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Transforming Civil Infrastructure Inspection through Augmented Reality: Technologies, Use Cases, and Integration Frameworks

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ABSTRACT

Civil infrastructure inspection remains labor-intensive, subjective, and hazardous when relying on traditional visual assessments and manual measurements. This review examines how augmented reality (AR) addresses these challenges. The aim is to map the state-of-the-art AR applications across core inspection areas and to evaluate their operational performance. A systematic scoping literature review was conducted over peer-reviewed journals, conference proceedings, and industry reports from the past decade, focusing on AR system design, deployment, and empirical results. Results demonstrate that AR tools can reduce inspection time by up to 30 percent, improve defect measurement accuracy to within millimeter-scale tolerances, and support remote collaboration and AI-augmented defect detection. However, there are still major issues with data interoperability, multi-user scalability, spatial registration accuracy, and cognitive load management. While AR has progressed from proof-of-concept to real-world pilots, the review concludes that its broad adoption depends on improvements in tracking accuracy, standardised data frameworks, and integration with cutting-edge technologies like 5G edge computing and AI-driven analytics.

INTRODUCTION

The growing complexity Civil infrastructure is aging and complex, which creates pressure for inspection methods that are accurate, efficient, and non-intrusive. Manual practices that rely on field notes and post processed photos are labor intensive, slow, and prone to human error, which can affect safety and cost. Digitalization and AI are reshaping these workflows and point to a need for modernized inspection approaches that scale across assets and agencies (Li *et al.,* 2022, Spencer *et al.,* 2025, Musarat *et al.,* 2024, Mondejar *et al.,* 2021).

Augmented reality, AR, addresses this gap by overlaying models and data on the physical asset in the field. Inspectors can compare BIM or design intent to as built conditions, record measurements and annotations in situ, and share context with remote experts. This is valuable for assets that are hard to access or visually complex, such as bridges, tunnels, and plants, where defects are small, numerous, or occluded (Xu & Moreu, 2021, Behzadan *et al.,* 2015, Koch *et al.,* 2015, Chen *et al.,* 2024).

Adoption is growing, yet important limitations remain. Outdoor registration can drift, data from AR often lacks seamless interoperability with BIM and asset systems, and prolonged headset use can affect comfort and cognition (Xu *et al.,* 2023, Binni *et al.,* 2025, Singh *et al.,* 2024, Danielsson *et al.,* 2020, Mallela *et al.,* 2020). This review focuses on how AR supports civil infrastructure inspection tasks today, which technologies and procedures enable reliable use, and where evidence of benefit is strongest. We synthesize field validations and case studies, identify open challenges, and outline priorities for research and practice.

AR Technology & Civil Infrastructure Inspection

Augmented reality (AR) is broadly defined as technology that overlays computer-generated content onto the real world in real-time. It sits on the mixed reality continuum, where users still see the physical scene and the system adds aligned digital information. Virtual reality replaces the scene entirely. For inspection work, AR and MR are the relevant modes because they keep inspectors in the work context while adding data and models that support decisions (Milgram & Kishino, 1994, Skarbez *et al.,* 2021, Zulfiqar *et al.,* 2023, Zhu & Li, 2021).

Civil Infrastructure Inspection Workflow and Challenges

Inspectors typically perform visual checks with simple tools, document defects such as cracks, spalls, corrosion, and deformation, then compile a condition report. Agencies schedule periodic walkdowns and deeper hands on surveys, sometimes with basic nondestructive tests. The approach is foundational, yet it is time consuming, hazardous in certain locations, and prone to variability between raters when quantitative data are limited (Phares

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et al., 2004, Zhou *et al.,* 2021, Zhou *et al.,* 2022, Yuan *et al.,* 2024, Abdelalim *et al.,* 2024, Vardanega *et al.,* 2024). These limits motivate AR tools that add precision, consistency, and traceability.

Enabling Components of AR–CI Systems

AR for civil inspection relies on a combination of tracking methods, hardware platforms, and software frameworks to achieve accurate, mobile, and interactive visualization. Here is an outline of the key components and how they support AR functionality.

Tracking and Registration Methods

Marker based methods use fiducials with known geometry and give reliable poses where light site preparation is acceptable (Fiala, 2004).

Markerless visual or visual inertial SLAM localizes from natural features, which avoids markers but can drift on long or low texture paths (Reitmayr *et al.,* 2010).

Hybrid approaches add RTK GNSS outdoors to anchor a global frame, while SLAM refines local motion, which improves stability in large scale settings. UWB, Wi Fi fingerprinting, and LiDAR are viable where infrastructure allows it (Trong & Dung, 2024, Prorok & Martinoli, 2013, Ashtari Nakhaei, 2018)

Hardware Platforms

Head mounted displays provide hands free overlays and voice or gesture input, useful where two handed tasks and persistent alignment matter. Handheld phones and tablets, ARKit and ARCore, are flexible and low cost for many jobsites. UAV assisted views extend AR concepts too hard to reach areas, for example bridge undersides, with annotated remote video for safer access (Xu & Moreu, 2021, Oufqir *et al.,* 2020, Zollmann *et al.,* 2014, Wen & Kang, 2014, Greenwood *et al.,* 2019, Yan *et al.,* 2019).

