XR5.0

Human-Centric AI-Enabled Extended Reality Applications for the Industry 5.0 Era

AI-Driven Anomaly Detection & Augmented Reality for Water Infrastructure (Pilot 3 - Operator 5.0 Training for Smart Water Pipes)

By

Harsh Manoj Shah, HOLO

Karim Ladjeri, EKSO

Sophia Ppali, CYENS

Fotis Liarokapis, CYENS

Andreas Andreou, CYENS

Dimitrios Dardanis, UPRC

Stergios Chairistanidis, UPRC

George Fatouros, INNOV

Despina Tomkou, INNOV

Robert Fejer, SIE

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Abstract

Every day, thousands of kilometers of underground water pipes are monitored, inspected, and maintained by skilled teams working in demanding conditions — with limited access to real-time information, paper-based instructions, and inspection methods that have changed little in decades. When something goes wrong, the cost in time, resources, and risk to public water supply can be significant.

Pilot 3 of the XR5.0 project asks a fundamental question: what if the operators responsible for keeping our water systems running could see through the ground, access expert guidance with the sound of their voice, and have an AI partner that automatically spots pipe defects before they become critical failures?

Pilot 3 of the XR5.0 project — Operator 5.0 Training for Smart Water Pipes — demonstrates how Extended Reality (XR) and Artificial Intelligence (AI) can fundamentally transform the way water infrastructure operators are trained, guided, and supported in the field. By integrating Augmented Reality (AR) overlays, Large Language Model (LLM)-powered voice assistance, Neurosymbolic AI (NSAI) anomaly detection, and Explainable AI (XAI) into a single cohesive platform, the pilot equips technicians and managers with real-time, context-aware decision support for the inspection, monitoring, and maintenance of underground pipe networks.

Validated at EKSO facilities in December 2025, the Pilot 3 Early Prototype brought together three powerful technologies: Augmented Reality (AR) to visually overlay underground pipe networks onto the operator's real-world surroundings; an AI-powered voice assistant to provide instant, spoken answers from technical documentation; and an automated video analysis system that can review hours of pipe inspection footage in minutes, identifying potential defects with a high degree of accuracy.

The results were encouraging. Operators rated the system's contribution to workplace safety at the maximum score. The AI voice assistant was unanimously valued as a tool operators would use in their daily work. The automated video inspection system reduced manual review workload by an average of 95%. And while the technology is still in development — with clear areas identified for improvement — the evaluation confirmed that this combination of AR and AI holds genuine, practical promise for the water sector.

This whitepaper presents the architectural design, integrated components, technical performance results, and user evaluation outcomes of Pilot 3, and outlines the roadmap toward a fully operational, field-ready solution for the water infrastructure sector.

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Introduction

Overview

The water infrastructure sector faces a growing operational challenge: aging underground pipe networks require increasingly frequent and complex inspection and maintenance interventions, while skilled operator availability is constrained. Traditional approaches to inspection and training — paper-based manuals, instructor-led classroom sessions, and in-person demonstrations — are costly, time-intensive, and difficult to scale. Moreover, they do not leverage the wealth of real-time sensors and operational data now available through Industrial Internet of Things (IIoT) deployments.

Pilot 3 of the XR5.0 project addresses this challenge directly. The pilot brings together a consortium of technology and domain partners — EKSO (water infrastructure operator), CYENS, UPRC, INNOV, and SIE — to co-develop and validate a human-centric XR and AI solution designed for the realities of field operations.

The solution combines three pillars of technological innovation:

- Augmented Reality (AR) for real-time, geolocated visualization of underground pipe infrastructure, anomalies, and sensor data directly in the operator's physical environment.
- AI-powered assistance via a Retrieval-Augmented Generation (RAG) LLM engine that provides hands-free, voice-driven access to technical documentation and procedural guidance.
- Neurosymbolic AI (NSAI) for automated CCTV-based anomaly detection, complemented by Explainable AI (XAI) mechanisms that make AI reasoning transparent and trustworthy to field operators.

Together, these technologies form a unified, operator-ready platform that improves situational awareness, reduces reliance on expert intervention, and supports a new generation of digitally empowered Operator 5.0 workers.

