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AI-Assisted UAV Photogrammetry for Safeguarding Archaeological Heritage in Peru

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***Abstract*—Peru's archaeological heritage extends across desert, coastal, mountain, and forest environments and is threatened by erosion, extreme rainfall, landslides, urban expansion, looting, vehicle intrusion, tourism pressure, and insufficient monitoring. This integrative literature review examines AI-assisted unmanned aerial vehicle (UAV) photogrammetry as a practical technology system for safeguarding that heritage. UAVs acquire overlapping images at centimetre-level resolution; structure-from-motion photogrammetry converts them into orthomosaics, digital elevation models, point clouds, and textured three-dimensional models; and artificial intelligence helps screen large image collections for possible archaeological features or change. Peer-reviewed studies, technical guidance, official Peruvian information, and UNESCO documentation were synthesised around technology functions, conservation decisions, governance, and four Peruvian examples. At Nazca, AI-supported analysis of drone imagery enabled researchers to identify 303 previously unknown figurative geoglyphs in six months. At Palpa, a high-resolution drone survey documented the Pista geoglyph and revealed details that were difficult to obtain from conventional imagery. At Chan Chan, UAV and close-range photogrammetry supported virtual reconstruction, while photogrammetry, laser scanning, and HBIM created reusable records for vulnerable earthen architecture. Chankillo illustrates how repeatable landscape-scale survey could support monitoring of towers, sightlines, access routes, and erosion. The review argues that digital capture is not itself rescue. Conservation value emerges when repeatable surveys are linked to expert verification, risk thresholds, intervention records, open but security-sensitive archives, local training, and institutional responsibility. A staged implementation model is proposed for Peru's heritage agencies and partners.**

***Index Terms*—archaeological heritage; artificial intelligence; conservation; photogrammetry; Peru; remote sensing; UAV**

I. Introduction

Peru contains archaeological landscapes of exceptional temporal, material, and environmental diversity. The Lines and Geoglyphs of Nasca and Palpa extend across roughly 450 km² of coastal desert [1]; Chan Chan is a vast earthen city whose fabric is highly vulnerable to El Niño rainfall and erosion [2]; Chankillo combines thirteen towers, observation points, and landscape features into an ancient calendrical instrument [3]; and Machu Picchu faces the combined management demands of steep terrain, geological risk, tourism, and infrastructure [4]. Beyond internationally recognised properties, thousands of less documented sites remain exposed to agricultural expansion, road construction, illicit excavation, vandalism, and climate-related hazards.

Conventional documentation remains indispensable, but it is often too slow or spatially limited for large, inaccessible, or rapidly changing sites. UAV photogrammetry offers a comparatively low-cost way to acquire repeatable, high-resolution aerial images. Structure-from-motion and multi-view-stereo processing transform overlapping photographs into georeferenced orthomosaics, digital elevation models (DEMs), dense point clouds, and textured three-dimensional models [13]–[16]. These products create measurable baselines: a wall's deformation, a new vehicle track, an erosion channel, a looting pit, or loss of surface material can be compared across survey dates rather than judged only from memory or isolated photographs.

Artificial intelligence adds a screening layer. Machine-learning models can rank image locations that resemble target features, segment visible damage, or highlight change between time periods. The strongest Peruvian demonstration is the 2024 Nazca survey, where an AI system applied to high-resolution aerial imagery guided field inspection and contributed to confirmation of 303 new figurative geoglyphs within six months [5]. However, discovery is not equivalent to preservation. Algorithms can generate false positives, reveal sensitive locations, or divert funds toward visually impressive models without producing physical conservation.

This review therefore asks three questions: What conservation functions can AI-assisted UAV photogrammetry perform? What do Peruvian cases demonstrate about practical value and limitations? Which management arrangements are required to convert digital records into heritage protection? The article treats the technology as a socio-technical conservation system comprising field planning, permissions, image acquisition, photogrammetric processing, AI-supported interpretation, archaeological verification, conservation decisions, archiving, and repeated monitoring.