Software Frameworks and Visualization

Engines such as Unity, often with the Mixed Reality Toolkit, or Unreal, handle rendering and input. Mobile SDKs supply tracking on devices. Inspection apps add measurement, annotation, and synchronization with BIM or asset systems, which turns AR views into maintained records rather than screenshots (Unity Technologies, 2025, MRTK, 2025).

Opportunities and Possibilities

Guided workflows and live data. AR can highlight checkpoints, show ghost markers at predefined locations, and overlay the positions of known issues while inspector's work. It can stream structural data into view, for example vibration, displacement, and damage history, as color coded graphics aligned to the asset. This shortens the path from observation to decision and can improve safety by warning about overstressed elements in context (Carter *et al.,* 2024, Banani Ardecani *et al.,* 2025, Danielsson *et al.,* 2020).

Defect measurement and traceable documentation. AR tools on headsets or mobiles can compute crack length and width directly from the overlay, which reduces manual measurement error and saves time. When photos or notes are captured, the system can log their holographic coordinates, which makes defects easy to relocate in future inspections and supports consistent reporting across teams and years (Malek & Moreu, 2022, Behzadan, 2005, Baek *et al.,* 2019).

Remote collaboration. Shared AR views let an offsite engineer see what the onsite inspector sees and annotate the live scene. This bridges skill gaps, reduces specialist travel, and speeds resolution. Commercial implementations and research prototypes report faster troubleshooting using this pattern (Davila Delgado *et al.,* 2020, Chantziaras *et al.,* 2021).

BIM and digital twins in the field. Registering a 3D BIM or a live digital twin to the physical asset enables side by side comparison of design or as built data with current conditions, detection of undocumented changes, and visualization of maintenance history. Past damage records and real time sensor data can be fused and presented through AR for interactive timelines and element level readings (Pan & Isnaeni, 2024, Carter *et al.,* 2024).

Interpretation. Near term value is highest where tasks are close range and information dense, for example guided checks, crack measurement, and issue documentation. For larger outdoor assets, plan for reliable localization and data pipelines so that AR outputs flow into asset systems without manual rework.

Applications of AR in Civil Inspection

Augmented reality is used across inspection tasks to place cues, annotations, and measurements on the asset in real time. Studies report reduced manual effort, improved safety, and opportunities to embed AI assisted detection into routine workflows. Uses span damage mapping, facility verification, and underground utility context, typically on phones, tablets, or head mounted displays with vision, GNSS, or sensor guidance (Behzadan *et al.,* 2015, Einizinab *et al.,* 2023).

Structural Health Monitoring & Damage Detection

AR has been applied to visualize structural defects (cracks, spalling, corrosion) on bridges, buildings, and other infrastructure. A HoloLens based tool by Moreu and Malek captured crack images and computed dimensions hands free, with field tests indicating faster inspection, higher accuracy, and improved comfort compared to manual methods (Moreu & Malek, 2021). Xu and colleagues demonstrated Time Machine Measure, which restores a saved mesh and aligns it to the current scene so inspectors can register past and present geometry and measure displacement or deformation on site without physical markers (Xu *et al.,* 2021, Xu & Moreu, 2021).

AI is increasingly integrated into AR, for example convolutional networks or lightweight detectors that flag candidate cracks or corrosion regions in the live camera view. In mixed reality, deep learning segmentation can outline defects in color directly on the surface so the inspector can verify or correct detections in place, a human in the loop pattern that improves speed while preserving judgment (Shojaei *et al.,* 2024, Moreu & Malek, 2021).

Practical deployments echo these gains. Yamaguchi *et al.* built a HoloLens support app for concrete crack inspection and reported more consistent marking of cracks. In lab based bridge work, AR assisted inspectors showed higher safety and lower workload than control groups. Image based documentation can be re anchored on site to compare historic damage to current conditions, which improves traceability across inspection cycles. These patterns align with broader reviews that find AR speeds routine measurements and clarifies sensor verification while acknowledging limits such as outdoor registration drift and data interoperability needs (Yamaguchi *et al.,* 2019, Maharjan *et al.,* 2019, Napolitano *et al.,* 2019, Xu & Moreu, 2021).