Use Cases

Pilot 3 addresses three primary industrial use cases, reflecting different relevant phases of water infrastructure maintenance activities:

Scenario 1 – XR-based Anomaly Detection in the Field

This first use case is interesting the anomaly detection and location operations of a sensorised potable water pipeline in operation. A sensor chain distributed on the pipeline gathers data detecting anomalies and probable presence of leakage. The XR solution provided to the maintenance operator helps the geolocalisation of the anomaly by bolstering a timely and effective speed of intervention.

The field crew receives the alert within a section of the monitored pipeline with a 5-10mt approximation; their first task is to get to the right spot to intervene and understand exactly where to access the pipeline to be repaired. Today, this often means consulting paper maps, and, in absence of evident surface signs of anomaly

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or leakage, proceed almost via various attempts using old fashioned devices (Geophones), or relying on the experience of the team's most senior member.

Figure 1 Image of a pipe burst anomaly.

In Pilot 3, operators used a smartphone AR application that overlays a live, accurate map of the underground pipe network directly onto their view of the real world. Walk toward a junction, and the pipes beneath your feet appear in the app, colour-coded by status and annotated with live sensor readings. Spot an anomaly alert, and the exact location is marked — no guesswork, no cross-referencing maps. The goal is to get the right information to the right person at the right moment, wherever they are standing without consulting paper maps or static digital dashboards.

Figure 2 The image from the AR app displaying a 3D pipe overlayed with sensor information.

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Scenario 2 – AI-Supported CCTV Operations

This second use case is interesting: the CCTV inspection phase generally carried out periodically within ordinary maintenance monitoring or specifically carried out for extraordinary intervention in pipeline networks. CCTV is a very critical activity for direct examination of a pipeline granting its operational integrity. With the help of a HD camera, the inspection is carried out by an experienced operator with a remotely controlled robot proceeding along the pipeline up to hundreds of meters from the access. The AI solution provided is intended to help the operator integrate his detection/examination activity as well as speeding up the overall procedure.

CCTV-equipped robots are routinely sent through underground pipes to record video footage of the pipe's internal condition. The resulting footage — sometimes hours of recording from a single inspection — must be carefully reviewed by a trained technician to identify cracks, blockages, root intrusions, or other defects. It is painstaking work, requiring sustained concentration and specialist expertise to distinguish a genuine fault from a shadow or a reflection.

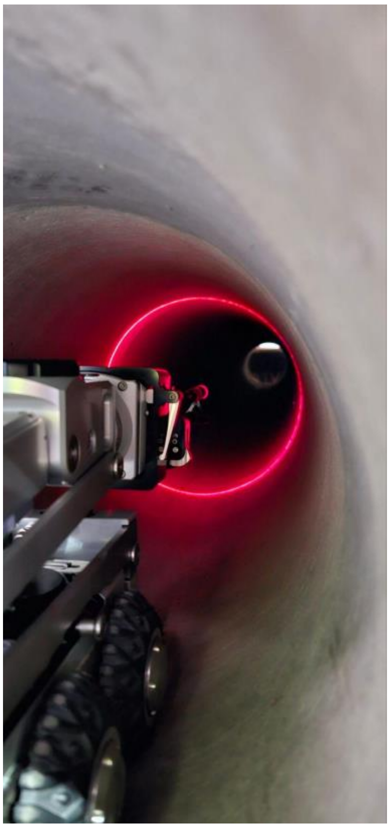

Figure 3 The image of a robot crawler within the pipe system.

The Neurosymbolic AI module of Pilot 3 tested an AI system capable of watching this footage automatically and flagging the frames that warrant human attention. The NSAI module automates anomaly detection in CCTV inspection videos, identifying defects such as cracks, disconnected segments, and root intrusions on a frame-by-frame basis. The system reduces manual inspection workload by an average of 94.9%, while

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providing explainable predictions that allow operators to validate and trust AI-generated findings. This transparency allows technicians to quickly verify the AI's findings rather than having to accept them on trust.