II. Methods

An integrative review was conducted to combine peer-reviewed technical studies with site-management and policy evidence. Searches completed in August 2026 combined terms including "Peru," "archaeology," "UAV," "drone," "photogrammetry," "LiDAR," "artificial intelligence," "Nazca," "Palpa," "Chan Chan," "Chankillo," "Machu Picchu," "monitoring," and "conservation." Sources were identified through scholarly search services and the publication portals of PNAS, Elsevier, MDPI, UNESCO, ICOMOS, Open Heritage 3D, and the Government of Peru. Citation chaining was used

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to locate foundational work on structure-from-motion, aerial archaeological survey, laser scanning, and digital heritage management.

Sources were included when they explained a relevant sensing or processing method; reported a Peruvian application; documented threats or management requirements at a Peruvian archaeological property; or addressed ethical, archival, and operational issues in digital heritage. The synthesis prioritised peer-reviewed and institutional sources and retained 32 references. Evidence was coded into five functions: discovery and inventory, metric documentation, condition assessment, surveillance and change detection, and communication or reconstruction. It was then mapped to conservation decisions, implementation requirements, and risks. Because technologies, sites, and outcome measures were heterogeneous, no meta-analysis was attempted. This is an integrative review rather than a claim of exhaustive systematic coverage.

TABLE I. TECHNICAL COMPONENTS AND CONSERVATION FUNCTIONS

Component	Primary output	Conservation use	Principal limitation
UAV RGB imaging	Overlapping geotagged photographs	Rapid coverage of walls, geoglyphs, routes, excavations, and terrain	Flight restrictions, wind, shadows, vegetation, and battery endurance
SfM photogrammetry	Orthomosaic, point cloud, DEM, textured 3D mesh	Metric baseline, mapping, volumetric analysis, deformation and surface-loss comparison	Accuracy depends on image geometry, scale control, calibration, and processing choices
LiDAR/laser scanning	Dense range-based point cloud	Complex geometry, low-texture surfaces, and complementary structural documenta-tion	Higher cost, specialist operation, and difficult data integration
AI image analysis	Ranked candidates, segmentation, anomaly or change alerts	Screens large areas and directs scarce expert attention	Bias, false positives, explainability, and sensitive-location disclosure
GIS, HBIM, and archives	Linked spatial, historical, condition, and intervention records	Turns survey products into prioritisation, maintenance, and institutional memory	Interoperability, long-term storage, access rights, and staff capacity

III. RESULTS

A. From Image Capture to Conservation Evidence

UAV photogrammetry produces conservation value through repeatability and measurement. A flight plan with consistent altitude, image overlap, camera settings, ground control, and coordinate reference can be repeated after a rainy season, earthquake, visitor incident, or conservation intervention. Orthomosaics support mapping; DEMs expose microtopography and drainage; point clouds enable cross-sections and surface-distance calculations; and textured meshes preserve form and appearance for inspection, research, or interpretation. Archaeological guidance consistently warns that attractive three-dimensional visualisation is not proof of metric reliability. Ground sampling distance, control-point distribution, camera calibration, reprojection error, coordinate accuracy, missing surfaces, and processing parameters must be reported [13]–[18].

AI is most useful when the area or image volume exceeds human screening capacity. It can rank candidate geoglyphs, classify land-cover or disturbance signatures, and identify pixels or surfaces whose appearance changed between surveys. Its output should be treated as triage rather than final archaeological identification. Field verification, comparison with historical imagery, contextual interpretation, and documentation of uncertainty remain essential. This human-in-the-loop arrangement reduces two dangers: accepting algorithmic patterns as archaeology and overlooking subtle evidence because a model was trained on visually dominant examples.