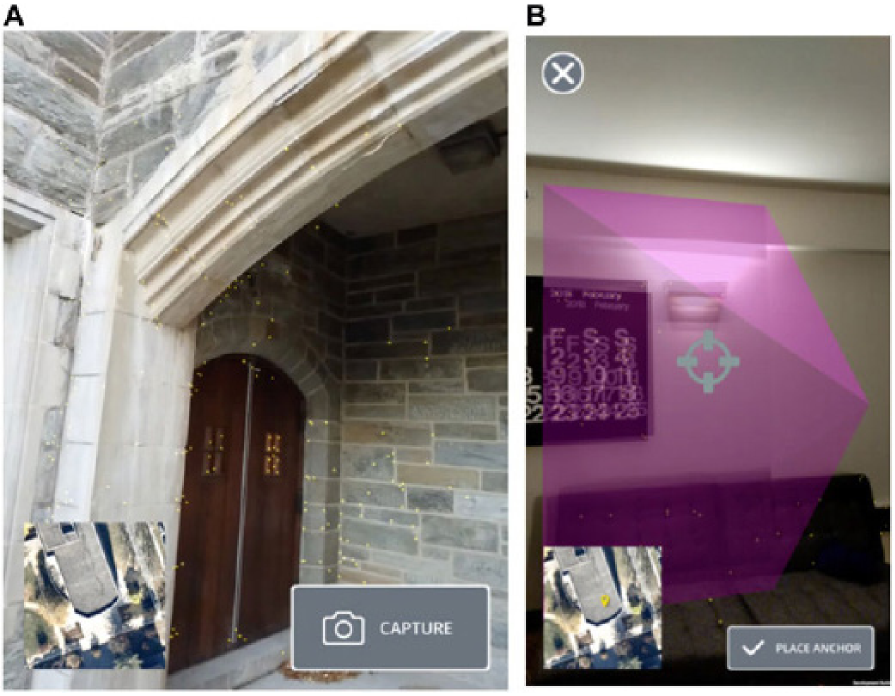

Figure 1: AR workflow for Bridge Inspection (Figure 12 from Xu, J., & Moreu, F., 2021 as adopted from Napolitano, R., Liu, Z., Sun, C., & Glisic, B., 2019). (A) Initial capture interface. (B) Reanchoring an image. The pink pyramid represents the relationship between the camera position and the image plane in terms of position and pose.

Bridge Inspection

AR plays a growing role in bridge inspection, especially when combined with unmanned aerial vehicles (UAVs). A new class of systems uses drones with stereo cameras and AR headsets: the drone flies around the bridge, streaming video to an AR HMD that superimposes computer-vision-generated annotations (Lapointe *et al.,* 2022). Van Dam *et al.* (2020) developed a drone-based AR inspection platform in which an operator flies a semi-autonomous UAV over a virtual bridge and performs visual search tasks. Stereo depth cameras on the UAV enable a video pass-through AR: defects detected by onboard vision (cracks, rust spots) are marked with virtual rulers or bounding boxes in the headset display Van Dam *et al.* (2020). In their VR-based study with 28 participants, (Van Dam *et al.,* 2020) analyzed how different AR cue designs (e.g., colored outlines) affect defect-detection performance. They found that target saliency significantly influenced detection rates, but different AR cue types had little effect on hit rates or misses (Van Dam *et al.,* 2020). In other words, even imperfect AR aids did not greatly distract or mislead inspectors in simple tasks.

Beyond this lab demonstration, the AR+drone concept holds practical promise. A UAV can reach hard-to-access sections (undersides, high towers) while the AR interface gives inspectors real-time metric feedback. For example, the AR interface might display the diameter of a detected crack or the tilt of a member (Greenwood *et al.,* 2019, Bristeau, 2011). In the Van Dam platform, operators could toggle world-fixed rulers and dimension tools on the live video. Such features turn a passive drone video into an interactive inspection tool.

Case examples from infrastructure agencies further illustrate AR's role in bridge inspection. Maharjan *et al.* (2019) used HoloLens for bridge deck inspection and noted inspectors felt more situational awareness with AR guidance Maharjan *et al.* (2019). Another project that has evaluated mixed reality for scanning bridge components is Trimble's BridgeInsight solution (commercial), which uses tablets/AR to visualize bridge models on site, enabling remote experts to point out defects. The key advantages of AR in bridges are clear: inspectors can perform remote, precise surveys without scaffolding and overlay structural analyses (stress maps, thermography) on the live view (Cuong *et al.,* 2021).

Building and Facility Inspection

In buildings and facilities, AR/MR (mixed reality) systems are employed to inspect envelopes (walls, windows, roofs) and mechanical/electrical/plumbing (MEP) systems. For building envelopes, AR headsets are used to overlay maintenance data onto the façade (Kosowatz, 2025). Spectar (Trimble) is a commercial HoloLens app that overlays 3D BIM on the jobsite, letting users align models via multi-point registration (Red Dot, 2025). For MEP inspections, AR is used to visualize hidden infrastructure. In one case study, a building project team used a HoloLens (Trimble XR10) with Spectar software to inspect installed HVAC and plumbing. Wearing the headset, the virtual BIM of ducts and pipes was overlaid on the field of view. Inspectors could "tap" on a virtual pipe in the AR scene to see its specifications, and then compare them to the actual installation as shown in Figure 3. This hands-free BIM visualization meant, for example, that an engineer could see if a conduit ran the correct route behind a wall without removing drywall (Girgin *et al.,* 2023). Survey results indicated that AR-augmented BIM reduced errors and field rework in MEP installations.

