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3D As-Built Environments in Extended Reality Applications: A Systematic Review

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ABSTRACT

Accurate integration and navigation of real-world 3D spaces are fundamental for next-generation Extended Reality (XR) systems, enhancing immersion, utility, and fidelity. This paper systematically reviews XR workflows using PRISMA guidelines, focusing on 3D data acquisition, modeling, visualization, and user interaction, based on 96 journal publications. Data collection for XR relies on photogrammetry, RGB-D cameras, and LiDAR, often enhanced by multi-sensor fusion, although real-time transmission and semantic alignment remain challenging. XR pipelines are dominated by Building Information Modeling (BIM) software and game engines, frequently integrating Computer-Aided Design (CAD) models and 3D scanned data. Visualization varies from photorealistic renderings to schematic representations, with Virtual Reality headsets favored for training and Augmented Reality devices applied in inspection and navigation. Interaction paradigms encompass controllers, gestures, gaze, voice, and haptics, with increasing reliance on Artificial Intelligence for multimodal fusion and processing. Despite progress, key challenges persist, including bandwidth limitations, manual 3D modeling, hybrid data management, interoperability issues, and scarcity of open-source solutions. Additional identified barriers involve balancing visual quality with performance in specific contexts, limited accuracy of non-invasive Brain-Computer Interfaces, and restricted market acceptance due to high costs. Overall, XR adoption remains constrained by technical, usability, and accessibility gaps.

1 | Introduction

Extended Reality (XR), encompassing Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), has experienced rapid growth in recent years, because of advances in hardware and software. The global XR market was valued at approximately $189 billion in 2024 and is projected to surpass $1000 billion in 2030 (Procedence Research 2025). Beyond videogames and entertainment, XR technologies are being utilized for training scenarios, human-machine collaboration, and digital twins, enabling seamless interaction with real and simulated environments (Coupry et al. 2021; Kintu and

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Abbreviations: AEC, architecture, engineering, and construction; AI, artificial intelligence; AR, augmented reality; ASR, automatic speech recognition; AV, augmented virtuality; BCIs, brain-computer interfaces; BIM, building information modeling; CAD, computer-aided design; DCC, digital content creation; DoF, degrees of freedom; FoV, field of view; GNSS, global navigation satellite system; HCI, human–computer interaction; HMD, head mounted display/device; HRTF, head-related transfer function; ICP, iterative closest point; IFC, industry foundation classes; IMU, inertial measurement unit; IoT, internet of things; LiDAR, light detection and ranging; MFCC, mel-frequency cepstral coefficients; MR, mixed reality; NeRF, neural radiance fields; NLU, natural language understanding; RGB-D, red green blue depth; SDKs, software development kits; SfM, structure from motion; SLAM, simultaneous localization and mapping; TSDF, truncated signed distance functions; UWB, ultra-wideband; VIO, visual-inertial odometry; VR, virtual reality; XR, extended reality.

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Extension 2024; Lampropoulos et al. 2022). Recent technological breakthroughs have significantly expanded the potential of XR beyond its initial applications. Among the most transformative advances are high-resolution passthrough capabilities, enabling seamless Mixed Reality (MR) experiences that merge digital and physical worlds (Banquiero et al. 2024); hand tracking interfaces, which reduce reliance on controllers and allow more natural human–computer interaction (HCI) (Heo et al. 2024); eye tracking combined with foveated rendering, optimizing performance while supporting novel interaction paradigms (Aalto and Steinert 2025); and enhanced scene understanding, which empowers XR systems to recognize, map, and semantically interpret real environments (Chou et al. 2024). These innovations not only reinforce the economic relevance of XR by unlocking new markets and applications, but also highlight the growing importance of accurately integrating and navigating 3D spatial environments, where the fusion of virtual and real elements becomes the foundation for next-generation interactive systems (Giannini et al. 2022; Liu, Ding, et al. 2024; Zhang et al. 2023).

The usefulness of XR, particularly in professional, industrial, and scientific applications, is often realized through the accurate representation of real-world assets and spaces (F. Zhu et al. 2025). The incorporation of real-world 3D models and environments is crucial for grounding XR applications in tangible reality, which enhances immersion, increases utility, improves understanding, and ensures the fidelity required for critical tasks such as infrastructure inspection, facility management, safety training, and precise design reviews (Annabestani et al. 2024). Creating and deploying these real-world 3D environments is inherently complex, demanding expertise from diverse domains, including 3D scanning techniques (e.g., LiDAR, photogrammetry), information modeling via Building Information Modeling (BIM) or Computer-Aided Design (CAD), integration of geospatial data with Geographic Information Systems (GIS), artistic 3D modeling, computer graphics, and specialized software development (Levy and Liu 2023; Rosati et al. 2024). This interdisciplinary nature underscores the technical sophistication of the methods and the wide variety of software tools involved, while the rapid evolution of these technologies makes a systematic review of current practices both timely and essential for guiding future research and development.

The role of 3D space in XR varies across Virtual Reality (VR), Augmented Reality (AR), and MR (Skarbez et al. 2021). In VR, users are fully immersed in digitally generated 3D worlds, where realistic rendering, intuitive navigation, and natural interaction are critical, supported by accurate spatial tracking, object occlusion, and depth perception (Dwivedi et al. 2022). AR overlays digital elements onto the real world, requiring precise pose tracking and environment-aware rendering to integrate virtual and physical elements, though dynamic content adjustment remains a challenge that can reduce immersion (L. Liu et al. 2023). MR, situated between VR and AR, merges real and virtual elements dynamically, demanding high-fidelity spatial interactions that adapt to real-world constraints (Rauschnabel et al. 2022). Across all XR forms, 3D immersion relies on reality capture sensors and ergonomic considerations to minimize discomfort, such as VR sickness caused by prolonged glasses or Head Mounted Display (HMD) use (Ferrão et al. 2023; Liu et al. 2023).

Despite the clear importance of 3D space in XR, there remains a lack of comprehensive studies focusing solely on the 3D environment surrounding XR devices, including perception, visualization, rendering, and interaction. Most research tends to explore XR from a hardware, application-based, or user-experience perspective without an in-depth analysis of how 3D space is constructed and optimized across XR environments (Davari and Bowman 2024). This gap in literature limits advancements in natural interaction paradigms, spatial tracking precision, and realistic rendering techniques, all of which are essential for enhancing user immersion (Giannini et al. 2022). This review aims to provide a focused discussion on the relevance of 3D space in XR, addressing the following Research Questions (RQ):

1. What techniques and technologies are effective for collecting 3D data to XR environments?
2. How are 3D data modeling pipelines and content types applied in XR applications?
3. What approaches visualize 3D data for enhanced understanding and immersion in XR environments?
4. How can users interact with 3D in XR systems?

The remainder of this paper is structured as follows. Section 2 compiles the related work, highlighting previous review studies. Section 3 presents the methodology for systematic search. Section 4 reports the main findings, including key results and observations derived from the analysis. Section 5 provides a discussion of current trends and future challenges. Finally, Section 6 concludes the paper.

2 | Related Work

Relevant research has been done on the uses of XR in the 3D environment, particularly in the AEC (Architecture, Engineering, and Construction) sector. The latest reviews published in recent years have been compiled in Table 1. In general, these works conclude that XR technologies, including AR/MR/VR, have proven effective for safety training, experiential learning, site inspection, and risk prevention. Numerous studies highlight XR's capacity to improve knowledge transfer, hazard recognition, and human performance (Casini 2022). Despite strong potential, XR research in the 3D environment focuses narrowly on safety, training contexts, and BIM.

