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Preventive Monitoring and Digital Twins for the Protection of Remote Archaeological Heritage

The EU-funded project ARGUS and the case of Monti Lucretili (Lazio, Italy)

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Introduction: Why remote heritage is at risk

Cultural heritage located in remote areas is exposed to a combination of anthropic and natural threats that can seriously compromise its integrity. In this context, remote heritage refers to archaeological and built sites located in hard-to-access or sparsely inhabited landscapes where continuous monitoring is difficult. Human activities, including unregulated tourism, looting, construction, and air pollution, generate direct and indirect pressures on monuments and archaeological landscapes. At the same time, natural disasters like earthquakes, floods, fires, or invasive species, also cause deterioration of the built heritage. The climate crisis intensifies erosion, landslides, floods, invasive species, and the accelerated degradation of materials. In this context, recent literature on risk management and preventive conservation highlights the need to move from isolated curative interventions to systematic preventive strategies capable of quantifying risks and anticipating damage in order to prioritise actions (Pedersoli et al. 2016).

The ARGUS project addresses these challenges by developing an integrated framework for preventive preservation based on multimodal monitoring, advanced digitisation, and decision support systems built on trustworthy artificial intelligence. It is grounded in the concept of the digital twin and proposes a coherent system capable of representing the state and evaluation of heritage assets. It integrates: sensor time series, satellite data, remote sensing, existing documentation, climate statistics, disaster data, and expert knowledge. The infrastructure relies on an advanced digitisation workflow and a portable measurement system for non-destructive physical and chemical monitoring. It also includes wireless sensor networks for in-depth structural and environmental assessment. Based on these data, ARGUS develops AI methods that model threat dynamics and their impacts as well as multimodal data-fusion techniques that combine climatic, meteorological, and pollution information (Lahat et al. 2015). A dedicated decision support system translates these analyses into operational tools for managers, authorities and local communities. At the same time, citizen-science activities, Living Labs, and Hackathons place the public at the heart of the monitoring and innovation cycle. These activities support knowledge exchange and strengthen local engagement with heritage monitoring.

Fig. 1: Installation of a tiltmeter at the Conventillo site for monitoring structural inclination.

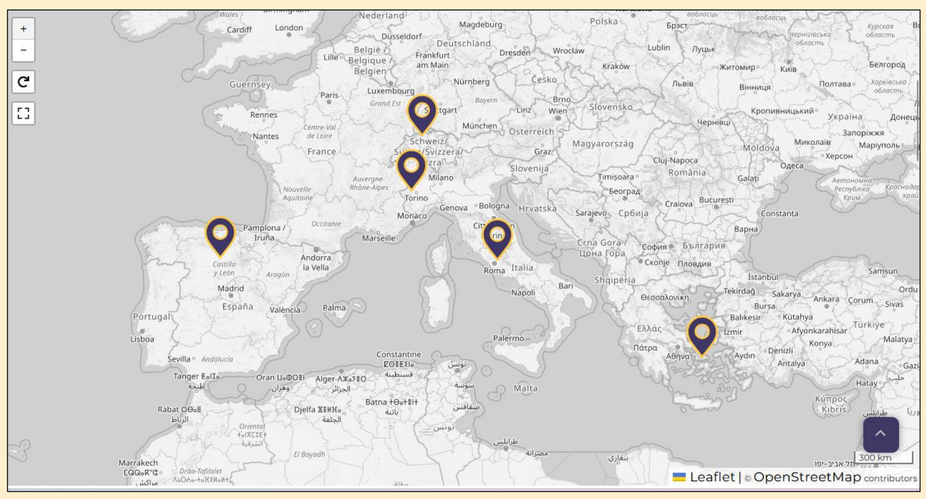

Fig. 2 Map showing the case study sites of the ARGUS project.

The Monti Lucretili Pilot Site

The landscape known as the Monti Lucretili (Lazio, Italy) constitutes an ideal case study for applying the monitoring approach proposed by the ARGUS project (Fig.2). Located in the central-eastern sector of Lazio, its rugged topography and extensive forested zones create a complex environment for heritage management. This landscape is an example of how different communities throughout history have used and perceived the territory, containing a constellation of sites from various periods that together exemplify remote built heritage. It is a landscape shaped by long-term rural occupation processes, agroforestry exploitation, and pastoral practices. This long-term rural occupation is reflected in a dense network of paths, vertical transhumance routes, agricultural terraces, dry-stone walls, ceramic scatters and microtopographic traces identified by archaeological survey (Bernardi & Farinetti 2023; 2024; Rossi & Moreno-Navarro 2025).

Within this complex landscape, the Monti Lucretili pilot site of the ARGUS project focuses on a group of heritage assets, which represent different typologies, vulnerabilities and conservation challenges within the same landscape:

- The castle of Montefalco in Sabina: a medieval castle likely dating between the 12th to 14th century AD. It is located on an exposed summit, suffering from substrate erosion, slope instability, weathering of wall surfaces, and generalized abandonment.
- Dry-stone walls and agricultural terraces: essential for understanding rural economy and mobility. They are at risk of disappearing due to structural collapse and soil loss caused by the abandonment of the structures and the loss of local knowledge.
- The rupestrian hermitage of Sant'Angelo al Morra (Conventillo): a structure that can also be dated to the 12th century AD and remained in use until the 18th century. It is partially carved into the rock and contains frescoes of great historical interest. It is vulnerable to humidity, water runoff, and rock detachments from the cliff face.
- The Roman villa attributed to the poet Horace: a leisure villa dating back to the 1st century BC. It is affected by invasive vegetation, intense rainfall and differential erosion of materials.