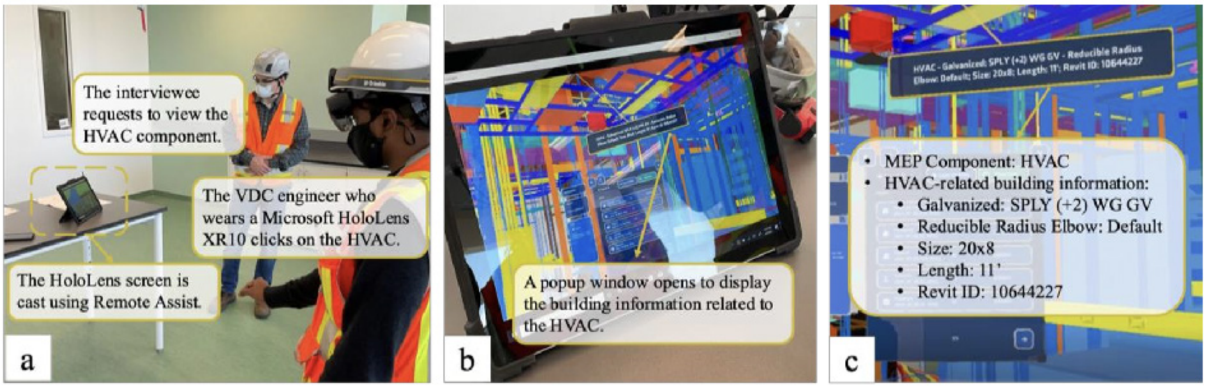

Figure 2: The interview setting during MR-based field inspections: (a) the interviewee requests to view a building component, (b) a popup window opens in the MR interface, and (c) displays the related building information. (As adopted from (Girgin *et al.,* 2023).

A cutting edge development is gaze based AR for inspection robots. Choi *et al.* (2024) demonstrated a mixed reality system where an inspector's eye gaze, captured by a HoloLens 2, selects the next inspection target for an autonomous robot. Holographic markers allow the inspector to look at a crack or joint, after which

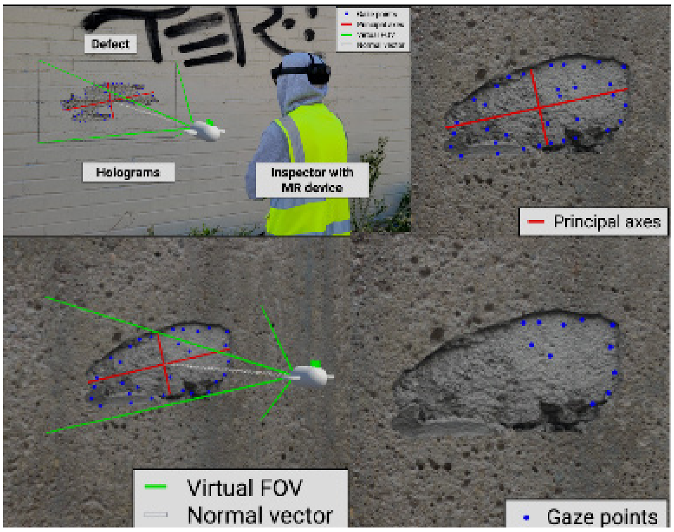

Figure 3: The interview setting during MR-based field inspections: (a) the interviewee requests to view a building component, (b) a popup window opens in the MR interface, and (c) displays the related building information. (As adopted from (Girgin *et al.,* 2023).

the system infers that location and dispatches a drone or ground rover. The interface can also estimate defect properties at the gaze point (Choi *et al.,* 2024). Although shown on bridge like assets, the same pattern applies to buildings, for example a damaged façade panel.

Underground Utility Mapping

AR assists crews in locating buried utilities and reducing strike risk by aligning subsurface detections with the work face. A field prototype combined ground penetrating radar with a head mounted display so operators could trace with GPR while a real time overlay "painted" detected pipes and depths on the scene, which sped path identification and hazard awareness (Pereira *et al.,* 2019). Reviews show two common approaches, GPS referenced AR that draws from geocoded utility databases, and sensing led AR that localizes from GPR or similar inputs, each with different alignment demands in the field (Kaddioui *et al.,* 2019). The main challenge is registration accuracy, small absolute errors can mislead crews at trench scale, so hybrid localization, RTK GNSS anchored frames fused with inertial and vision, is a practical path for outdoor work (Xu & Moreu, 2021, Binni *et al.,* 2025).

Safety Inspections and Fall Hazard Detection

AR improves safety checks by guiding coverage and highlighting gaps. A mixed reality system for high rise screening tracked the worker's gaze and "painted" inspected areas in the view, while onboard vision models flagged uninspected gaps or tears, which created a clear record of what was checked and where follow up was needed (Liu *et al.,* 2024). Experiments on AR for industrial quality inspection also show performance gains when overlays are simple and task focused, which supports using light weight cues during safety rounds (Seeliger *et al.,* 2023).

Figure 4: AR safety inspection interface (Liu *et al.,* 2024)

Worker's "brush" safety barriers with their view, and the headset colors inspected regions green while logging coverage. The system highlights uninspected or damaged sections, which helps inspectors achieve full perimeter coverage and detect fall hazards more reliably (Liu *et al.,* 2024). Beyond edge screens, AR can flag generic site fall risks and support training with interactive simulators, for example VirtualFallProtect. In practice, early evaluations show that head-worn AR reduces paperwork because inspectors annotate hazards in the field and generate compliance reports on the spot, and the coverage visualization prevents duplicate checks and omissions (Liu *et al.,* 2024).