However, while these studies demonstrate the benefits of XR in specific applications, the integration of 3D models in XR highlights ongoing challenges that limit broader practical adoption. Integration between XR and BIM has received increasing attention, though practical implementation remains limited. Challenges such as system interoperability, multiple BIM dimensional adoption, and poor real-time synchronization hinder widespread use. There is a lack of maturity models and evaluation tools specific to BIM-based XR applications; therefore, some reviews focus directly on bibliographic research compiling

TABLE 1 | A comparative analysis of review articles on XR in the 3D environment published in the last years.

Author	Technology	Category	Coverage start	Publication
Sidani, Matoseiro Dinis, et al. (2021)	AR	BIM	2013	2021
Casini (2022)	XR	Smart Building Operation and Maintenance	2018	2022
Schiavi et al. (2022)	AR/VR	BIM data flow	2010	2022
Z. Monla et al. (2023)	AR/VR	Maturity Evaluation BIM	2011	2023
AL-Dhaimesh and Taib (2023)	AR	Case studies in BIM design	2010	2023
Wang et al. (2023)	AR	BIM implementation	2000	2023
Amin et al. (2023)	AR	BIM	2010	2023
Muñoz-La Rivera et al. (2024)	XR	Security management	2010	2024
Rocha et al. (2025)	AR/VR	BIM education	2015	2024
Akindele et al. (2024)	VR	Construction health and safety	2010	2024
Bressan et al. (2024)	XR	Case studies in BIM	2016	2024

case studies (Bressan et al. 2024; Schiavi et al. 2022), while Casini (2022) focuses on market research.

XR applications have shown promise throughout the building lifecycle, especially in collaborative design, construction planning, maintenance, and energy optimization, with Unity, Revit, and ArchiCAD as dominant platforms. The effectiveness of XR is influenced by user factors like prior knowledge, cognitive load, and engagement. Each XR sub-technology has its own applications, and existing reviews may encompass all of them or focus on one. MR and AR facilitate real-time monitoring, retrofitting, and remote collaboration (Bressan et al. 2024). VR supports operation and maintenance through immersive simulations and human-centered interfaces (Akindele et al. 2024). The current work encompasses all XR and compares the application of AR/MR/VR.

Many research studies group XR-BIM interaction in stages: design, pre-construction, construction, operation and management (Sidani, Matoseiro Dinis, et al. 2021); or functions: positioning, interaction, visualization, collaboration, integration, and automation (Amin et al. 2023). However, to the best of the authors' knowledge, there is no state of the art that focuses on the data workflow (data collection, modeling, visualization/perception and interaction) proposed in this paper. This workflow encompasses the entire process from acquiring real-world data to delivering meaningful experiences to the end user. Each stage (collecting accurate spatial and semantic information, creating and integrating 3D models, visualizing data effectively to support perception, and enabling intuitive interaction) represents a critical component for ensuring the fidelity, usability, and effectiveness of XR applications across professional and scientific contexts.

3 | Methodology

To ensure reproducibility, transparency and quality, the PRISMA principles (Page et al. 2021) are followed in this work. The workflow of the study selection process, from identification in databases to final inclusion, is shown in Figure 1.

3.1 | Search Criteria

The literature review used SCOPUS as a bibliographic database. SCOPUS guarantees the quality of all its indexed publications (journals, conferences, book chapters, etc.). In addition, SCOPUS has advanced search tools, filters, and analysis of articles, as well as traceability in citations.

The keywords used in this review were divided into two sets. On the one hand, keywords that refer to 3D data or models and techniques for their generation. On the other hand, the focus was on XR-related technologies. To ensure a manageable number of articles, the search was limited to publication titles. The search performed was “(geospatial OR bim OR citygml OR 3d-scan OR point-cloud OR reality-model OR 3d-mapping OR lidar OR photogrammetry OR laser-scanning) AND (extended-reality OR mixed-reality OR augmented-reality OR virtual-reality OR xr OR mr OR ar OR vr)”.

3.2 | Screening, Eligibility, and Appraisal Criteria

The selection of articles was based on a sequence of filters. The first filters were those provided by the database. Articles included were published in English since 2021. Considering that XR technology is evolving rapidly, and several new commercial devices (AR glasses and VR headsets) are released every year, we considered that studying papers from the last four years represents a current use of XR technology.

Since the language-year filter returned 391 publications, to reduce the quantity and maintain the best quality, we opted to filter and include only journal articles. Of the remaining 163 journal articles, the subject area filter was applied to eliminate publications related to medicine, genetics, pharmacology, biology, chemistry, economics, finance, arts, etc. and preserve engineering, computer science, social sciences, mathematics, materials, energy, earth and planetary sciences, etc.

The last inclusion/exclusion criterion was based on an analysis of the quality of the remaining 120 journal articles, eliminating articles with low quality, previously unfiltered state-of-the-art reviews, retracted, and articles with no access. The final number of articles in the review was 96.

3.3 | Bibliometric Analysis

The search returned a total of 803 publications from 1994 to the present and with a notable increase from 2018. The oldest paper is from 1994 and mentions the conceptualization of the VR model (Latta and Oberg 1994). As for AR, the first publication dates from 1998 on the application in reality models (Klinker et al. 1998). In contrast, the first article that mentions MR in the title dates from 2008 (Pohl and Hoffmann 2008). Although the definition of MR is based on the Virtuality Continuum reality by Milgram and Kishino in 1994 (Milgram and Kishino 1994), that MR concept referred to encompass AR and Augmented Virtuality (AV), whereas today MR refers to a greater immersion of AR. Figure 2 shows the evolution of the number of publications of VR, AR, MR and XR.

VOSviewer (van Eck and Waltman 2010) was used for textual analysis, filtering publications in English from 2021 onwards. 391 publications (title and abstract) were loaded into VOSviewer, a specialized software employed in qualitative research and textual data analysis. VOSviewer counted the terms with more than 10 repetitions and generated three clusters (Figure 3). On the one hand, there is the cluster related to data (point cloud, image, 3D models), characteristics (feature, accuracy), and generation techniques (photogrammetry). Another cluster is related to BIM context (construction, engineering, management). Finally, the smallest cluster is related to education (students, participants, immersion, VR).

The analysis subject areas and countries of publication focused only on the 163 journal articles, whose quality will be manually evaluated later before a detailed review. Figure 4 shows the number of articles by subject area. The main subject areas of publication in XR are *Engineering* (30%) and *Computer Science* (23%), the same for all the technologies covered by XR: AR, VR and MR. However, there are slight variations in the rest of the subject areas. AR is more applied in *Medicine* (8%), *Materials Science* (7%) and *Physics and Astronomy* (6%), while VR is more

FIGURE 1 | PRISMA workflow.

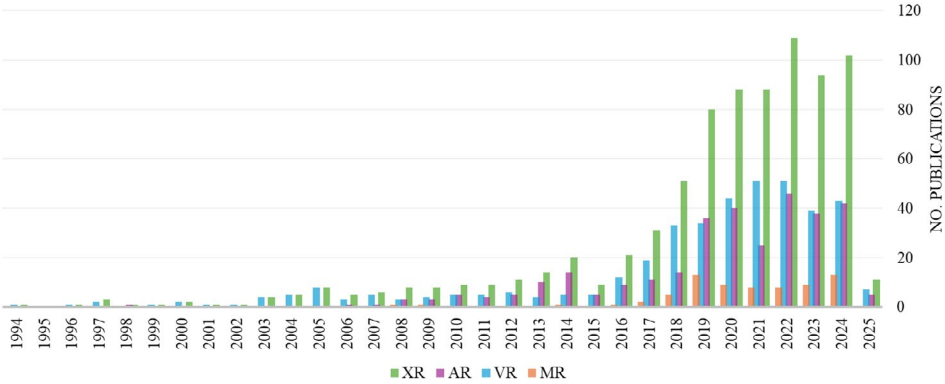

FIGURE 2 | Evolution of the number of publications according to search criteria.