B. Peruvian Applications

Nazca provides the clearest example of AI-assisted aerial archaeology. Sakai and colleagues deployed an AI system across the Nazca region and used its ranked candidates to guide field survey. The project confirmed 303 previously unknown figurative relief-type geoglyphs in six months, nearly doubling the number known from earlier work [5]. The conservation implication is not simply faster discovery. A more complete inventory improves buffer-zone planning, impact assessment, patrol priorities, and evaluation of roads or vehicle movement. Yet publication of precise coordinates must be controlled because visibility can also increase vandalism or illicit visitation.

At Palpa, Pavelka, Šedina, and Matoušková used high-resolution drone surveying at the Pista geoglyph to produce detailed orthophoto and elevation products [7]. Earlier Nasca–Palpa photogrammetric work had already shown the benefit of three-dimensional recording for extensive geoglyph landscapes. The Pista case demonstrates a scalable monitoring principle: repeat the same flight after exceptional rainfall, nearby construction, or traffic incidents; align the datasets; calculate surface or microrelief differences; and send only significant changes for archaeological inspection. It converts a one-time map into a condition-monitoring instrument.

Chan Chan demonstrates the technology's relevance to fragile architecture. UAV and close-range photogrammetry were used to reconstruct Palacio Tschudi and map Chimú architecture for conservation [6]. At Huaca Arco Iris, combined photogrammetric methods supported virtual reconstruction [9], while later work integrated photogrammetric documentation with HBIM to organise geometry, materials, damage, and conservation information [10]. A 2019 documentation campaign at Palacio Tschudi and Palacio Rivero combined terrestrial LiDAR, terrestrial photogrammetry, and drone imagery [11]. This complementarity matters because earthen walls contain occluded spaces, low-texture surfaces, reliefs, and protective roofs that may not be captured reliably from one

platform. UNESCO identifies El Niño, erosion, plundering, and development pressure as persistent risks [2], [27]. Repeat surveys can locate new cracks, wall loss, moisture pathways, roof failure, encroachment, and graffiti, but physical stabilisation and drainage remain the actual conservation interventions.

Chankillo offers a forward-looking application. The site's significance depends on the spatial relationship among thirteen towers, observation points, buildings, horizon, and solar movement [3]. UAV photogrammetry can document tower geometry, slope erosion, footpaths, visitor movement, and changes to sightlines or buffer-zone land use. Periodic orthomosaics and DEMs could identify gully development or unauthorised access before damage becomes severe. Three-dimensional landscape models can also support interpretation without encouraging unrestricted movement through fragile sectors. This is a proposed management application grounded in the site's attributes, not evidence that a comprehensive AI monitoring programme is already operational.

TABLE II. PERUVIAN EXAMPLES AND TRANSFERABLE LESSONS

Site or case	Technology demonstrated	Documented or proposed contribution	Transferable lesson
Nazca region	AI screening of high-resolution aerial imagery plus field verification	303 new figurative geoglyphs confirmed in six months [5]	Use AI to prioritise expert inspection; protect sensitive coordinates
Pista geoglyph, Palpa	High-resolution UAV photogrammetry	Detailed orthophoto and terrain documentation [7]	Repeat standardised flights to detect microtopographic change
Palacio Tschudi and Huaca Arco Iris, Chan Chan	UAV and close-range photogrammetry, laser scanning, HBIM	Virtual reconstruction and structured conservation records [6], [9]–[11]	Combine sensors and connect geometry to damage and interventions
Chankillo	Proposed repeat UAV survey linked to GIS	Monitoring towers, erosion, routes, sightlines, and buffer-zone change	Define conservation indicators before acquisition
Regional patrols	Government use of drones to detect possible huaqueros	Faster surveillance of dispersed archaeological areas [26]	Integrate alerts with lawful response teams and evidence protocols

C. Risks, Governance, and Institutional Capacity

The technology introduces legal, ethical, and operational risks. Flights require aviation and heritage permissions, and operations near visitors, communities, wildlife, or steep terrain require safety planning. Imagery may capture people, private land, sacred places, active excavations, or exact locations of unprotected remains. Open access supports research and accountability, but unrestricted publication may facilitate looting. Data governance should therefore distinguish public derivatives, controlled research datasets, and restricted operational layers. UNESCO's Recommendation on documentary heritage and its Recommendation on the Ethics of Artificial Intelligence support preservation, accessibility, transparency, and accountable use while recognising legitimate restrictions [20], [32].

