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Sensor-Driven Preventive Preservation for Subterranean Cultural Heritage: The ARGUS Pilot in the Baltanás Underground Wine Cellars (Spain)

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1. Background

Cultural heritage is increasingly vulnerable to climate change, air pollution, and human activity. Traditional "repair after damage" approaches often act too late, when deterioration becomes irreversible. Preventive preservation—based on continuous monitoring, early detection, and data-driven mitigation—offers a proactive alternative.

Advances in IoT, AI, and digital twins now allow heritage managers to deploy low-power, non-invasive sensor networks that characterize environmental, structural, and anthropogenic risks in real time. The EU-funded ARGUS project introduces a threat-to-sensor mapping methodology that systematically links heritage hazards with the most appropriate sensing technologies. Pilots include open-air archaeological sites, medieval structures, and underground complexes.

2 . Case Study: The Baltanás Underground Wine Cellars (Palencia, Spain)

The Baltanás complex comprises **374** subterranean wine cellars, a unique ethno-historic landscape used since at least **1543**.

Figure 1. Cellar town of Baltanás. Drone capture by Pablo Sanz.

Table 1. Summary of subterranean risk factors and their impacts

Risk Factor	Description
High humidity	Leads to condensation, salt crystallization, and microbial growth
Poor ventilation	Causes stagnant air and buildup of pollutants
Structural instability	May result in micro-cracking and deformation
Vibration	From traffic, visitors, or seismic activity
Human activity	Opening doors and movement change airflow and cause localized disturbances
Ventilation dynamics	Relies on doors, chimneys, and unloading ducts, creating complex airflow paths

3. Threat-to-Sensor Mapping (ARGUS Methodology)

Table 2. Threats, risks and applied sensors.

Preservation Threat	Risk Description	Assigned Sensor(s)
Ground / structural vibrations	Micro-cracks from traffic & visitor activity	Accelerometers; vehicle/person counters
Excessive humidity	Material decay, bio-growth	Temperature & humidity probes (ambient, internal)
Poor ventilation	Condensation & gas accumulation	Airflow sensors; counters (door-opening correlation)
Airborne pollutants	CO, NO_2, SO_2 promoting decay	Gas sensors
Extreme weather events	Local collapses not detected by vibration	Meteorological data + structural sensors

4. Sensor Deployment in Cellar 88

A multi-sensor network was installed over several field missions:

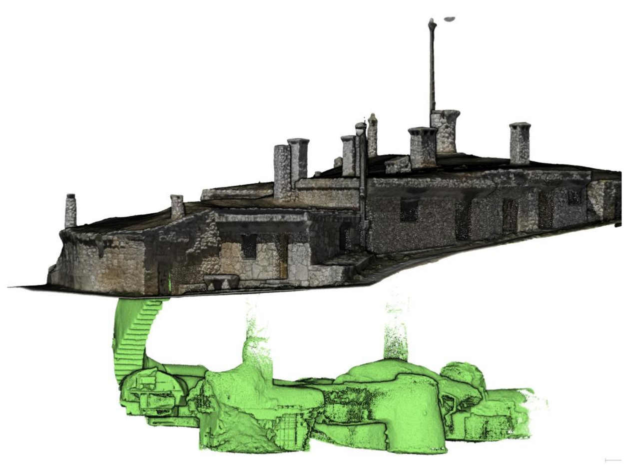

Figure 2. Point cloud of Cellar 88.

Table 3. Deployed sensors inCellar 88.

Sensor Type	Purpose / Measurement Focus
Accelerometers (×2)	Structural and ground vibration
Airflow sensors (×4)	Airflow origin, direction, and intensity
Ambient T/RH sensors (×4)	Microclimatic baseline (temperature & relative humidity)
Internal humidity blades (×3)	Moisture content inside walls
PIR + airflow sensors	Detect entry events and door-induced airflow shifts
Vehicle/person counter	Correlate human/vehicle activity with vibrations and airflow changes
GNSS rover	Long-term ground deformation (expansion–contraction cycles)

Two and a half years of continuous **temperature/humidity data** (starting April 2023) provide the first long-term microclimate baseline for the cellar network.