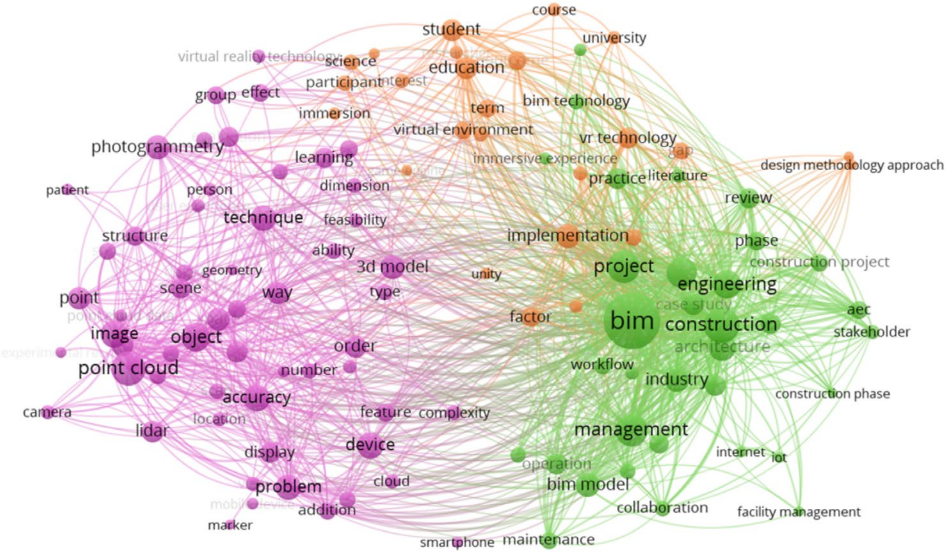

FIGURE 3 | VOSviewer Network analysis on terms contained in title and abstracts.

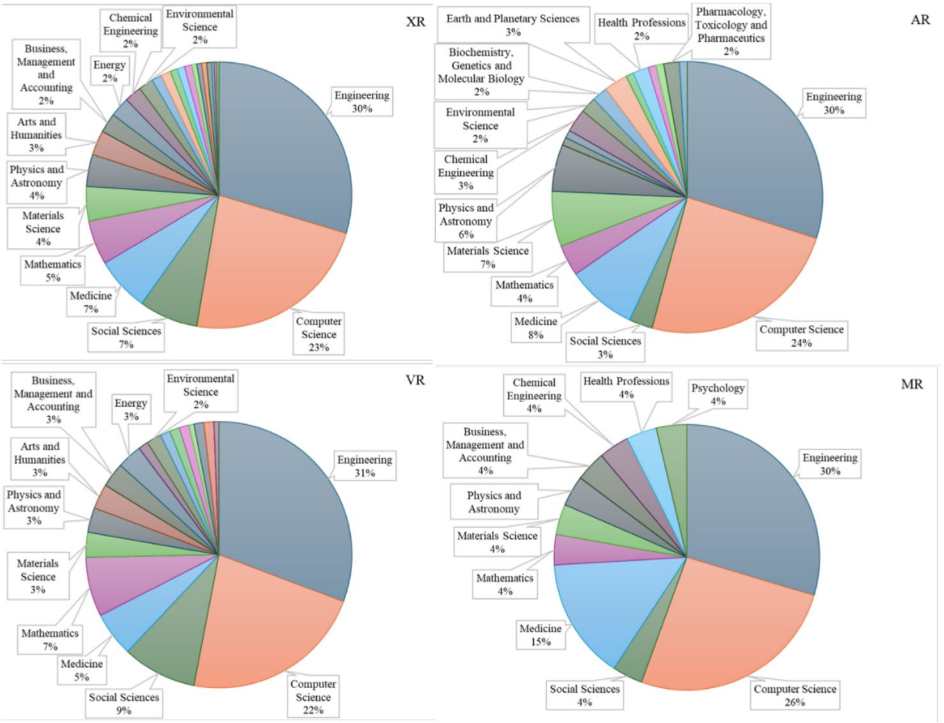

FIGURE 4 | Number of articles by subject area categorized under the terms XR, AR, VR, and MR.

relevant in *Social Science* (9%), *Mathematics* (7%) and *Medicine* (5%). The number of publications in MR is smaller and prevents drawing clear conclusions.

The journals with the highest number of publications are shown in Figure 5. The distribution reveals that *Automation in Construction* is the leading journal for research at the intersection of XR and 3D environments with 10 publications, followed closely by *Applied Sciences* and *Buildings*, each with 9 articles. Other relevant journals, such as *Smart and Sustainable Built Environment*, *Sustainability*, *Energies*, and *Drones*, also contribute significantly to the field, albeit with a lower frequency of three publications each.

The distribution of journal articles by country is shown in Figure 6. Most of the arithmetic published in the XR context belongs to China (24%), USA (14%), and South Korea (8%), although in the case of South Korea, the number of AR publications is greater than VR. The countries with the most publications in VR after China and the USA are Australia, France, and Italy. The number of publications in MR is smaller and prevents drawing clear conclusions. The institutions with the most articles published in XR are Politecnico di Milano (6 articles), Chinese Academy of Sciences (5 articles), and University of Tehran (4 articles). Considering the total number of articles analysed, this maximum number of publications per institution indicates that there is no clear hegemony of one institution over the others.

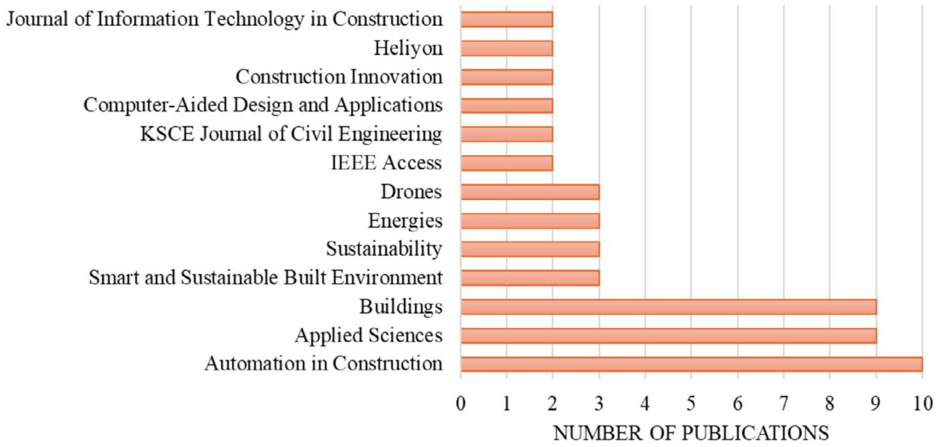

FIGURE 5 | Bibliometric distribution of publications across leading journals.