Digital sustainability is equally important. Proprietary project files, undocumented coordinate systems, missing camera metadata, or obsolete formats can make a survey unusable after staff turnover. Each campaign needs a data-management plan, stable identifiers, open preservation formats where possible, processing logs, accuracy reports, checksum-controlled backups, rights metadata, and named institutional custodians. Local archaeologists, conservators, surveyors, students, and community representatives should participate in defining indicators and interpreting change. Dependence on short foreign missions can produce excellent models without durable Peruvian capability.

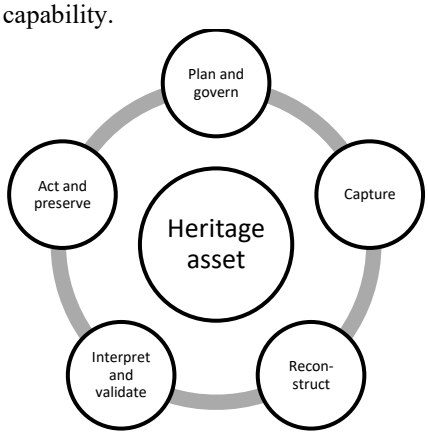

Fig. 1. AI-Assisted UAV Photogrammetry as a Conservation Cycle

IV. DISCUSSION

The reviewed evidence supports a shift from project-based digitisation to risk-based monitoring. Fig. 1 begins with a conservation question, not a drone. Managers should specify the asset, threat, decision, urgency, required accuracy, and acceptable uncertainty. Permissions and data rules are established before flight. Images are then processed into documented spatial products; AI and experts interpret candidates or change; verified findings trigger intervention, patrol, research, closure, drainage, stabilisation, or communication; and later surveys evaluate whether risk or condition changed. Feedback makes the archive cumulative rather than a collection of disconnected models.

A national programme need not scan every site at maximum resolution. A tiered portfolio is more defensible. Tier 1 uses satellite imagery and local reports to identify broad land-use change. Tier 2 deploys UAV orthomosaics to vulnerable or uncertain areas. Tier 3 adds ground control, repeat photogrammetry, laser scanning, material assessment, or structural monitoring for high-value and high-risk assets. AI can rank candidates across Tiers 1 and 2, while conservators determine escalation. This allocation reduces cost and prevents technically ambitious recording from consuming budgets needed for roofs, drainage, guards, community agreements, or emergency stabilisation.

Peru already has a practical surveillance example: cultural authorities in Lambayeque reported using drones during preventive operations to detect possible huaqueros [26]. The next step is institutional integration. Drone

observations should enter a case-management system containing time, coordinates, imagery, confidence, response, legal status, and outcome. For Chan Chan, the same logic can link surface models to HBIM elements and conservation histories. For Nazca and Chankillo, GIS can connect detected change to boundaries, attributes of outstanding value, access routes, and authorised activities. Technology then supports accountability: managers can show why a sector was prioritised, what intervention occurred, and whether it worked.

Evaluation must move beyond flight counts, model polygons, or social-media reach. Useful indicators include area surveyed per staff hour, horizontal and vertical accuracy, percentage of AI candidates verified, false-positive rate, time from alert to inspection, new damage detected, interventions prioritised, condition change after intervention, archive completeness, staff trained, and local participation. Financial evaluation should include equipment, software, permits, travel, control surveying, processing, storage, maintenance, and staff time. A cheap flight can produce expensive and unusable data if standards and custody are absent.