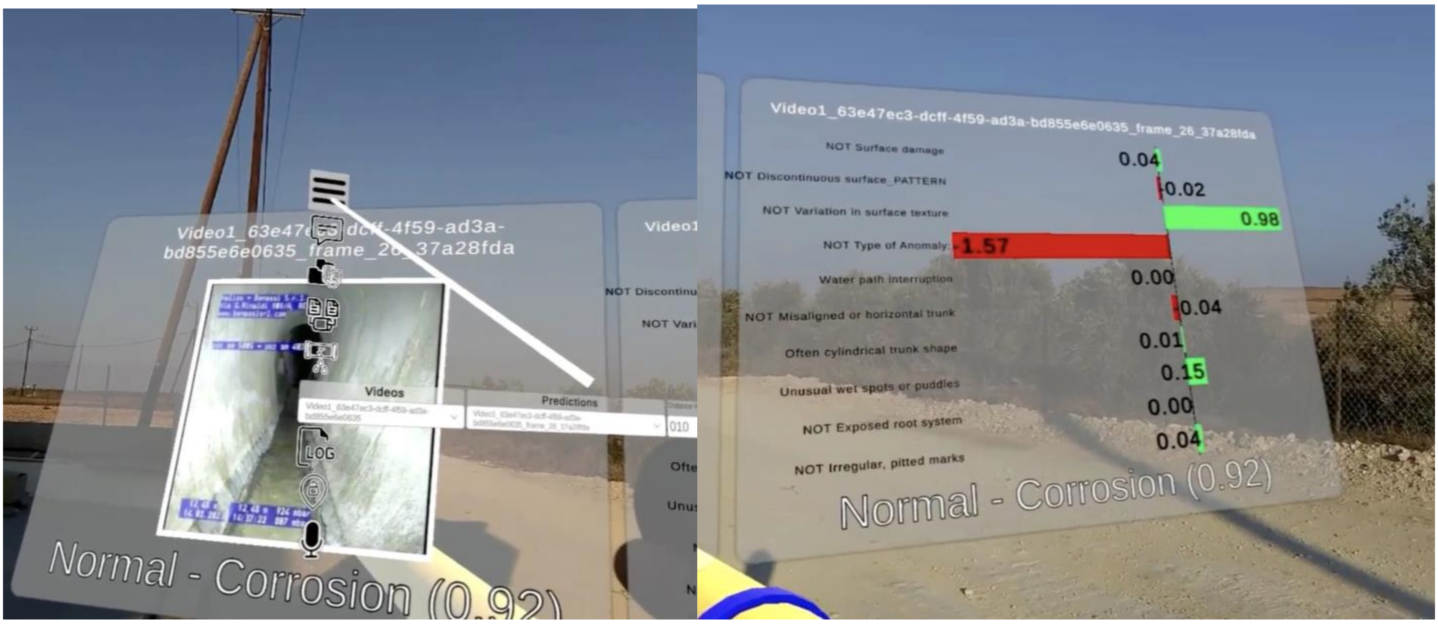

Figure 4 The AR application displaying the AI-results from the video anomaly detection module.