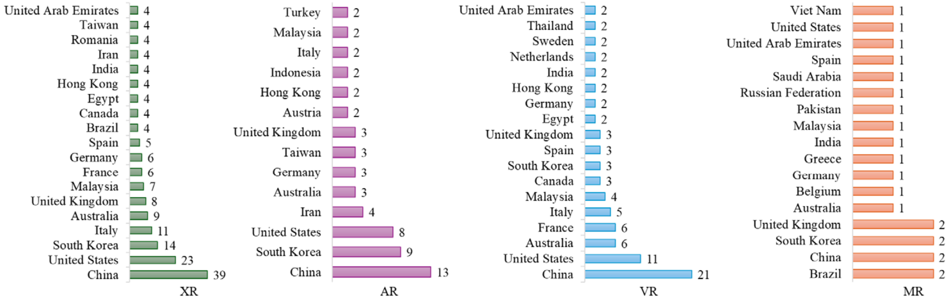

FIGURE 6 | Distinction between countries in the XR context.

3.4 | Research Constraints Overview

The primary limitations of this literature review stem from the scope and sources of the analysed publications. A concise search string was employed to capture a broad spectrum of relevant studies aligned with the research objectives; while this approach ensures focus and reproducibility, it may omit some relevant work that uses alternative keywords. SCOPUS was selected as the primary database due to its comprehensive quality assurance and advanced analytical capabilities. Although there are overlaps with other databases, articles from Web of Science and Google Scholar may be omitted. In addition, the review was based solely on academic publications, excluding information from private companies and other industry sources. The focus on journal articles was maintained to ensure the highest research quality and manageable scope in this rapidly advancing field, but unfortunately several papers published in leading computer science conferences (such as CVPR, ICCV, etc.) were excluded too.

4 | Findings

4.1 | What Techniques and Technologies Are Effective for Collecting 3D Data to XR Environments?

Data acquisition in XR involves capturing geometric, textural, and positional data from the physical environment or generating synthetic models for virtual spaces. This section provides a comprehensive overview of data acquisition and collection methodologies in XR, addressing data types, multi-sensor fusion, and dynamic environment processing.

4.1.1 | Data Collection

Data collection methods for XR can be broadly classified into passive and active sensing (Qiu et al. 2023). Passive sensing relies on sensors like RGB cameras to capture ambient light, while active sensing, including LiDAR and RGB-D cameras, emits energy to directly measure depth and position.

RGB cameras serve as fundamental passive data collection tools, capturing multiple overlapping 2D images to record the visual appearance of an environment (Baron et al. 2024; de Oliveira et al. 2022; Drofova et al. 2023; Kalacska et al. 2021; Stanga et al. 2023). It is cost-effective and versatile, widely used to capture source data for cultural heritage preservation, virtual tourism, and game asset creation. High-quality images yield detailed, textured 3D models when subsequently processed through reconstruction pipelines like photogrammetry or Structure from Motion (SfM), but data collection performance depends on lighting, field of views (FoVs), and extensive image overlap, with large datasets requiring significant computational resources during the reconstruction phase (Banfi and Previtali 2021; Wu et al. 2023).

RGB-D cameras (e.g., Microsoft Kinect, Intel RealSense) capture color and depth data simultaneously, enabling real-time 3D reconstruction for AR/VR applications like environmental mapping and gesture recognition in devices such as Microsoft

HoloLens 2 (Lee et al. 2024; Navares-Vázquez et al. 2025). These affordable, portable devices balance data richness and speed but are limited by short depth ranges and noise in bright or outdoor conditions.

LiDAR employs laser pulses to generate precise point clouds, excelling in large-scale applications like urban planning, industrial modeling, and digital twins (Becker et al. 2024; Kalacska et al. 2021; Papadopoulou and Papakonstantinou 2024). Its high accuracy and reliability across lighting conditions make it ideal for complex geometries, though it involves costly equipment and large data volumes requiring efficient management (Casado-Coscolla et al. 2023; Wu et al. 2023).

Complementary sensors, such as Inertial Measurement Units (IMUs), Global Navigation Satellite System (GNSS), and Ultra-Wideband (UWB) systems, enhance XR systems by providing positional and orientation data (Evangelidis et al. 2021). IMUs support head tracking and motion capture, while GNSS and UWB systems enable absolute positioning in outdoor or large indoor settings. These sensors improve robustness when integrated with primary methods but are limited by environmental interference and reliance on other systems.

Table 2 summarizes and contrasts the key data acquisition methods and sensors in terms of principles, advantages, limitations, and typical applications. Each method addresses specific XR needs, with trade-offs in cost, accuracy, and environmental adaptability.

4.1.2 | Data Representations in XR Systems

Data representations in XR are critical for creating immersive virtual environments, each tailored to specific applications. This section examines several key representation types, including meshes, volumetric grids, and advanced radiance-based formats, highlighting their characteristics and use cases.

CAD and Building Information Modeling (BIM) models are structured mesh representations with semantic geometry and parameterized topology, widely used in architecture, engineering, and construction (AEC) (Abouelkhier et al. 2024; Addy et al. 2023; Alhady et al. 2024; Banfi and Previtali 2021; Lee et al. 2024; Liu, Liu, and Chen 2024). Created in software like Revit and exported as FBX or IFC formats, they support design visualization, virtual inspections, and collaborative workflows in XR environments, optimizing construction planning and maintenance (Alijani Mamaghani and Noorzai 2023; Martins et al. 2024; Panya et al. 2023; Rashidi et al. 2022; Yu et al. 2022).

Generic Meshes consist of triangular polygons without semantic topology, offering versatility for XR applications such as gaming, digital assets, and cultural heritage visualization (de Oliveira et al. 2022; Stanga et al. 2023). Generated via photogrammetry, 3D scanning, or manual modeling, these meshes can be textured for enhanced realism and are ideal for rapid asset creation where complex semantic data is unnecessary (Drofova et al. 2023; Kalacska et al. 2021; Yasin Yiğit and Uysal 2025).

TABLE 2 | Comparison of data collection methods and sensors.

	Principle	Advantages	Limitations	Typical applications
RGB cameras	Captures 2D image sequences (requires external processing for 3 D)	Low cost; flexible scales; detailed textured models	Sensitive to lighting/textures; does not measure depth directly	Cultural heritage; virtual tourism; games
RGB-D cameras	Captures RGB color and depth data	Real-time; integrated data; affordable/portable	Limited depth range; noise in bright/outdoor conditions	AR/VR mapping; gesture recognition
LiDAR	Laser-based distance measurement	High accuracy; fast for large areas; robust in lighting	Expensive; large data volumes	Urban planning; industrial modeling; digital twins
Other sensors (IMUs, GNSS, UWB)	Positional/orientation data	Enhances accuracy; supports integration; outdoor usability	Not standalone; environmental interference	Head tracking; motion capture; large-scale positioning

TABLE 3 | Comparison of 3D representations.

Representation	Structure	Advantages	Limitations	Typical applications
CAD/BIM models	Semantic geometry, parameterized topology	Structured data; supports collaborative workflows; precise for AEC	Complex creation; software-specific formats	Architecture; construction planning; virtual inspections
(Generic) Meshes	Triangular surfaces	Versatile; rapid asset creation; easily textured	Less suited for complex workflows	Gaming; digital assets; cultural heritage
Volumetric, Neural, and Gaussian Representations	Voxel grids, continuous neural networks (MLPs), or explicit 3D Gaussian primitives	Robust to noise; photorealistic rendering; high-fidelity visualization	Computationally intensive; requires advanced hardware	Virtual tourism; large-scale rendering

Volumetric, Neural, and Gaussian Representations encompass several advanced data structures for scene reconstruction. Volumetric representations, such as Truncated Signed Distance Functions (TSDF), encode surface distances in voxel grids to provide robust, dense scene reconstruction resilient to sensor noise (Casado-Coscolla et al. 2023). More recent advanced data structures include continuous neural implicit representations, which use multi-layer perceptrons (MLPs) to store spatial radiance and volume density, and explicit 3D Gaussian primitives, which parameterize the scene using a collection of anisotropic continuous volumetric particles (Rossoni et al. 2023; Lim et al. 2022; Zhang et al. 2022). These novel representation formats deliver photorealistic rendering for high-fidelity XR applications like virtual tourism and large-scale environment visualization.