Community participation should be designed as part of the monitoring architecture rather than added after technical processing. Residents, guides, farmers, schools, and site workers often recognise unusual vehicle movement, fresh excavation, altered drainage, or wall deterioration before a periodic specialist mission occurs. A controlled reporting channel can combine geotagged observations with scheduled UAV coverage, while archaeologists verify significance and authorities decide whether coordinates can be shared. Participation also improves legitimacy when flight routes cross inhabited or culturally sensitive landscapes. Consent, notification, benefit sharing, and feedback on resulting actions are therefore operational requirements, not merely public-relations activities.

Emergency use requires a related but faster protocol. After intense rainfall, earthquake, fire, vandalism, or suspected looting, managers need a pre-approved flight area, trained operator, baseline dataset, safe launch points, standard naming rules, and a short damage-assessment template. Rapid orthomosaics can identify access failures and affected sectors; targeted oblique images can document unstable walls; and change maps can prioritise ground inspection. The resulting model should never encourage entry into unsafe areas or substitute for structural and material expertise. Its purpose is to reduce uncertainty, direct scarce personnel, and preserve evidence before cleanup or stabilisation changes the scene. Periodic exercises can test whether agencies can retrieve the baseline, collect compatible data, process it quickly, and convert the findings into authorised conservation work.

The evidence base also has limitations. Technical case studies commonly report visual or geometric products but rarely quantify whether documentation prevented loss. Cross-site comparisons are complicated by different cameras, altitudes, control networks, software, terrain, and accuracy metrics.

TABLE III. IMPLEMENTATION AGENDA FOR PERU

Priority	Recommended action	Evaluation indicator
Risk-led selection	Rank sites and sectors by significance, exposure, vulnerability, and decision urgency	Share of missions tied to a documented conservation decision
Acquisition standard	Specify overlap, control, coordinate system, accuracy, metadata, safety, and repeat routes	Percentage of datasets passing metric and metadata checks
Human-in-the-loop AI	Record training data, confidence, false positives, and expert verification	Precision, recall, verification time, and documented uncertainty
Conservation integration	Link alerts and 3D records to inspections, work orders, patrols, and intervention histories	Median alert-to-response time and condition outcome
Data stewardship	Maintain preservation files, access tiers, backups, rights, and institutional custodians	Retrievability and completeness after staff or software change
Local capability	Train Peruvian staff and involve communities in threat definition and interpretation	Certified teams, repeat missions led locally, and community participation

AI performance at Nazca cannot be assumed for earthen-wall cracks, forest sites, or looting detection. Seasonal shadows and vegetation may mimic change, and increasingly automated workflows may conceal uncertainty. Future research should conduct prospective monitoring studies that define threats and thresholds before acquisition, compare UAV, satellite, terrestrial, and community-reporting strategies, publish accuracy and error matrices, and follow conservation decisions through to physical outcomes.

V. CONCLUSION

AI-assisted UAV photogrammetry is a promising technology system for safeguarding Peru's archaeological heritage because it combines rapid coverage, metric three-dimensional documentation, repeatable monitoring, and prioritised interpretation. The evidence is strongest when technology is tied to a concrete heritage problem. At Nazca, AI helped screen aerial imagery and accelerated confirmation of 303 geoglyphs. At Palpa, drone photogrammetry documented subtle geoglyph terrain. At Chan Chan, photogrammetry, laser scanning, and HBIM created complementary records for vulnerable earthen architecture. At Chankillo, the same methods could monitor geometry, erosion, access, and landscape relationships.

Nevertheless, a digital surrogate does not rescue a site. Rescue occurs when verified evidence changes a conservation decision, triggers timely action, preserves institutional memory, and reduces future loss. Peru should therefore adopt a tiered, risk-led programme with standardised acquisition, human verification of AI outputs, controlled access to sensitive coordinates, interoperable archives, local professional capacity, and outcome-based evaluation. Used in this way, drones and AI can strengthen—not replace—archaeological expertise, community stewardship, legal protection, and physical

conservation.

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