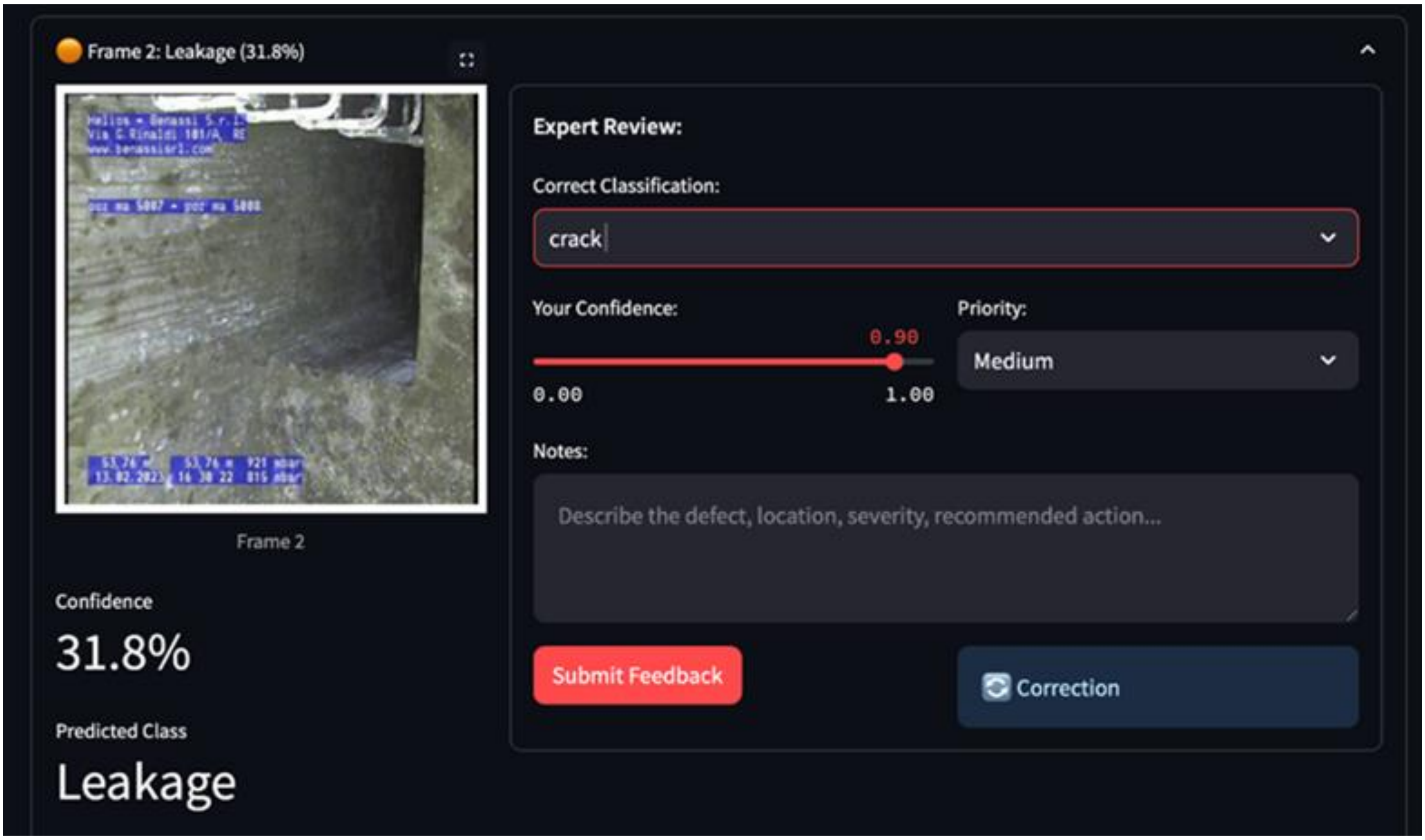

Figure 5 The image illustrates the video anomaly detection module.

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Scenario 3 – AI-Powered AR Training Support for Maintenance

This third use case is intended to grant pipe maintenance operators with full documental access to support either training or operational activities in different contexts: office or jobsite. The solution aims at offering a flexible instrument able for different needs speeding up information access in manuals, instruction documents, procedures bibles, operations check lists. Timely and reliable documentation consultation is efficient and effective.

Before undertaking a complex maintenance activity, a site manager or technician needs to review the correct procedure, confirm the safety checklist, and make sure the right equipment is at hand or all the phases have been correctly carried out. Digging through folders of technical manuals under time pressure, often in difficult field conditions, is neither efficient nor reliable. Sometimes it is simply not possible. The same solution can result in extreme support for more simple training activities outside of a job site.

In Pilot 3, operators could simply ask a question — "What is the procedure for preparing a relining site?" or "What safety checks are required before we begin?" — and receive a spoken, accurate answer sourced directly from EKSO's own technical documentation. No typing, no searching, no waiting to reach a colleague by phone. Just a clear, reliable answer when and where it is needed.

Figure 6 Image of a training procedure on site).