Table 3 compares these representations in terms of structure, advantages, limitations, and applications.

4.1.3 | Multi-Sensor Integration for Enhanced XR Data Acquisition

Multi-sensor fusion addresses the limitations of individual sensors including noise, drift, and environmental interference. Recent studies indicate that, especially in dynamic or GNSS-denied environments, robust 3D scene understanding and spatial perception rely heavily on these hybrid approaches (Becker et al. 2024; Shih et al. 2021).

Fusion of RGB images and IMU data enables real-time pose estimation of devices, offering robust tracking in dynamic or low-texture environments. VIO leverages high-frequency inertial motion cues to compensate for ambiguities in visual tracking, making it foundational for AR (Wu et al. 2023). In practical applications, RGB + IMU fusion is widely adopted for indoor point cloud segmentation and intelligent inspection in construction. By combining IMU-derived pose correction with RGB image features, this approach achieves accurate point cloud segmentation and virtual object localization. Results demonstrate enhanced segmentation accuracy in complex indoor scenes, with particularly strong performance in low-texture areas. Furthermore, aligning real-world imagery with BIM models through RGB-IMU fusion significantly reduces drift. While this strategy provides low computational overhead and strong resilience to rapid movements, it still faces challenges in illumination variability and real-time processing on embedded platforms (Liu, Liu, and Chen 2024).

Fusing RGB-D sensing with IMU data allows for the simultaneous capture of dense geometry and motion cues, making this approach highly suitable for indoor mapping, defect detection, and progress monitoring in XR applications. Depth cameras provide pixel-level distance measurement, while the IMU supplies high-frequency dynamic compensation, enabling stable tracking even with occlusion or motion blur. Studies have shown that registering point clouds and depth information with BIM models yields precise 3D reconstruction and real-time inspection, which is especially advantageous for spatial alignment of complex components. The strengths of this fusion approach lie in its high-fidelity reconstruction and robust occlusion handling (Liu, Liu, and Chen 2024; Shih et al. 2021). However, it entails increased power consumption and higher requirements for precise sensor calibration.

Fusion of LiDAR and RGB modalities supplies XR applications with high-precision depth and rich texture information, excelling in city-scale, industrial, and large indoor–outdoor scene modeling (Becker et al. 2024; Chi et al. 2022). In this process, sparse yet accurate LiDAR point clouds are aligned with dense RGB imagery to produce high-quality 3D models containing both geometric and color attributes (Kalacska et al. 2021). Recent studies highlight that cloud–edge–client architectures for point cloud XR benefit significantly from LiDAR–RGB fusion, yielding improved scene fidelity and supporting multi-user immersive collaboration. The advantages of this approach include robust adaptation to lighting and scale changes as well as enhanced long-range perception. However, significant drawbacks include the high cost of LiDAR hardware, the complexity of rigorous spatial–temporal calibration between distinct sensors, and the immense computational burden of synchronizing and processing large datasets for real-time rendering.

Integrating UWB or GNSS with VIO provides XR systems with absolute positioning, effectively reducing cumulative drift in large-scale or long-duration tasks. This fusion method leverages high-frequency visual-inertial updates with global references from UWB or GNSS, making it suitable for outdoor mapping, construction sites, and mobile robotics where stable tracking is essential. Empirical evidence demonstrates that, in geovisualization systems combining UAV LiDAR with virtual reality, GNSS-assisted VIO achieves low-drift registration of large-scale point clouds. Additionally, joint fusion of point clouds, VIO, and GNSS establishes the technical foundation for seamless navigation across indoor–outdoor environments. The advantages of this strategy are strong positional consistency and outage resilience. Nevertheless, notable limitations exist: GNSS signals are highly susceptible to multipath effects and signal degradation in indoor or dense urban environments, while UWB deployment requires time-consuming manual installation and calibration of infrastructure anchors. Furthermore, integrating these disparate data sources demands sophisticated filtering algorithms, which exacerbates computational scalability issues on mobile XR devices.

4.1.4 | Real-Time Processing Techniques for Dynamic XR Environments

Dynamic environments in XR are scenes with continuous changes like moving objects, varying lighting, or user interactions. Dynamic environment processing is vital for real-time scene updates and multi-user collaboration in XR (Shahinmoghadam et al. 2021; Wang et al. 2022).

One major approach is volumetric fusion using the TSDF, which incrementally fuses each incoming depth frame into a global voxel grid to produce a smooth, high-density 3D surface model in real time. This method, exemplified by the KinectFusion system, enables accurate dense reconstruction of static scenes using commodity depth cameras (Newcombe et al. 2011). Extensions such as DynamicFusion further allow non-rigid scene reconstruction by estimating a dense volumetric 6-DoF motion field that warps the fused model to align with live sensor input. Like KinectFusion, DynamicFusion continuously refines the model as new measurements arrive and updates the displayed scene accordingly (Newcombe et al. 2015). TSDF-based fusion techniques are robust to sensor noise due to frame-wise averaging but are susceptible to ghosting artifacts or blurring when objects move rapidly, as motion geometry may be smeared across frames (Lee et al. 2024).

Another important method is BIM-to-scan deviation detection, which aligns real-time point cloud scans with pre-existing Building Information Models (BIM) to identify geometric discrepancies (Martins et al. 2024; Tan et al. 2024). The process typically involves coarse initial localization—using feature matching or approximate pose estimation—followed by precise registration through algorithms such as Iterative Closest Point (ICP). Subsequently, deviation analysis based on point-to-model distance highlights the spatial mismatches between as-designed and as-built components. This approach supports automated construction quality control and digital twin maintenance by detecting structural deviations or omissions. However, it is computationally intensive and highly dependent on the accuracy of the input scan data. Field-deployed workflows are often time-consuming and manual, which limits the feasibility of real-time analysis without algorithmic optimization.

A third category focuses on efficient point cloud streaming for multi-user XR. Point cloud soft multicast combined with edge compression has been developed to address bandwidth and latency challenges in delivering dense 3D content to multiple clients simultaneously (Casado-Coscolla et al. 2023). In this framework, point cloud data is adaptively partitioned by spatial tiling or level of detail, and compressed at the edge or server to match each user's network conditions. Critical coarse scene content is delivered first to all users, with finer details layered progressively for clients with sufficient bandwidth (Fan et al. 2023). This ensures consistent shared environments while maintaining low latency, avoiding the “cliff effect” where a single weak client degrades the global experience. The trade-off is increased system complexity, as this method requires advanced encoding strategies, graph-based compression, and dynamic transmission scheduling (Ueno et al. 2023).

4.2 | How Are 3D Data Modeling Pipelines and Content Types Applied in XR Applications?

4.2.1 | 3D Content Generation Pipelines and Software Tools

Out of the 96 selected papers, 59 describe a 3D data modeling pipeline as part of their research methodology. Across these works, the reported pipelines reveal a diverse array of software solutions (Figure 7). Due to varying levels of methodological detail across the selected papers, the underlying 3D content generation methods appear highly fragmented. A substantial portion of studies (39 out of 59) focus on the integration of BIM data into XR applications (Garbett et al. 2021; Martins et al. 2024; Zhou et al. 2024).