Digital Twin & BIM Integration

Linking AR to digital twins and BIM keeps field and model in sync. In practice, the headset estimates a precise six degree of freedom pose, aligns to a GIS or BIM frame, and lets inspectors view attributes, histories, and sensor data while logging new observations back to the twin (Binni *et al.,* 2025, Sakr & Sadhu, 2024). Commercial tools, for example Trimble Connect AR and Spectar, support pinning model elements to the asset and capturing as built updates in place, which adds context and shortens closeout cycles (Kosowatz, 2025, Red Dot, 2025). Effective pipelines depend on interoperable data, studies note friction moving AR annotations into IFC and asset systems and recommend standardized identifiers and schemas for field notes, measurements, and model links (Vernica *et al.,* 2021, Singh *et al.,* 2024, Huahui & Deng, 2018).

Mobile and Wearable AR Systems

Smartphones and tablets, ARKit and ARCore, are ubiquitous and low cost, good for quick alignment and documentation, although holding the device reduces freedom and depth sensing may be limited on some models (Oufqir *et al.,* 2020). Head mounted displays provide stereoscopic depth, hands free operation, and integrated cameras, which supports measurement and guided tasks in tight spaces, with tradeoffs in weight, comfort, and cost (Xu *et al.,* 2023, Danielsson *et al.,* 2020).

Lab and pilot studies report lower workload and faster data capture with HMDs for bridge and facility checks, while tablets remain preferred for group walkdowns and broad reviews (Maharjan *et al.,* 2019, Bae *et al.,* 2013).

Emerging and Minor Applications

Promising niches include traffic asset inspection and smart city overlays that fuse IoT with AR views, post disaster triage and damage mapping, progress monitoring by overlaying planned versus actual, asset information portals that reveal hidden networks from tagged covers, and immersive training for safety and equipment use (U.S. Department of Commerce, 2021, Kamat & El Tawil, 2007, Kosowatz, 2025, Halder *et al.,* 2022, Kaddioui *et al.,* 2019, Gattullo *et al.,* 2022, Quandt & Freitag, 2021).

Table 1: Examples of Major AR–CI Tools (Commercial and Research-Based)

Domain	**Tool/App**	**Core Functionality**
Structural SHM (crack detection)	Time Machine Measure (HoloLens app)	Restores historical 3D scans on-site so inspectors can overlay past and present meshes and directly measure deformations (Xu & Moreu, 2021)
Bridge Inspection	Drone-based AR Inspection Platform	UAV-mounted stereoscopic cameras stream video; AR superimposes detected defects and measurement cues (rulers, bounding boxes) (Van Dam *et al.,* 2020)
Building/MEP Inspection (Girgin *et al.,* 2023)	Spectar (Trimble, HoloLens)	Overlays 3D BIM models onto the real world with multi-point alignment, giving in-situ access to MEP design data and history
Underground Utilities	AR + GPR Utility Locator (Pereira *et al.,* 2019)	Uses ground-penetrating radar and AR to visualize the path and depth of buried pipes/cables on-site (Xu & Moreu, 2021; Pereira *et al.,* 2019).
Safety Inspection	AR Safety Inspector	Wearable AR tracks which perimeter-screen sections have been checked and uses ML to flag gaps in fall-protection systems (Liu *et al.,* 2024).
Digital Twin/BIM Integration	AR-DT Integrator	Automatic 6-DoF registration aligns field view with a GIS-enabled digital twin, enabling AR visualization of asset data and auto-updating BIM (Binni *et al.,* 2025).
Smart City / Emergency Response	AR IoT Overlay (NIST CHARIoT concept)	Merges real-time IoT data streams (traffic, sensors) into an AR interface for responders, e.g., showing live vehicle or alarm info in scene (U.S. Department of Commerce, 2021)
Post-Disaster Assessment	AR Damage Overlay	Projects pre-event building models onto a damaged structure in AR to quickly identify new structural failures (Kamat & El-Tawil, 2007).

Note: The table includes both commercial systems (e.g., Spectar) and research prototypes (e.g., Liu et al.'s (2024) AR safety app. Each tool is validated either in field trials or simulation studies as cited above, demonstrating tangible benefits (e.g., time savings, improved detection) in its domain.

MATERIALS AND METHODS

This study adopts a systematic scoping review methodology aimed at synthesizing existing literature and practical deployments of augmented reality, AR, in civil infrastructure inspection, CI (Xu & Moreu, 2021; Behzadan *et al.,* 2015). Following the Preferred Reporting Items for Systematic Reviews and Meta Analyses, PRISMA, framework, the review was conducted in three main stages, literature identification, selection, and synthesis.

Literature Identification

The search focused on academic databases including Scopus, IEEE Xplore, SpringerLink, ScienceDirect, and Google Scholar. Keywords included combinations of "augmented reality," "civil infrastructure inspection," "BIM integration," "structural health monitoring," "AI assisted inspection," and "mixed reality." Timeframe was limited to 2010–2025 to capture modern applications and technical advancements (Xu *et al.,* 2023).