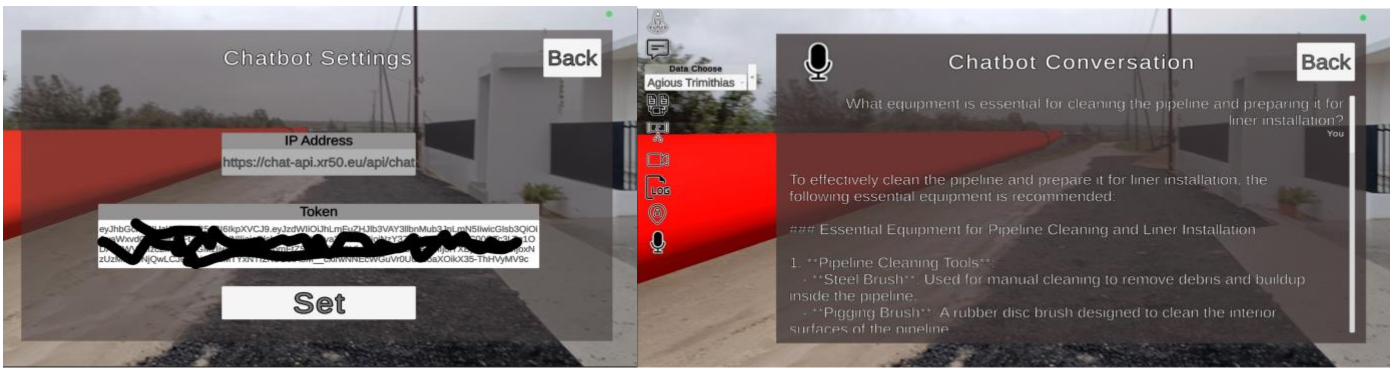

Figure 7 Chatbot settings and AI written response.

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XR5.0 Pilot 3 Application

The Pilot 3 system architecture is built on the XR5.0 Reference Architecture and integrates multiple layers and services into a cohesive operational environment. The architecture is structured around four core layers:

- Management Layer: An Admin/Manager interface accessible via web browser, enabling management of training materials, and training programs.
- Platform Layer: The XR5.0 Training Platform, which hosts the Training Asset Repository (XR Training Materials and Training Programs) and the Training Program Authoring Tool.
- Intelligence Layer: A suite of AI services including the LLM Engine (for the AI voice and domain-aware chat assistant), the Smart Pipes API (for sensor data ETL processing and anomaly geolocation), and the Active Learning & Neurosymbolic AI (AL & NSAI) service for CCTV anomaly detection.
- Field Layer: The Pilot 3 XR Application running on Android devices. The XR app integrates a plugin for XR training program execution (XR Training Plugin).

