Autonomous Integrated Systems in Archaeology

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ABSTRACT

This research paper presents a transformative, autonomous dual-system framework that is designed to meet the critical challenges of modern field archaeology: physical safety, increasingly prohibitive operational costs, and technical limitations imposed by manual surveying. Cultural preservation historically plays an important role in archaeology, but global archaeological efforts are often hampered by a "funding paradox." While some regions enjoy robust institutional support for archaeological endeavors, many globally significant sites remain unexplored due to government budget constraints and the high risks associated with manual excavation. Through a primary research interview with global archaeology expert Mohammed Abualsaid, our team identified three primary barriers to progress: extreme labor risk, including venomous wildlife and unstable underground water sources; the high cost of human missions; and the absence of integrated, real time decision-making technology. To address these problems, we propose a fusion of the Subsurface Autonomous Ground Explorer (SAGE) and the Aero-Recovery & Transport Drone (ART-D). The SAGE node features a complex sensor fusion array that integrates Ground Penetrating Radar (GPR) imaging, Infrared (IR) thermography techniques, and high-definition computer vision capabilities for creating real time maps of the subsurface. This research will show that high risk human excavation can be alleviated by incorporating precision robotics and will thereby lower the barrier for archaeological missions and provide a means for underfunded countries to retain their heritage while keeping archaeologists everywhere safe.

INTRODUCTION

Often seen in a very sanitized form of adventure on screen, archaeology today is instead a highly resistant activity in physical, economic, and operational terms. Due to mounting global urbanization, a regime in which more than 55% of the population of the world currently inhabits urban areas the requirement for “rescue archaeology” (archaeological excavations necessary ahead of new developments) is now subtended to represent the chief spurring component of this field. Moreover, in many regional European countries, rescue archaeologies now represent more than 90% of all activity related to archaeologies. Not surprisingly under such pressing requirement stipulations, however, the equipment and operational practices involved in such missions to date have not yet matured from 20th-century manual limitations a directly threatening component to a balance positioned between history maintenance and development rate.

The Economic Barrier

The “funding paradox” is still a huge challenge. Even though the global cultural heritage management market is valued in billions, the funding is not equally dispersed. In fact, according to the National Science Foundation (NSF), the funding for archaeological study may be dwarfed when compared to other fields of science; for example, when changes in funding took place at the fed, millions of dollars for grants related to archaeology disappeared or had been pulled back, so that researchers had been working with outdated hardware. In areas not in the high-level investing areas such as the UAE, for example, governments do not consider archaeology a high-level funding concern. Because of this shortage, there is manual survey involved, which is much more time consuming. It has been validated that whereas high-tech methods such as 3D laser scanning would cut the time spent on the collection of data for such missions by 50 percent, the high CAPEX for such high-tech hardware is not feasible for most missions, so they are limited to procedures involving more time-consuming methods

Occupational Hazards and Labor Risks

The environment surrounding an excavation site is very adverse. Archeologists are challenged by a list of ‘triple threats’: both biological and geological.

•Biological Risks: In arid areas such as Egypt or the Levant, the excavation pits with shade can become vermin habitats.

• Geological Hazards: Trench failures rank high among the causes of injuries. Extensive support is mandated by safety regulations, including OSHA, for trenches exceeding 1.5 meters, but despite this, underground water entry remains a threat to life.

•Environmental Stress: Heat-related illnesses are a major occupational hazard. There have been reported cases of deaths among young archaeologists from heatstroke in recent years because temperatures have regularly exceeded 40°C (104°F) in the excavation site.

The Technological Stagnation

There is a gap between the existent technology and field application. While GPR and LiDAR systems exist, they are infrequently combined within a single, autonomous decision-making framework. Most ground-penetrating radar systems today still require a human expert to interpret complex "radargrams," which is highly subjective and sometimes results in the mistaken destruction of delicate pieces. In addition, manual recording using notebooks and physical grids wastes time and introduces transcription errors. Without a movement towards sensor-fused robotics, this profession remains shackled to high-risk, high-cost, low-efficiency labor that jeopardizes the safety of researchers and the history they uncover.

LITERATURE REVIEW

Ground Penetrating Radar (GPR) Physics and Computational Evolution

Ground Penetrating Radar (GPR) is a non-invasive geophysical method that utilizes radar pulses to image the subsurface. In general terms, the basic principles of GPR are based on the propagation and reflection of electromagnetic (EM) waves. When the SAGE rover issues a pulse into the terrestrial substrate, the wave travels until it reaches a boundary between materials having different electrical properties, particularly their dielectric constants.

The contrast between "matrix" and "feature" in an archaeological context creates data: dry sandy soil may have a dielectric constant of 3−5, whereas a ceramic vessel, for instance, or a limestone block may be within the range of 6−12. This contrast reflects part of the EM wave back to the receiver. The "two-way travel time" it takes the signal to return allows the system to calculate the object's exact depth by means of $d = 2v \cdot t$, in which v is the velocity of the wave in that particular soil medium.