Inclusion and Exclusion Criteria

Papers were included if they:

- Reported AR applications specifically for civil inspection (bridges, buildings, tunnels, etc.)
- Presented either prototype development, field validation, or commercial case studies
- Provided quantifiable or qualitative evaluation (e.g., time saved, accuracy improved, user satisfaction)

Papers were excluded if they:

- Focused solely on virtual reality (VR) without AR components

- Were unrelated to infrastructure or were purely conceptual without deployment or simulation

Data Extraction and Analysis

For each selected source, data was extracted based on: AR hardware used, tracking method, inspection domain, integration with BIM or AI, benefits reported (e.g., accuracy, safety), and limitations observed. These were thematically categorized to identify patterns in use cases, technological barriers, and future directions. Where applicable, field observations and personal professional experience as a civil engineer were also reflected to validate claims and contextualize gaps (Pan & Isnaeni, 2024; Moreu & Malek, 2021).

Challenges and Limitations

While augmented reality presents a compelling vision for the future of civil infrastructure inspection, its widespread adoption and full potential are currently constrained by a series of inherent challenges and practical limitations (Behzadan *et al.,* 2015; Okanlawon *et al.,* 2025). These impediments range from fundamental technical hurdles in spatial computing to broader considerations concerning user interaction, data ecosystems, and regulatory frameworks. Critically understanding these challenges is essential for guiding future research and development towards robust and widely applicable AR solutions in the civil engineering domain (Pan & Isnaeni, 2024; Binni *et al.,* 2025).

Registration Accuracy and Drift

Accurate alignment of virtual overlays with the real world is fundamental to AR inspection, yet remains a key limitation. In large outdoor infrastructures, bridges, highways, pipelines, GPS or GNSS can provide only rough absolute location, often ±1–3 m, and no reliable orientation (Mallela *et al.,* 2020). Differential or real time kinematic, RTK, GPS can improve horizontal accuracy to centimeters, but requires base stations or CORS networks and still suffers outdoors in urban canyon conditions (Binni *et al.,* 2025; Mallela *et al.,* 2020). Inertial and visual inertial SLAM or VIO systems, for example HoloLens, ARCore, provide orientation and relative motion, but drift accumulates over distance. As one study notes, "drift issues restrict the system's area of use and limit scalability" in open environments (Binni *et al.,* 2025). Marker based methods can lock AR to fixed points with high accuracy, but they are impractical for large or dynamic sites, markers must be pre-installed and calibrated, and coverage becomes burdensome over broad areas (Mallela *et al.,* 2020). In practice, purely visual tracking often fails in feature poor outdoor scenes, for example bare concrete, water (Xu & Moreu, 2021), requiring hybrid solutions.

Scalability and Interoperability

Existing AR inspection tools often struggle to scale across multiple sites or among many users. A tightly coupled AR setup, for example one specific 3D model and tracking configuration, may work in one location but must be reinitialized and re registered at each new structure (Perla *et al.,* 2016). Without robust global localization, AR mapping cannot hand off seamlessly from one site to another. Similarly, multi user collaboration is largely experimental, some AR platforms allow shared scenes, for example cloud based holoportation, but in practice each device often builds its own coordinate frame, making it hard for teams to see the same content consistently (Pan & Isnaeni, 2024).

Interoperability with existing construction data is also a challenge. Civil infrastructure BIM or CAD models exist in many formats, Revit, Tekla, Civil3D, and there is no single way to feed them into AR. Proprietary models often must be manually exported, for example to FBX or glTF, for use in an AR app (Singh *et al.,* 2024; Huahui & Deng, 2018). Likewise, AR inspection outputs, annotated images, point clouds, logs, do not yet map cleanly into standard asset databases. There is no common schema to link an AR hologram or defect annotation to a BIM element or GIS feature. This fragmentation contrasts with mature workflows in industry, for example IFC for BIM geometry and CityGML for GIS, that have seen limited adoption in AR (Al Hajj *et al.,* 2020; He *et al.,* 2020).

User Experience and Cognitive Load

Studies show that, when properly designed, AR can reduce mental workload by presenting context sensitive cues in situ (Gattullo *et al.,* 2022). For example, overlaying a pipeline diagram on the actual pipes helps the inspector recognize and recall relevant information without consulting paper drawings. In practice, AR headsets and tablets can improve task efficiency for experienced users, and many users report that AR guidance increases confidence and reduces errors in inspection tasks (Woodward & Ruiz, 2023). However, these benefits come with tradeoffs. Contemporary AR headsets have limited field of view, often less than 60 degrees, and can induce eye strain or fatigue during extended use. They also add physical weight and heat, which may be uncomfortable for field workers. In high stress or hazardous tasks, AR can even impair situational awareness if not carefully managed (Hirzle *et al.,* 2022).

