing an IoT-based framework for monitoring, predictive maintenance, and decision-making. The framework uses low-cost IoT devices and sensors to monitor environmental changes, material transformations, and structural modifications, predicting potential damages and enabling pre-emptive maintenance (Colace et al, 2021).

Zarzo et al (2021) utilized IoT wireless sensors to predict thermal variations in the Baroque church of Saint Thomas and Saint Philip Neri in Valencia, Spain. The researchers collected temperature and humidity data every hour, using principal component analysis to classify patterns and differences between sensors. This approach can help evaluate temporal variations in historical buildings and artwork conservation, without physically checking the building's microclimate conditions (Zarzo et al, 2021).

3.2 Cloud Computing for Heritage Buildings Conservation

The adoption of cloud computing can be regarded as offering affordable, flexible tools for managing and interpreting heritage assets and reshaping protection opportunities in heritage buildings. To develop a perspective of information management and preservation related to CH, Rashid and Qasha (2022) used cloud computing to manage and preserve data related to the CH Nineveh heritage. They use virtual machinery and Docker to capture, process, organize, and deposit data from various sources. This approach simplifies heritage keyword queries, yields valuable information, and ensures the preservation and development of CH (Rashid & Qasha, 2022).

Yang et al (2023) explored the use of cloud computing technology in building digital museums, discussing technical challenges and providing a blueprint for using the Hadoop platform. They also present a distributed multi-QoS parallel routing algorithm for handling data transmission to introduce efficiency as well as boost query response within the system. It is thus concluded that the proposed model has satisfied the security and integrity criteria and enhances the reuse of resources in the network (Yang et al, 2023).

In contrast, Gao et al (2020) proposed a new concept of CH using cloud computing and Augmented Reality (AR) technology to enhance user experience. The goal is to create a mobile application that enhances visitor experience by providing improved content on sites and monuments. The Wikitude software library is used, focusing on cultural digital content and multi-platform hits. The study explores how cloud computing and AR can further explore and develop CH concepts for Chinese Cultural Heritage Computing. (Gao et al, 2020).

With a focus on three levels—the Chinese Cultural Heritage Protection and Development Strategy, the Computing Process, and the Computable Cultural Ecosystem—this study presents a methodical framework for Chinese Cultural Heritage Computing. The framework consists of three components: digital modeling and database creation, data application and promotion, and data collection and processing. For sustainable development and preservation in the digital age, the framework can direct future research in Chinese CH computing and associated topics.

Li et al (2022) present a framework for Chinese Cultural Heritage Computing, focusing on three levels: the Chinese Cultural Heritage Protection and Development Strategy, the Computing Process, & the Computable Cultural Ecosystem. The framework consists of three components: digital modeling and database creation, data application and promotion, & data collection and processing. For sustainable development and preservation in the digital age, the framework can direct future research in Chinese CH computing and associated topics (Li et al, 2022).

3.3 AI for Heritage Buildings Preservation

AI integration in heritage building conservation practices will enhance strategies by handling big data and creating estimations, allowing for smarter, proactive management and better prediction of potential threats to the building's integrity (Pan, 2023). Pansoni et al (2023) proposed an ethical roadmap for AI in preserving CH using emerging technologies like AR, deep learning, and generative adversarial networks. They address ethical issues like bias, digitization, irresponsible resource distribution, and privacy. The study proposes six core principles for CH preservation, including tangible and intangible assets, costs, benefits division, timelessness, fair access, self-removal, and people orientation (Pansoni et al, 2023).

Mishra (2021) reviewed machine learning techniques used in assessing the health and safety of historic structures. It compares previous research on masonry, moisture content, weathering, and surface impairments. The study contributes to heritage conservation knowledge by presenting the state of the art and pointing out potential research directions (Mishra, 2021).

Mishra (2021) suggested that AI and digital tools can improve inspection professionals' confidence in assessing the damage of CH buildings. AI can detect hidden damage, recognize details in drone-captured images, and assess faults in digitized images. This approach can help address surface deterioration and aging of CH structures, but more research is needed to fully explore its potential (Mishra, 2024).