5. Installation Challenges & Lessons Learned

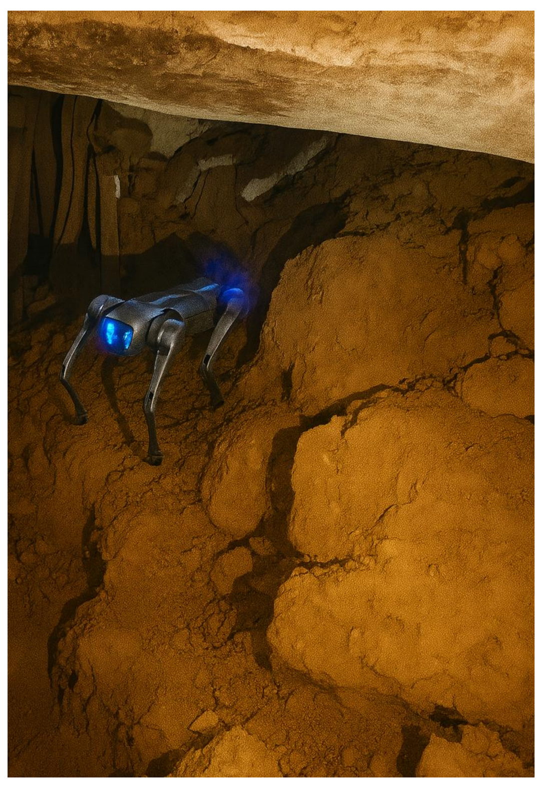

Figure 3. Collapse in cellar 88.

Challenges

Multiple site visits required: 5+ field trips due to complex underground geometry.

Communication failures: WiFi and LoRaWAN signals attenuated by dense earth/stone.

Storm-related collapses: Not detected by current sensors or satellite data.

Blind installation: Data only retrievable days later → complicated calibration.

Lessons Learned

Iterative installation is essential for subterranean environments; Communication strategy must be site-specific; Real-time validation tools would drastically reduce installation time; Storm-driven phenomena require additional structural and meteorological sensors; Cross-disciplinary coordination accelerates problem-solving.

6. Microclimatic Results (2023–2025)

Temperature & Relative Humidity

- The cellar shows strong thermal inertia → damped seasonal oscillations.
- **RH** remains near **saturation for long periods**, especially in deeper zones.

Seasonal dynamics:

- Winter: Stable RH, minimal temperature variability.
- Summer: Greater fluctuations near vents and entrances.

Preservation Implications

- Persistent humidity supports mold and fungal colonization, consistent with multispectral imaging data.
- Long-term datasets are required to capture multi-annual cycles and detect anomalies.
- Data feed into AI-based anomaly detection prototypes for early warnings.

(a)

(b)