Data Management and Standardization

AR inspection generates and relies on large, heterogeneous data, high resolution images and video, 3D meshes or point clouds, annotated models, sensor logs, and more. Managing this data poses challenges. Many AR apps simplify 3D models to keep performance real time, which risks losing detail. After an inspection, field generated data, photos, laser scans, AR log files, must be reconciled with the asset's BIM or IoT database (Vernica *et al.,* 2021). Currently, this is often done manually. There is no universally accepted data schema for AR annotations or defect reports, so each tool may use a proprietary format. This one off approach means AR records can remain siloed unless custom ETL, extract transform load, scripts are built. While industry is developing open BIM standards, for example IFC ISO 16739, for geometry and Asset Administration Shell concepts for twin data, integration with AR is nascent (Article & Kansara, 2021). Table 2 compared traditional and R based inspection on key aspects.

Table 2: Comparing traditional and AR-based inspection on key aspects.

Aspect	**Traditional (non-AR)**	**AR-based Inspection (Pros & Cons)**
Localization/Tracking	Survey instruments or fixed markers provide high absolute accuracy and stability over large areas (Mallela *et al.,* 2020).	AR tracking (GPS or SLAM) is mobile but drifts over time. GPS gives only position, no orientation. Markerless SLAM needs static features. Hybrid RTK+VIO can achieve cm accuracy, but is complex (Binni *et al.,* 2025; Mallela *et al.,* 2020).
Scalability	Can cover multiple sites by relocating equipment; multi-user data sharing is via drawings/reports.	Single AR sessions rarely share maps across sites; multi-user AR is experimental. Adding users requires network sync. Drift and different coordinate frames limit large-area AR (Binni *et al.,* 2025).
Data Capture & Integration	Camera photos and notes are easily stored but lack spatial context. Data export (PDF, CSV) is standard.	AR captures spatial 3D data and context-rich media. However, it produces large point clouds/meshes that strain devices. Outputs (hologram anchors, meshes) require custom post-processing to import into BIM.
User Cognitive Load	Workers use manuals/printouts and standard tools; moderate memory load but no new hardware strain.	AR can reduce memory load by showing context-sensitive info. But HMDs have limited FOV, may distract or overload if too much info is shown. Proper UI design is critical for safety (Gattullo *et al.,* 2022; Quandt & Freitag, 2021).
Safety/Privacy	No electronic logs; clear line-of-sight.	HMDs may block vision or hearing, raising safety concerns. Continuous recording means potential privacy issues (faces, environments). Data must be managed under general privacy laws (Dick, 2021).
Regulatory/ Standardization	Uses established inspection standards and common data formats (e.g., IFC, PDF).	No AR-specific regulations yet; industry guidance is emerging. AR software often uses proprietary models and APIs, hindering interoperability. Industry initiatives are needed to define standards (Omrany *et al.,* 2023).

RESULTS AND DISCUSSION

The review synthesized over 70 scholarly and industry publications, revealing consistent trends in how AR is transforming civil infrastructure inspection:

Technological Impact

- Accuracy & Speed: AR applications demonstrated up to 30% reduction in inspection time and improved defect measurement to sub centimeter precision (Malek & Moreu, 2022; Shojaei *et al.,* 2024). These improvements stem from real time overlays and automated geometry capture.
- Operational Efficiency: Hands free devices like HoloLens facilitated safer inspections in hazardous locations. Remote collaboration tools allowed senior engineers to supervise inspections virtually, reducing travel and decision delays (Carter *et al.,* 2024).

Challenges in Practice

- Tracking Limitations: Visual SLAM often drifted in outdoor settings with low texture surfaces, leading to misaligned overlays. Hybrid approaches, for example GNSS plus VIO, mitigated this but increased hardware complexity and cost (Xu *et al.,* 2023; Binni *et al.,* 2025).
- Data Fragmentation: Lack of standardization across AR output formats, for example annotations, mesh data, created post processing burdens. Integration with BIM platforms still required manual conversions (Singh *et al.,* 2024; Pan & Isnaeni, 2024).
- Cognitive Load: While AR reduced the need to switch between paper plans and real structures, extended headset use caused discomfort and occasionally information overload during inspections (Woodward & Ruiz, 2023; Quandt & Freitag, 2021).

User Experience Observations

From both reviewed studies and pilot deployments, users noted:

- High initial learning curve, especially for aligning virtual models with physical structures (Maharjan *et al.,* 2019; Girgin *et al.,* 2023).
- Greater situational awareness, especially when structural health monitoring (SHM) data was overlaid in real time.

- Preference for tablet-based AR for quick documentation and headset-based AR for immersive, hands-free inspections.

5.4 Alignment with Field Experience

Personal experience in pilot AR-enabled inspections confirmed the literature's observations:

- While inspecting HVAC systems and embedded piping, AR overlays reduced wall openings by visualizing internal routes with BIM aligned holograms (Behzadan, 2005; Baek *et al.,* 2019).
- Field use showed that tablet-based AR tools are more suited for fast-paced, mobile teams, while headset AR tools are better for stationary, high-risk inspection zones (e.g., high bridges, confined tanks).