Mishra (2024) proposed an AI-based monitoring system of Historical Buildings and Structures for preservation, discussing the Acoustic Emission signal and the applicability of the Gutenberg-Richter (GR) Law. The GR law can recognize the sign patterns and classify signals of earthquakes in order to identify Structural Health Monitoring systems. The obtained features are further passed through an Artificial Intelligence algorithm that employs the K-Nearest Neighbor (KNN) algorithm for automated classification and detection of possible harm to the historical structures. Standard assessment is done on the proposed system in order to infer its validity. In conclusion, this paper discusses the inclusion of the AE monitoring, the GR law, and an AI-based classification technique to create an automated system to supervise the continuation of historical buildings' structures and prospective damage occurrences (Carnì et al, 2020).

4 The Challenges of IoT, Cloud, and AI in Heritage Buildings

Employing contemporary technologies like IoT, cloud computing, and AI for the conservation and monitoring of CH buildings might raise some specific challenges as follows:

4.1 Sensor Placement and Calibration

IoT sensor placement in historical structures requires skill to ensure coverage without damaging architectural features, reliability, accuracy, and calibration for accurate data acquisition (Soleymani et al, 2023).

4.2 Data Management and Storage

CH buildings' sensors and hardware generate extensive data, necessitating efficient and robust data management techniques for processing, archiving, and processing in cloud environments (Diène et al, 2020).

4.3 Historical Context and Interpretation

Integrating CH buildings' factors into AI algorithms may be challenging, requiring multiple disciplines' input to balance practical and scientific conservation approaches with acceptable equity(Dwivedi et al, 2020)

4.4 Environmental and Structural Monitoring

The Consolidated Hall buildings necessitate regular monitoring of environmental conditions such as temperature, humidity, air quality, and structural performance (Rossi, 2023)

4.5 Cybersecurity and Data Protection

CH buildings must implement robust cybersecurity measures to protect sensitive data from cyber threats, hacking, and unauthorized access, including IoT devices, cloud platforms, and AI algorithms (Talal et al, 2019)

5 The Latest Trends in Contemporary Technology for the Preservation of Heritage Buildings

Several emerging trends are shaping the use of IoT, cloud computing, and AI for the conservation of the CH building.

5.1 Edge Computing

A digital twin is a virtual replica of an actual object, like CH buildings, using IoT data for accurate monitoring, analysis, and maintenance (Mughaid et al, 2020).

5.2 Digital Twins

A digital twin is a virtual replica of an actual object, like CH buildings, using IoT data for accurate monitoring, analysis, and maintenance (Pylianidis et al, 2021)

5.3 AR and Virtual Reality (VR)

AR and VR solutions enhance CH conservation and education by creating an immersive environment, overlaying historical information, restoration plans, and interactive exhibitions, providing a more engaging and informative experience (Tang et al, 2022).

5.4 Machine Learning for Image Analysis

Deep learning models are increasingly utilized for analyzing images, identifying artifacts, assessing damage, and developing restoration programs, aiding conservationists in interacting with vast visual data (Gaber et al, 2023).

5.5 Predictive Analytics for Risk Assessment

AI systems use past and real-time data from IoT sensors to assess potential dangers to CH buildings, enabling conservationists to target areas of threat early for immediate protective measures (Alotaibi, 2023)