Analyzing reported software tools highlights several dominant categories where BIM authoring and coordination software, most notably Autodesk Revit, forms a cornerstone of many XR pipelines. Complementary tools are used for more general modeling tasks, including Digital Content Creation (DCC) software such as Autodesk 3ds Max and Blender, as well as CAD suites like Autodesk Navisworks and AutoCAD, which support model optimization and editing (Alirezaei et al. 2022; Banfi and Previtali 2021; Rossoni et al. 2023; Shekargoftar et al. 2022). Specialized data types often require dedicated solutions, for instance, generating 3D point cloud and textured mesh data with photogrammetric modeling software such as Agisoft Metashape (Banfi and Previtali 2021), Autodesk ReCap (Martins et al. 2024), and Bentley ContextCapture (Yasin Yiğit and Uysal 2025), or analyzing geospatial datasets with toolsets such

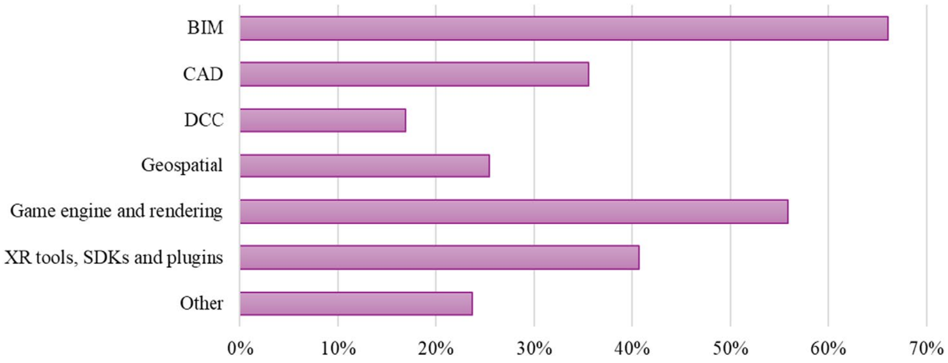

FIGURE 7 | Percentage of mentions among selected papers for each software tool category.

as ESRI ArcGIS (Papadopoulou and Papakonstantinou 2024) and CloudCompare (Kalacska et al. 2021).

Game engines can be identified as essential tools for XR development, serving as both application platforms and end-user environments in combination with XR devices such as HMDs (Barros-Sobrín et al. 2024; Chen et al. 2024; Conde et al. 2025, 5; Potseluyko et al. 2022; Shahinmoghadam et al. 2021). Among the surveyed literature, Unity emerged as the most frequently adopted platform (44%), followed by Epic Games Unreal Engine (8%). Both engines are accessible through free-tier licensing, which reduces entry barriers, though neither is fully open source. Their extensive ecosystems and developer communities contribute to their dominance in XR applications. Furthermore, various game engine-related and real-time rendering-based plugins and tools, including Enscape, Fuzor, IrisVR, and Twinmotion, are used especially to enhance data interoperability, interactivity, and visualization capabilities with data such as BIM models (Alhady et al. 2024; Alizadehsalehi et al. 2021; Zhou et al. 2024). In contrast, only two studies reported the use of web-based libraries and frameworks, such as Three.js (Evangelidis et al. 2021).

Beyond game engines, many XR applications involve the development of custom components using common programming languages such as the reported C, C# and Python. As well as the use of various AR/VR Software Development Kits (SDKs) such as ARCore and ARkit (Alirezaei et al. 2022).

4.2.2 | Utilizing Real-World 3D Models in XR Applications

The reviewed literature demonstrates a broad spectrum of 3D model content used to represent real-world environments and spaces. Reflecting the reported content pipelines, a significant majority (41 out of 59) rely on BIM models. These models encompass diverse domains, such as bridges (Alhady et al. 2024), multi-storey building structures (Abouelkhier et al. 2024), building interiors (Shahinmoghadam et al. 2021), transportation infrastructure such as metro stations (Chen et al. 2024), and utility networks such as gas pipelines (Shekargoftar et al. 2022).

Alongside BIM, many XR applications incorporate 3D scanned data. Examples include laser-scanned point clouds of road environments (Skirnewskaja et al. 2024), large urban scenes (Casado-Coscolla et al. 2023), and bridges (Martins et al. 2024), as well as 3D mapping outputs such as topographic models and textured meshes of natural environments (Kalacska et al. 2021; Papadopoulou and Papakonstantinou 2024).

Several studies combine different types of 3D content. For example, Evangelidis et al. (2021) integrate 3D scanned environments with synthetic objects, while Lee et al. (2024) combine synthetic BIM models with point clouds acquired with a Mixed Reality headset.

In addition to BIM and 3D scanned models, XR applications are often enriched with complementary data such as orthomosaics (Papadopoulou and Papakonstantinou 2024), thermal imagery (Shahinmoghadam et al. 2021), GIS vector layers (Shekargoftar et al. 2022), and real-time IoT sensor streams (Banfi et al. 2022; Chen et al. 2021; Shahinmoghadam et al. 2021).

The reviewed publications also highlight differences in the intended nature of 3D models. Photorealistic models aim to replicate the physical world with high visual accuracy, typically achieved through textured meshes. These models provide highly immersive experiences, making them valuable for simulations, virtual tours, and detailed inspections that require strong contextual realism. By contrast, information models emphasize semantic attributes, relationships, and metadata rather than visual fidelity. BIM models exemplify this category, containing information on components, materials, costs, and schedules, which support analysis, querying, and decision-making. Among the 59 studies, 25 (42%) reported modeling approaches with a clear focus on photorealism, while 43 (73%) emphasized semantic or conceptual data. Nevertheless, the boundary between photorealistic and information-driven models is often blurred, as many pipelines employ elements of both approaches.

4.3 | What Approaches Visualize 3D Data for Enhanced Understanding and Immersion in XR Environments?

4.3.1 | XR Devices Used for Visualization

Among the over 60 visualization-relevant studies surveyed, visualization hardware clusters into three main families: VR head-mounted displays (HMD), handheld or wearable AR displays, and non-standard displays. The largest proportion deploys VR

HMD: tethered systems such as the HTC Vive and Valve Index dominate safety-training and design scenarios (Hao et al. 2021; Papadopoulou and Papakonstantinou 2024; Rashidi et al. 2022; Zhou et al. 2024), while stand-alone units like the Meta Quest 2 are favored where cable-free is critical, e.g., for classroom use (M. Bagher et al. 2023). Approximately one-third of the papers rely on handheld or wearable AR displays: smartphone-based AR, leveraging ARCore or ARKit, underpins most on-site inspection, emergency navigation applications (Ahn et al. 2024; Song et al. 2023; Valizadeh et al. 2024), whereas optical see-through headsets such as Microsoft HoloLens 2 and Nreal Light appear in defect management for construction inspections (May et al. 2022), remote collaboration (Sun and Qiao 2022), and spatial cognition studies (Wang et al. 2025, 2024). The remaining studies investigate specialized or experimental XR setups. Examples include a 4K spatial-light-modulator head-up display for automotive assistance (Skirnewskaja et al. 2024) and a soft-multicast testbed that streams real-time point-cloud video to untethered headsets for edge-computing research (Ueno et al. 2023).