Future Research Directions

The current limitations of augmented reality in civil infrastructure inspection, coupled with the rapid evolution of supporting technologies, illuminate several promising avenues for future research. These directions aim not only to overcome existing challenges but also to unlock new functionalities. A major frontier is endowing AR systems with real time computer vision and machine learning. Deep learning models, especially CNNs, have demonstrated high accuracy in detecting cracks, corrosion, spalling, and other defects in infrastructure images (Talebi *et al.,* 2025). Embedding such models into AR could allow automatic flagging and classification of defects as the inspector looks at the structure. Current research is exploring lightweight CNNs and vision transformer models optimized for on device inference or fast offloading. A challenge is the need for large, annotated datasets of defects in the wild. Another direction is integrating vision with NLP or semantic queries, an inspector might ask the AR system, via voice or text, to "show all visible spall patches on column 3" and the system would use AI to fulfill the request. Compared to traditional visual inspection, or even fixed cameras, AI driven AR promises higher consistency and speed. Nevertheless, robustness to varying lighting, weather, and unusual damage remains an open problem. Researchers are also beginning to fuse data from non-visual sensors, for example acoustic, LiDAR, into AR, using multimodal AI to detect subsurface defects invisible to a camera (Riemens *et al.,* 2022; Snow *et al.,* 2023; Seckin *et al.,* 2025). AR is poised to become a two way interface with infrastructure digital twins, DT. In the near future, inspectors could not only pull information from a DT, for example overlay hidden utilities or historical damage models, but also contribute data back to it in real time. A recent study exemplifies this synergy, a hybrid RTK plus VIO AR system provided on field access to BIM based DT data and simultaneously registered captured inspection images back into the DT's knowledge graph (Binni *et al.,* 2025). This bidirectional linkage allows predictive maintenance, AR could alert the inspector to anomalies suggested by the DT model, for example "this crack is in a high stress area," while the inspector's observations refine the DT's future predictions. Over time, the DT and AR will form a feedback loop. Enabling this requires advances in real time synchronization and ontology alignment.

Integrating AR with robots and drones promises to extend inspection reach and reduce human risk. Drones and unmanned ground vehicles equipped with cameras can access difficult or dangerous areas, for example high bridges, tunnel linings, underwater piles. When these platforms stream video to a human operator, overlaying AR cues on the live feed can provide remote situational awareness (Halder *et al.,* 2022). Nsflow highlights that AR plus drone systems can provide inspectors with an augmented view of the remote environment and enhanced guidance (Adamska, 2025). On the other hand, robots themselves might use onboard AR to interpret their sensor data, for example an inspection robot could project a heatmap of detected corrosion onto its 3D scan of a structure for teleoperators. One recent project used a quadruped robot for remote construction monitoring, the robot sent live imagery, which was annotated with the current BIM state in the AR display. The study noted, however, that AR drift still affected alignment over time in this setting (Halder *et al.,* 2022). In future, more autonomy is anticipated, drones with embedded AR or AI could autonomously flag defects during flight, or robotic arms with AR guidance could perform routine probe measurements. Compared with stationary sensors or manual platforms, AR augmented robots could combine the spatial intelligence of robots with the rich context of AR. Key challenges remain in reliable communications, low latency links, precise robot localization, so AR overlays are stable, and safety, fail safes if control links drop.

The rollout of 5G and multi access edge computing, MEC, is expected to greatly enhance AR applications. Ultra-low latency 5G networks, less than 20 ms round trip, allow AR devices to offload heavy computation, real time SLAM, deep learning inference, multi user synchronization, to nearby edge servers, which can send back only minimal overlay instructions. Studies indicate that end to end latency must stay below about 20 ms for AR to feel smooth (Bamforth, 2025). Private 5G on large sites, campus or construction sites, could provide high bandwidth to stream live 4K video for remote AR, or to share AR sessions among users. With edge computing, a complex AI model, for example for crack segmentation, can run on a server rather than on the HMD, enabling richer analysis.

Recognizing the fragmentation of current AR ecosystems, several initiatives are emerging to standardize AR inspection. The Khronos Group's OpenXR is a royalty free API standard that aims to unify AR or VR development across hardware, HoloLens, Magic Leap, and more. Compliance with OpenXR means AR applications can more easily run on multiple devices. Industry guidelines, for example from the Augmented Reality for Enterprise Alliance, explicitly recommend using OpenXR and even support for open AR cloud

SDKs (Seeliger *et al.,* 2023).

CONCLUSION

Bridges, tunnels, and structures require accurate and effective inspection techniques, which augmented reality is uniquely suited to accomplish. This review has shown that AR applications streamline tasks from crack measurement to underground utility mapping, delivering faster workflows and sub-centimeter accuracy in defect quantification.While digital twin synergies let inspectors both consume and update complete infrastructure models in real time, integrations with artificial intelligence help to automate anomaly detection. Still, these benefits are limited by ongoing challenges like spatial drift in open environments compromises registration accuracy; ergonomic restrictions and information overload compromise user acceptance; and the lack of common data standards limits seamless integration with BIM and GIS platforms. Looking ahead, accelerating AR effectiveness will require further research into hybrid tracking (combining RTK-GNSS, SLAM, and LiDAR), cognitive-centric interface design to optimize mental workload, and the development of interoperable data schemas. Investment in 5G-enabled edge computing and lightweight AI models promises to deliver real-time analytics without burdening field devices. Through better, faster, and more consistent research, the infrastructure community can move AR from pilot projects to a mainstream inspection era that protects assets and lives by addressing technical and organizational challenges.

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