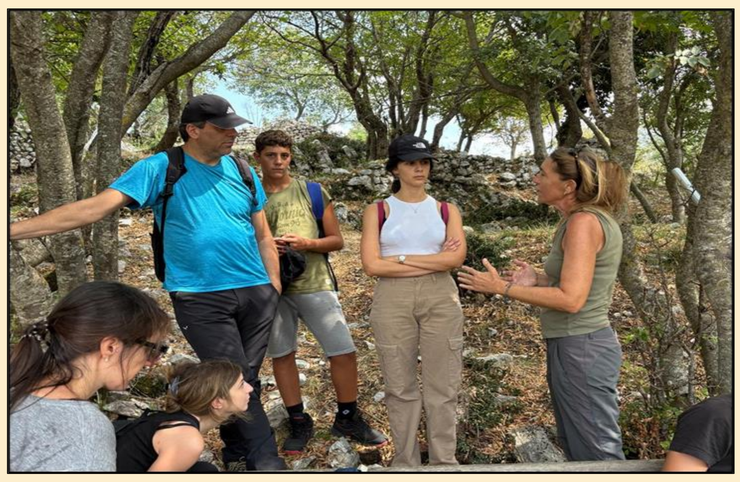

Fig. 3 Living Lab at the Castle of Montefalco: community engagement in decision making for sensor installation.

Monitoring Strategy and Sensor Deployment

The ARGUS project implements a multiscale monitoring strategy that integrates real-time satellite data with low-impact in situ sensors, enabling the observation of both landscape-scale processes and site-specific dynamics. Satellite monitoring provides continuous information on environmental and climatic conditions, supporting the interpretation of local measurements and the assessment of risks affecting heritage within a broader landscape context.

This approach is combined with a network of in situ sensors recording critical parameters for preventive conservation, including tiltmeters, crackmeters, temperature and humidity sensors, meteorological sensors, pyranometers, vibration sensors and people-counting devices. Data are transmitted in real time via LoRaWAN to the project digital infrastructure (Fig. 1, Fig. 4).

Sensor deployments address site-specific vulnerabilities at Conventillo, the Villa of Horace and Montefalco in Sabina, while GNSS sensors support the monitoring of ground displacement on selected dry-stone wall-supported agricultural terraces to monitor ground displacement and slope instability. Together, satellite and in situ data enable early risk detection, evaluation of environmental stress and support informed conservation planning. In this framework, monitoring strategies combine real-time satellite data and in situ sensors to address heritage not only as a set of individual sites, but as a diffuse cultural landscape, where risks and vulnerabilities operate across multiple spatial scales.

From Monitoring to Decision Making

The digital twin combines all collected data with existing cartography, documentation and remote imagery. AI models interpret patterns, identify risk evolution and support managers by:

- Detecting early signs of instability
- Quantifying environmental stress on built structures
- Modelling the impact of climate variability
- Guiding maintenance plans and prioritising conservation efforts
- Improving preparedness through predictive scenarios

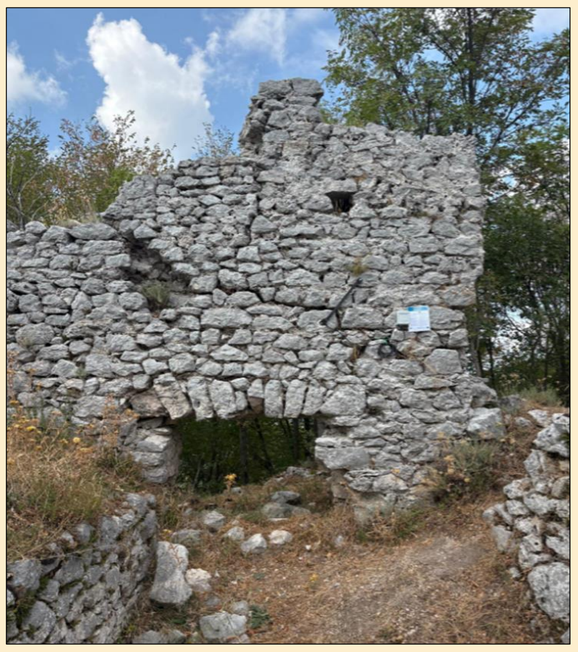

Fig. 4: Crackmeter installed at the Castle of Montefalco for monitoring structural fractures.

Community and Stakeholder Engagement

Citizen-science activities and Living Labs involve local communities in data collection, interpretation and stewardship (Fig. 3). These initiatives strengthen collaboration with municipalities, cultural authorities and park managers. The system also improves communication strategies by making monitoring results accessible through visual platforms and interactive tools.

Conclusions

The Monti Lucretili pilot demonstrates how integrated monitoring, digital twins and AI can support the protection of remote archaeological heritage. The approach provides a scalable model for preventive conservation that assists decision making, enhances community participation and contributes to long-term heritage management.

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