4.3.2 | Application Scenarios of XR Visualization

The applications cover three principal domains. First, the building life-cycle, i.e., planning, construction, and operation, dominates the surveyed studies. Immersive BIM/IFC walk-throughs are used to appraise design alternatives or analyze wind comfort (Gan et al. 2022; Hao et al. 2021; Panya et al. 2023). During construction, interactive job-site simulators and AR overlays, which visualize schedule progress or highlight dimensional deviations, support both safety training (Abotaleb et al. 2023; Abouelkhier et al. 2024) and real-time production control (Chi et al. 2022; Hsieh et al. 2023). In the operational phase, mixed-reality guidance is coupled with spatial data for bridge defect logging (Martins et al. 2024) and subsurface-pipeline visualization (Shekargoftar et al. 2022). Second, cultural-heritage digitization and public engagement employ immersive VR exhibitions of historic building models or photogrammetric reconstructions (Banfi and Previtali 2021; Stanga et al. 2023) and in situ AR overlays that resurrect historical events and artifacts on their original sites (Shih et al. 2021). Third, environmental and risk visualization leverages volumetric flood scenarios and semantically segmented urban point clouds to support hydrological planning (Papadopoulou and Papakonstantinou 2024; Rydvanskiy and Hedley 2021).

These studies show a clear link between what is visualized and how closely it is rendered. When the aim is to show fine surface details (such as the texture of embankments, areas of rivers, or historic façades), researchers keep the models photorealistic, using full-color point clouds or meshes with textures (Banfi and Previtali 2021; Papadopoulou and Papakonstantinou 2024). By contrast, tasks that require quick and clear communication (such as progress checks, deviation alerts, or evacuation guidance) often simplify the same BIM geometry into basic solids, bright icons, or flat arrows (Ahn et al. 2024; Chi et al. 2022). Depending on the purpose, a single IFC model can be rendered either as a high-detail design visualization or as a minimal schematic representation. A more recent trend combines both approaches, layering heat maps, defect reports, or IoT sensors over textured models to deliver visual realism alongside task-relevant information (Chen et al. 2024; Sun and Qiao 2022).

4.4 | How Can Users Interact With 3D Data in XR Systems?

4.4.1 | Technical Framework of Interaction Dimensions

The effective realization of immersive interaction across XR domains relies on technical frameworks centered on data capture, transformation, and feedback generation. These frameworks process user/environmental data streams through domain-specific pipelines to enable bidirectional communication, with significant methodological evolution driven by advances in sensing, AI, and spatial computing evident in recent literature.

Gestural and limb interaction centers on capturing and interpreting spatial body movement data. Mobile AR utilizes 2D touchscreen swipe data for simple commands (Zhang et al. 2025). In contrast, 3D spatial gestures and full-body interactions rely on richer sensor streams, such as inertial measurement unit (IMU) data tracking limb orientation or computer vision-derived skeletal joint position data. The core data manipulation involves: filtering noisy sensor inputs, segmenting gesture sequences from continuous motion, and applying machine learning models (e.g., CNNs, RNNs) to classify specific gestures or reconstruct accurate body poses in real-time (Zhang et al. 2024). This evolution enables markerless tracking for applications like BIM-guided assembly synchronization (Lee et al. 2024) and safety gesture recognition (Abotaleb et al. 2023).

Visual interaction systems transform gaze vectors and scene geometry into behavioral insights. Key data manipulations include: compensating for head movement, calculating point-of-regard on virtual surfaces, detecting fixations and saccades, and inferring user attention or cognitive load. Eye tracking captures high-frequency gaze coordinate data (e.g., pupil position) using infrared cameras, and can correlate it with object coordinates (e.g., BIM) (Kamari et al. 2021), enabling the generation of attention heatmaps for design validation (Kim et al. 2021). Light field rendering now synthesizes depth-adaptive focal data using LiDAR-scanned point clouds (Casado-Coscolla et al. 2023), allowing natural inspection of utility pipeline hierarchies (Shekargoftar et al. 2022) without visual fatigue.

Speech and auditory interaction processes audio waveforms into semantic commands and spatial soundfields. Voice interaction captures raw audio waveform data via microphones, with critical data manipulations encompassing: noise suppression in challenging environments (e.g., construction sites), Mel-Frequency Cepstral Coefficients (MFCC) feature extraction, Automatic Speech Recognition (ASR) conversion to text data, and Natural Language Understanding (NLU) intent derivation via cloud-AI pipelines (Zhang et al. 2025). Spatial audio synthesis dynamically maps head pose vectors (from IMUs) to Head-Related Transfer Function (HRTF)-processed binaural streams, updating interaural time/level differences in real-time to generate 3D soundscapes. This creates immersive navigation cues for emergency scenarios (Valizadeh et al. 2024) and enhances situational awareness in safety training (Abotaleb et al. 2023).

Haptic and force feedback interaction centers on sensing touch/force data and generating corresponding tactile or kinesthetic feedback signals. Devices like haptic gloves capture pressure distribution data or finger joint angles and manipulate arrays of actuators to synthesize spatially and temporally varying tactile sensation data on the skin, simulating textures or contact events. The core manipulation involves precisely mapping virtual object properties (stiffness, texture) and interactions (collisions) to appropriate feedback signals (Martins et al. 2024) and creating the illusion of manipulating physical objects, such as feeling the resistance when lifting a rebar (Chi et al. 2022). Force feedback devices detect the forces users exert and use motors or responsive materials to create opposing resistance forces, enabling virtual prototyping of structural components with authentic mechanical feedback (Al Mashhadany et al. 2024).

4.4.2 | Interaction Paradigms Classified by Technology Type

The core interaction mechanisms across VR, AR, MR, and XR are defined by their technological foundations, shaping how users perceive and manipulate digital-physical environments. This section delineates these paradigms through their distinct data capture and feedback modalities.

VR technology achieves immersive experiences through fully virtual environments, with interaction relying on hardware tracking and feedback systems. Controller-based systems utilize 6DoF positioning for virtual object manipulation, while haptic modules simulate tactile feedback (Martins et al. 2024). Controller-free interaction employs computer vision for real-time gesture capture, enabling lightweight operations in educational contexts (Abouelkhier et al. 2024). Advancements in markerless tracking now enable sensor-free limb motion capture through embedded cameras (Lee et al. 2024).

AR interaction integrates real-world environment recognition with virtual information manipulation. Mobile implementations depend on computer vision techniques like SLAM algorithms for spatial anchoring (Zhang et al. 2025). Spatial gesture interaction in HMD captures mid-air gestures for direct interface control (Yoon and Lee 2023). Voice interaction combined with environmental sensing enables dynamic adaptation in field applications (Garbett et al. 2021).

MR leverages physical rule integration between virtual and real entities. Cross-reality manipulation allows interaction with physical objects using virtual tools, with physics engines simulating force dynamics (Al Mashhadany et al. 2024). Multimodal fusion integrates gaze, gesture, and voice for efficient operations—such as gaze-confirmed gesture selections during structural inspections (Chi et al. 2022). Environmental feedback systems map physical properties to haptic responses when virtual-real collisions occur (Becker et al. 2024). Unified platforms facilitate dynamic VR-to-AR shifts where virtual models are projected onto physical surfaces (Banfi et al. 2022). Emerging non-invasive neural interfaces support attention-based targeting in training scenarios (Abotaleb et al. 2023). Predictive interaction systems employ multi-sensor fusion to anticipate user actions (Shahinmoghadam et al. 2021).

5 | Discussion: Current Trends and Future Challenges

5.1 | Real-Time Data Transfer

Real-time data transfer has become a cornerstone for the maturation of XR ecosystems, enabling seamless collaborative design reviews, immersive field operations, and adaptive facility management workflows. The convergence of multimodal interactions (Lu et al. 2025)—such as eye tracking, gestures, and voice commands—relies on the rapid and continuous exchange of data streams to deliver a natural, synchronized user experience. Similarly, the integration of Artificial Intelligence (AI) for contextual adaptation and the evolution toward embedded spatial computing are predicated on the availability of low-latency, high-throughput data pipelines (Abreu et al. 2023).