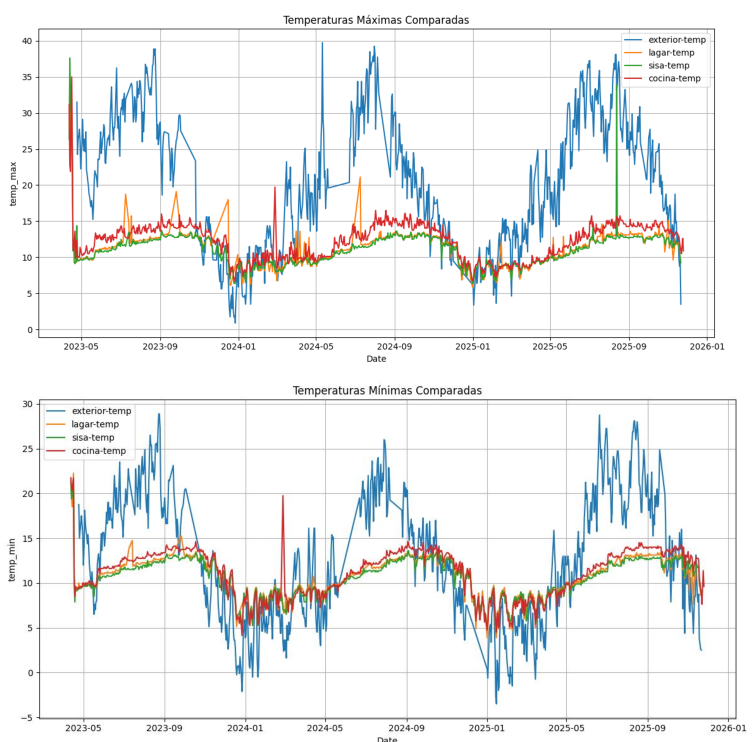

Figure 4. Cellar 88 (a) Max. Temperature and, (b) Min. Temperature.

7. AI-Enabled Anomaly Detection (Preliminary)

Machine learning algorithm trained on 2+ years of T/RH data identifies atypical humidity spikes, rapid changes, and prolonged deviations.

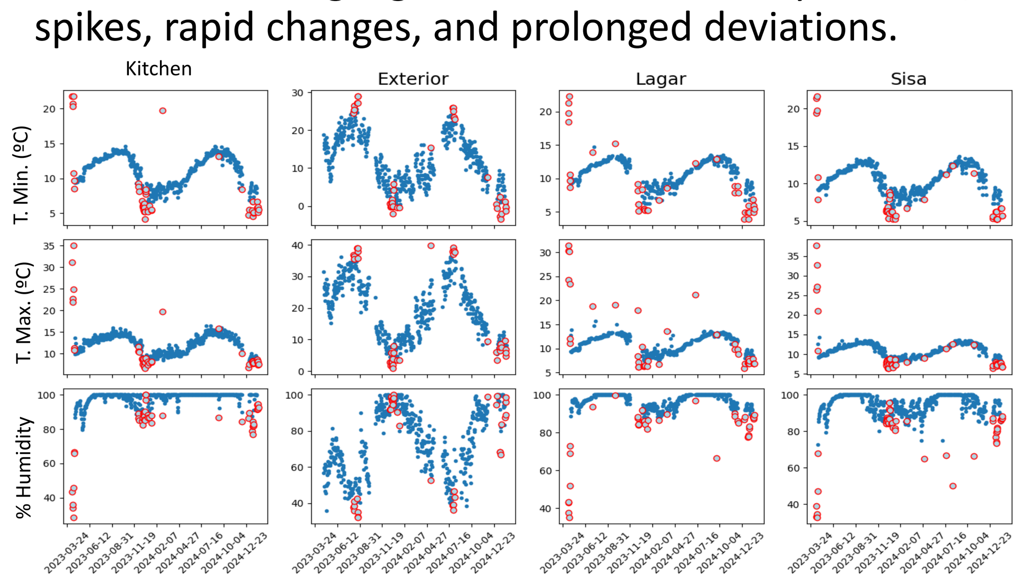

Figure 5. Anomaly detection.

Early anomalies coincide with heavy rainfall events, unexpected openings, and periods of limited ventilation.

Alerts can trigger targeted inspections, ventilation adjustments, or visitor-flow management.

This is a major step toward digital twin development, enabling predictive simulation of risk scenarios.

8. Towards Scalable, Sustainable Preservation

The Baltanás pilot demonstrates:

- ✓ The feasibility of preventive, sensor-driven monitoring in fragile subterranean heritage.
- ✓ The usefulness of a threat-to-sensor mapping methodology for site-specific deployments.
- ✓ The added value of cross-disciplinary collaboration (engineering + heritage + local authorities).

Next Steps

- ➢ Extend anomaly detection to gas, vibration, and airflow sensors.
- ➢ Integrate visitor activity into microclimate modeling.
- ➢ Develop a full AI-coupled digital twin for predictive conservation.
- ➢ Scale the methodology to additional heritage sites.

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