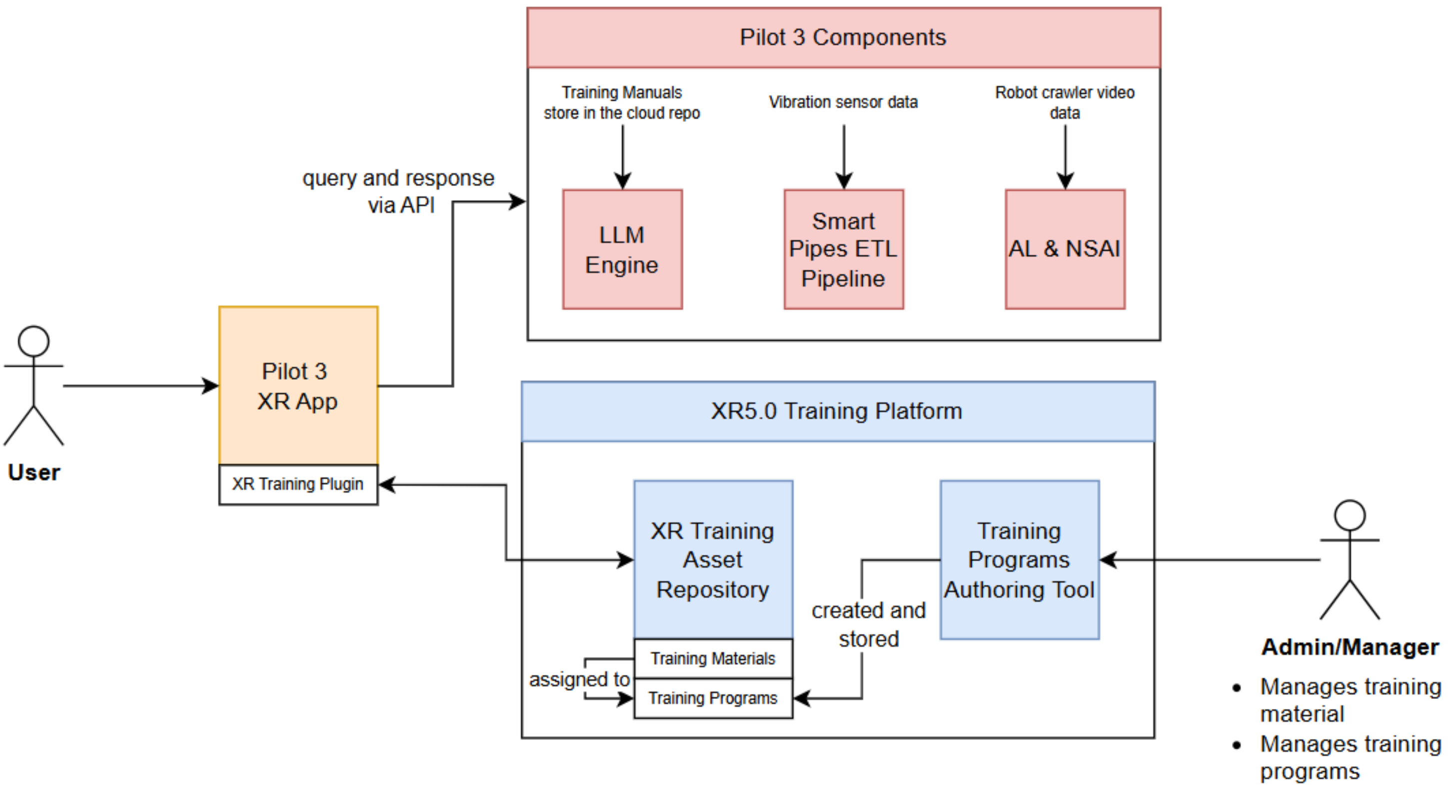

Figure 8 The architecture diagram of Pilot 3.

Integrated Technical Components

The following XR5.0 technical components were integrated and deployed in the Pilot 3 Early Prototype:

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AR Mobile Application

Built in Unity and deployed on Android smartphones (Samsung Galaxy S21), the AR application serves as the primary field interface. It integrates:

- Geospatial AR alignment using mobile GPS and compass/gyroscope sensor fusion, achieving 3–5 metre GPS accuracy and heading estimates of ±3°–7° in field conditions.
- Dynamic rendering of geolocated pipe network models at 60 FPS, with an average 0.1 seconds to display a full 10-segment pipe.
- Real-time sensor data retrieval and visualization from the Smart Pipes API, including vibration readings and anomaly alert markers.
- Direct integration with the AI assistant for voice-driven guidance and with NSAI outputs for anomaly marker display.

Figure 9 Selecting sensor data to display on pipe.

XR5.0 AI Assistant (RAG-based LLM Engine)

The AI Assistant — developed instantiated with EKSO's operational documentation — provides voice-driven access to inspection manuals, maintenance procedures, safety protocols, and CCTV analysis guidelines. Key capabilities include:

- Speech-to-Text (SIE STT): average transcription latency of 33.7 seconds for user prompts in field conditions.
- LLM-based response generation via Retrieval-Augmented Generation, evaluated using the RAGChecker framework against diverse representative operational queries as well as human evaluation.
- Text-to-Speech (Azure TTS): average audio generation time of 1.62 seconds for 230-word responses.
- The optimal deployment setup features faithfulness score 0.929, hallucination rate 0.037, claim recall 0.854.

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Neurosymbolic AI (NSAI) for CCTV Anomaly Detection

Developed by UPRC, the NSAI module combines Deep Neural Networks with symbolic reasoning to detect and classify anomalies in CCTV pipeline inspection videos. Distinct from black-box approaches, the NSAI system leverages Concept Bottleneck Models and learns rule-based reasoning that applies transparently, enabling operators to understand why a specific frame has been flagged as anomalous. Evaluated on two real CCTV inspection videos provided by EKSO:

- Average precision: 84.7% | Average F1 Score: 98.6%
- Average inspection workload reduction: 94.9%
- Processing speed: 9.05 frames per second | Real-time ratio: 0.30
- False positive rate: 9 false positives across both videos combined.

Active Learning (AL) Integration

The Active Learning component is integrated with the NSAI module to identify data points (frames) that yield high Information Gain and incorporate expert knowledge by leveraging human-in-the-loop techniques. In cases of low model prediction confidence or high estimated information gain, the system requests expert feedback to validate or correct the AI decision. Operators can also provide input ad-hoc, enabling continuous model improvement from real field data. In the current prototype stage, the AL UI integration is planned for the next iteration.