However, this reliance introduces critical technical and infrastructural challenges. Real-time applications demand aggressive data compression to manage the massive volume of sensor and interaction data without overwhelming network bandwidth. Yet, excessive compression risks degrading signal fidelity, impairing gesture recognition accuracy, or causing delays in collaborative tasks (Gu et al. 2024). Latency remains another key bottleneck: even small delays can disrupt spatial alignment, induce motion sickness, or reduce user trust in XR systems. Additionally, bandwidth constraints—particularly in mobile or remote field settings—limit the scalability of shared XR environments, restricting the number of simultaneous participants or the fidelity of streamed assets.

Promising solutions include adaptive compression algorithms that balance efficiency and quality in real time, edge computing approaches to offload processing closer to data sources, and the implementation of standardized streaming protocols to ensure cross-platform interoperability. Overcoming these barriers will not only reduce cost and improve accessibility but also accelerate the transition toward a fully mature XR ecosystem capable of supporting rich, collaborative, and context-aware experiences at scale.

5.2 | Process Automation

Integrating real-world 3D content into XR applications is inherently multidisciplinary, as shown by the wide variety of modeling pipelines, data types, and software tools reported in the literature. A heavy reliance on manual effort across the pipeline remains a key challenge and includes steps such as 3D model optimization and editing for later application development. Automation through computational and AI methods helps to mitigate these bottlenecks, for example with novel scene representations such as NeRF (Mildenhall et al. 2021) and their faster derivatives, such as 3D Gaussian Splatting (Kerbl et al. 2023). These rapidly evolving techniques are increasingly complementing existing 3D model data types such as meshes or point clouds.

5.3 | Open-Source and Cross-Platform

Open-source adoption within XR research appears relatively sparse. In the reviewed literature for modeling, only two papers reported wider use of open-source software or libraries, both in the context of web-based XR applications. Nevertheless, web-based ecosystems (e.g., WebXR, Three.js, Babylon.js) are developing rapidly, partly driven by the global metaverse hype and the practical requirement for collaborative, multi-user applications.

In relation, as XR applications are expanding across devices such as headsets, smartphones, and tablets, raising the demand for cross-platform consistency. While efforts like unified formats (e.g., glTF), standards (e.g., OpenXR), and adaptive UI design have emerged, seamless interoperability remains limited. As (Ueno et al. 2023) show, even with well-engineered multicast streaming, challenges such as rendering delays and synchronization issues persist, especially in collaborative multi-device settings.

5.4 | Photorealism and Visual Overload

XR visualization is increasingly moving toward photorealism, using point clouds and texture mapping to enhance immersion (Banfi and Previtali 2021; Papadopoulou and Papakonstantinou 2024). Recent methods like VR-GS demonstrate real-time interaction with Gaussian splats and realistic lighting in VR, enabling both high fidelity and efficiency (Jiang et al. 2024). However, such rendering is still demanding, especially for mobile devices like Quest or smartphones. It remains challenging to balance performance and visual quality in large, dynamic scenes. Outdoor AR also suffers under strong sunlight, where poor visibility hinders usability (Perry 2021).

A further challenge lies in visual overload, especially in geospatial XR, where multiscale terrain models, semantic overlays, and dense annotations can easily overwhelm users (Schiavo et al. 2025). Without clear hierarchy or context-aware filtering and optimization, such scenes often result in cognitive fatigue and misinterpretation (Casado-Coscolla et al. 2023). This underscores the relevance of cartographic principles, such as generalization, symbol abstraction, and scale-aware design, which have long guided effective 2D spatial information communication (MacEachren 1995). Recent studies have begun adapting these to XR; for example, Olberding and Vetter (2023) propose dynamic 3D symbols that respond to user perspective, and Hruby et al. (2021) reframe scale generalization for immersive spaces. Building on this, future research in geospatial XR could benefit from systematically integrating cartographic design principles to improve spatial clarity and reduce visual overload in immersive environments.

5.5 | Multimodal Interactions

The advancement of digital technologies has propelled multidimensional evolution alongside persistent challenges within XR. Key technological trajectories driving this evolution encompass the fusion of multimodal interactions (integrating complementary inputs such as eye tracking, gestures, and voice commands to enhance operational efficiency in collaborative design reviews (Garbett et al. 2021))and the rise of lightweight interaction paradigms, particularly enabling controller-free operation through gesture and voice control for field applications (Yoon and Lee 2023). Concurrently, significant progress is evident in the synergy between AI and XR, leveraging natural language processing for contextual adaptation in facility management (Shahinmoghadam et al. 2021), as well as hardware evolution toward embedded spatial computing in compact devices (Sidani, Dinis, et al. 2021).

Nevertheless, critical barriers impede broader adoption, including limitations in the accuracy of non-invasive Brain-Computer Interfaces (BCIs) for complex commands (Lahtinen et al. 2024), fragmentation in cross-platform standards despite open protocol initiatives (Sun and Qiao 2022), and constrained market acceptance due to premium pricing and content scarcity (Ang et al. 2022). Addressing these intertwined technical and market bottlenecks remains crucial for achieving ecosystem maturation of immersive technologies.

6 | Conclusions

Extended Reality (XR) is rapidly expanding within industrial and scientific applications. This paper systematically reviewed the role of real-world 3D spaces in XR applications, following PRISMA principles focus on data acquisition, 3D modeling, visualization, and user interaction. Based on a detailed review of 96 journal publications, the authors have reached the following main conclusions:

- Data Collection and Multi-Sensor Fusion: Diverse techniques like photogrammetry, RGB-D cameras, and LiDAR are key for capturing 3D data, each with trade-offs in cost and accuracy. Multi-sensor fusion is vital for robust tracking and dense geometry, yet real-time high-quality point cloud transmission and semantic alignment in dynamic environments remain challenging.
- 3D Modeling Workflows and Data Types: BIM software (e.g., Revit) and game engines (Unity, Unreal Engine) are dominant in XR content pipelines, often complemented by CAD tools. Real-world XR applications heavily use BIM, frequently combining content types and enriching them with 3D scanned data, GIS or IoT streams.
- XR Visualization Hardware and Applications: VR HMDs are favored for training and design, while handheld/

wearable AR displays are used for on-site inspection and emergency navigation. Visualization content balances photorealism for fine details with simplified schematics for clear communication, often layering task-relevant information over textured models.

- Interaction Paradigms and Technical Frameworks: XR systems support diverse interactions (controllers, gestures, gaze, voice, haptics), leveraging machine learning for real-time processing. Trends include multimodal interaction fusion and AI-XR synergy.
- XR workflows still face major challenges including bandwidth limits, lack of automation, hybrid data handling, and shortage of open-source solutions and content. Visualization struggles with balancing quality and performance, interoperability across devices, and usability in outdoor or mobile contexts. Interaction barriers include limited accuracy of BCIs, high costs, and restricted market acceptance.

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Ethics Statement

This research was conducted in accordance with recognized ethical standards for academic research. No personal, sensitive, or identifiable information was collected during the study. All data were either publicly available, anonymized, or generated by the authors. As the study did not involve human participants, animals, or interventions, formal approval from an institutional ethics committee was not required. The authors affirm that the methodologies employed adhere to best practices ensuring integrity, transparency, and reproducibility. All sources, tools, and datasets were properly cited.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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