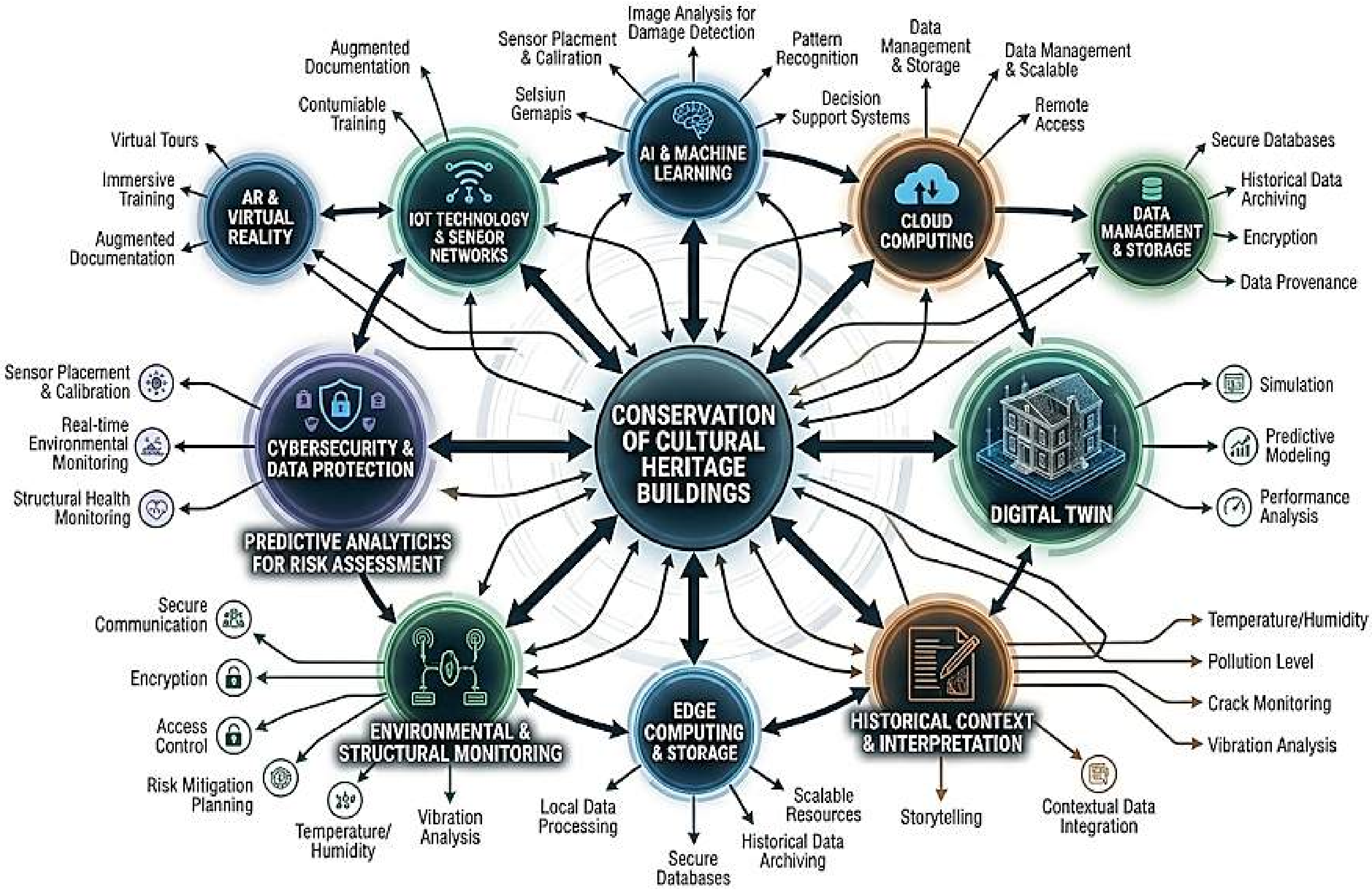

Figure 3: Integration of Modern Technologies in the Conservation of Cultural Heritage Buildings.

Figure 3 illustrates the incorporation of contemporary digital technologies in the preservation of cultural heritage buildings.

6 Conclusion

Modern technologies like IoT, cloud computing, and AI can significantly enhance the preservation and conservation processes of CH buildings. This work highlights the benefits of IoT systems and cloud technologies in managing heritage structures, including monitoring, documentation, restoration, and public awareness. IoT systems detect potential problems, enabling early intervention, while cloud technologies enable high-accuracy restoration and real-time monitoring, ensuring timely maintenance and longevity. AI and ML models are being utilized in heritage structure conservation to predict mechanical breakdowns, enabling early corrective measures to maintain structural integrity and durability.

The work emphasizes the necessity of coordinated action by stakeholders, technology experts, and CH professionals to ensure the systematic incorporation of contemporary technologies in CH buildings while considering practical difficulties and ethical questions.

As the concept of heritage preservation progresses, it can be seen that IoT, cloud computing, and AI will be of great importance in the future preservation of such architectural marvels by enhancing ways of identification and celebration of the architectural masterpieces for future generations.

7 Availability of Data and Materials

All information is included in this article.

8 Acknowledgement

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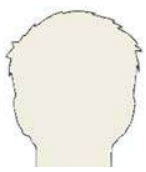

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