Explainable AI (XAI) Visualizations

Developed by UPRC and integrated by CYENS, the XAI module presents AI reasoning visually within the AR application. The NSAI component outputs structured explanations — for example, identifying visual features such as 'Watermarks or rings', 'Disconnected segments', and 'Visible cracks' — along with their weighted contribution to the anomaly prediction. These feature-contribution scores are rendered within the AR interface, giving operators an intuitive, interpretable basis for trusting or overriding AI recommendations. Full UI integration is planned for the next prototype iteration.

Smart Pipes API

Developed by SIE, the Smart Pipes API provides the data backbone for the pilot. Suited for XR applications, It implements modular ETL workflows for ingesting vibration sensor streams, computing time-series anomaly scores, and calculating geo-location coordinates for anomaly markers. The API exposes RESTful endpoints that the AR application queries dynamically. Performance evaluation demonstrated:

- High performance throughput scaling from 1.326 to 45.500data points per second across 1-minute to 3-hour query intervals.
- API response times ranging from 450 ms (1-minute query) to 2 seconds (3-hour query), with no database bottlenecks observed.
- A primary optimisation method suited for low power devices such as Smartphones and XR Smartglasses is represented by the ability to query the timeseries dates either inline by retrieving all data points at once, suited for shorter time intervals under 24 hours or streaming, suited for much larger periods.

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Table 1 Summary of Pilot 3 components.

Component	Status	Key Achievement
AR Mobile Application	**Deployed**	*60 FPS, 3–5m GPS accuracy, real-time sensor viz*
XR-enabled AI Assistant	**Deployed**	*Faithfulness 0.929, Hallucination 0.037 (k=5)*
Neurosymbolic AI (NSAI)	**Deployed**	*F1 Score 98.6%, 94.9% workload reduction*
Active Learning	**Integrated / UI Pending**	*Expert feedback loop, ad-hoc correction enabled*
Explainable AI (XAI)	**Integrated / UI Pending**	*Feature-contribution explanations for predictions*
Smart Pipes API	**Deployed**	*979 pts/s throughput, geo-anomaly localization*
XR5.0 Training Platform	**Pending**	*Structured training programs delivered in-app*

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Pilot Evaluation

Evaluation Approach

The Pilot 3 Early Prototype was evaluated on December 5, 2025 at EKSO facilities in two Italian locations: Pozzallo (Ragusa) for UC3.1.1 and UC3.2.1, and Settimo Milanese (Milan) for UC3.1.2. Evaluation participants were experienced EKSO managers and technicians with limited prior exposure to XR technologies, representing the target end-user group precisely.

The evaluation framework combined quantitative technical performance measurements (profiling, service instrumentation, ground-truth comparison) with a structured user survey covering technical performance, usability and user experience, work impact and effectiveness, task load index, social and economic impact, and component-specific feedback. This dual approach ensured that both system-level capabilities and real-world human factors were rigorously assessed.

Figure 10 Images of early pilot evaluation at EKSO site.

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Technical Performance Results

Key technical performance metrics achieved during the evaluation are summarised below:

Table 2 Summary of key technical performance metrics.

Metric	Result	Context
AR Rendering Speed	**0.01s / segment**	*Full 10-segment pipe in ~0.1 seconds*
AR Frame Rate	**60 FPS**	*Stable during continuous API updates*
GPS Fix Accuracy	**3–5 metres**	*Dependent on satellite visibility at site*
Compass Heading Noise	**±3°–7°**	*Magnetic interference from metal infrastructure*
STT Latency (SIE)	**33.7 seconds**	*14-word user prompt transcription average*
TTS Latency (Azure)	**1.62 seconds**	*230-word audio response generation*
LLM Chatbot Response Time	**10.9 seconds**	*Combined STT + inference + response*
AI Faithfulness (k=5)	**0.929**	*Optimal retrieval config for deployment*
AI Hallucination Rate (k=5)	**0.037**	*Lowest across all configurations tested*
NSAI Precision	**84.7% avg**	*Across 2 real CCTV inspection videos*
NSAI F1 Score	**98.6% avg**	*Harmonic mean of precision and recall*
NSAI Inspection Reduction	**94.9% avg**	*Reduction in manual inspection workload*
SmartPipes Throughput (3h)	**979 pts/s**	*Linear scaling confirmed across intervals*

User Evaluation Results

End-users rated the system across five dimensions. Results are averaged across manager and technician participants:

Table 3 Summary of early pilot prototype user evaluation

Evaluation Criterion	Rating (/ 5)	Key Insight
System Stability & Responsiveness	**4.0 / 5**	*Reliable operation with minor delays*
Visual & Interaction Quality	**4.5 / 5**	*Smooth, well-integrated user experience*
Hardware Setup & Ease of Use	**3.5 / 5**	*Initial field calibration requires support*
Interface Intuitiveness	**3.5 / 5**	*Navigable; first-time XR users need guidance*
Comfort & Confidence in Use	**4.0 / 5**	*Stable operation supported task focus*
Workplace Safety Improvement	**5.0 / 5**	*Highest-rated benefit across all categories*
Task Enablement w/o External Help	**4.0 / 5**	*On-demand guidance reduces expert reliance*

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Future Use of AI Assistant	**5.0 / 5**	*Unanimously valued hands-free support*
Recommendation for New Employees	**4.5 / 5**	*Strong onboarding and training potential*
Sustainability Contribution	**4.5 / 5**	*Reduced travel, fewer site visits expected*
Benefits over Traditional Methods	**4.5 / 5**	*Clear added value vs. paper-based approaches*
Overall Satisfaction	**3.5 / 5**	*Positive overall; reliability refinement needed*

Key Findings

The evaluation produced several important cross-cutting findings:

Strengths

- Workplace safety was the standout benefit: the ability to visualize underground infrastructure in AR, reducing trial-and-error and improving situational awareness, resonated most strongly with field participants.
- The AI Assistant was universally embraced for future use, validating the concept of hands-free, voice-driven access to technical documentation in field operations.
- The AR application demonstrated strong rendering performance and pipeline visualization accuracy, providing operators with reliable visual references during simulated intervention tasks.
- The NSAI module achieved near-complete detection of expert-labelled anomalies, with a 94.9% inspection workload reduction, demonstrating compelling efficiency gains for CCTV review operations.

Areas for Improvement

- AI response hallucination perception: despite objectively low hallucination rates (0.037 at k=5), users perceived AI response reliability as moderate (2.5/5), indicating the need for improved source attribution and transparency features in the UI.
- Anomaly detection user trust: the NSAI performed strongly in lab evaluation but received low trust ratings (1.0/5) from end users, reflecting the early state of XAI UI integration. Operators could not yet see or interpret model explanations in the interface.
- AR marker precision: sensor data and anomaly markers received a clarity rating of 2.5/5, primarily due to mobile GPS limitations and visual clutter in complex scenes.
- Interface localization: participants requested Italian language support and more intuitive menu layouts for operational field conditions.
- Smart Pipes API data transfer: large dataset queries (3-hour windows) require 114 seconds transfer time — a known bottleneck with a clear optimization path via metadata separation.

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CONCLUSIONS

Summary

Pilot 3 of the XR5.0 project has demonstrated that the convergence of Augmented Reality, AI-powered voice assistance, Neurosymbolic anomaly detection, and Explainable AI can deliver meaningful, measurable value for water infrastructure operators. At the Early Prototype stage, the integrated system already achieves strong technical foundations — high-fidelity AR rendering, reliable sensor data integration, low-hallucination AI guidance, and near-complete CCTV anomaly detection — while generating consistently positive user perceptions around safety improvement, operational support, and innovation potential.

The evaluation confirmed that XR and AI technologies are not merely additive enhancements to existing workflows but represent a qualitative shift in how operators can access information, perceive their environment, and make decisions in complex field conditions. The 5/5 workplace safety rating and the unanimous willingness to use the AI assistant in future operations reflect a clear endorsement from the field.

Lessons Learned

- User trust in AI requires explainability at the interface level: high technical performance metrics do not automatically translate to user trust. Visible, interpretable AI reasoning is essential for operational acceptance.
- Mobile-first interaction is the right entry point: operators new to XR strongly prefer smartphone-based interfaces with AR reserved for high-value spatial tasks.
- Connectivity and data transfer optimization are critical for field deployment: identified optimizations to the Smart Pipes API can reduce transfer times by up to 74%, directly improving field usability.
- Human-in-the-loop mechanisms build confidence: the Active Learning design — enabling expert feedback to improve AI models iteratively — was well received conceptually and will be prioritized for UI implementation.

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CONTACT:

Project Coordinator: Matteo Falsetta, GFT
Whitepaper Contact:
Dissemination Manager: Elina Papadopoulou, INNOV

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