The Current Problem: "Radargram" Bottleneck

Despite its usefulness, conventional GPR suffers severely from what is known colloquially as the "Radargram" problem. A standard result of a GPR survey is a hyperbola of reflection, and this is notoriously hard to interpret by eye. Under current practice for archaeological expeditions, it takes a very skilled geophysicist to manually interpret a "Radagram" by picking out the undesirable "clutter" of roots, rocks, and soil saturation levels to get a meaningful image of the "cultural heritage." This can result in "false alarms," where excavators will dig out a boulder after hours of digging because it's a "5000-year-old temple."

The Innovation

Integration between Real-Time Machine Learning The SAGE system goes above and beyond human analysis by utilizing Convolutional Neural Networks. Through training the developed Machine Learning model with thousands of known patterns from radargrams for pottery, bone, and masonry, the spacecraft is able to engage in "object classification" in real-time. This Optimization allows the rover to create a 3D volumetric representation of the subsurface instantly. Contrary to the messy 2D image, the SAGE rover "optimizes" the view by projecting a digital representation of the archaeological site, enabling the rover to self-manipulate and excavate the site without.

Infrared (IR) Thermography and Thermal Inertia

Although the GPR works superbly in detecting the density, it may be deceived by air pockets and moisture in the soil. To overcome these issues, the system incorporates the usage of Infrared Thermography. This technique analyzes the 'Thermal Inertia' of the soil, i.e., the rate at which the Earth re-radiates the solar radiation. The presence of archaeological features such as a burial pit filled with sediment, an empty tomb, or a stone footing affects the variation of the surface temperature. For example, an empty chamber represents an insulator where the soil above an empty tomb will be relatively cooler during the daytime and warmer during the night for a longer period. Using high-resolution thermal cameras, the SAGE rover can locate these "thermal anomalies." In other words, upon the detection of a thermal footprint indicative of an empty void by the IR sensor and a structural boundary at the same location by the GPR sensor, the project attains "multi-modal verification," which would not be possible with human land surveying.

System Design: SAGE & ART-D Framework

The SAGE (Subsurface Autonomous Ground Explorer)

The The SAGE vehicle is essentially the 'Mobile Lab' and command center for each excavation dig site. However, the SAGE vehicle is mounted with a tread-based platform to overcome the unpredictable ground conditions encountered in active dig sites: Egypt's soft sand or Macedonia's rocky terrain. Indeed, treads provide a larger surface area in contact with the ground compared to wheels to prevent 'Ground Pressure' (P=F/A) that may unintentionally crush ancient artifacts buried just centimetres beneath the surface of the ground.

The Sensor Fusion Layer The real strength of SAGE is in its Sensor Fusion Layer. It is not based on a single source. It integrates:

1. GPR: For subsurface density

2. IR Thermography: For Void Detection & Soil Disturbances

3. LiDAR (Light Detection & Ranging): For the purpose of forming a high definition 3D map of the surface terrain to insure that the rover avoids obstacles and dangerous slopes.

The Confidence Score Algorithm

At the nucleus of SAGE is its Autonomous Decision Engine. For our confidence score (CS) algorithm, we have developed a proprietary recipe using Bayesian Probability.

1. If the CS value exceeds 85%, the rover will label the area a "High-Value Target" and send a "Safe Dig" message to the recovery team. This ensures that the area will not be the target of "blind digging."

The ART-D (Aero-Recovery & Transport)

The final and most fragile part of the archaeology process is the removal of the artifact. Although very skilled and dexterous, human hands bring a biological risk to artifacts. Skin oils and bacteria on hands can cause a quick deterioration of artifacts such as leather or textiles or a sample of ancient DNA.

Precision Soft Touch Grippers

The problem of precision in retrieving samples is resolved in the ART-D Drone with Soft Robotics. It employs pneumatic soft touch grippers made of compliant polymers instead of hard metallic claws. They exert equal pressure all around the sample, just like a human hand. But unlike human hands, it doesn't come with the possible contaminants. Whether it is a bone sample from a calcified bone or the rim of a delicate ceramic piece, it will grip it with a strength proportional to the weight of the sample as indicated by SAGE.

GPS Synchronization and Vertical Extraction In order to protect the artifact from any damage due to lateral motion or ground tremors (which can often break delicate artifacts), the ART-D uses Real-Time Kinematic (RTK) GPS. The SAGE rover sends out the precise location of X,Y,Z where the artifact was discovered. The aircraft sits directly on target, extracts it vertically without any deviation, and then carries it to a mobile preservation laboratory. This is called 'Air-Bridge,' because it provides precision to what is currently one of the most perilous aspects of archaeology the transfer of artifacts from tunnels to laboratory analysis.

METHODOLOGY

Addressing the very high-stake requirement of transporting ancient, often brittle artifacts over uneven terrain via UAV, our team has conceived a revolutionary containment medium: the Tunable Rheological Smart Gel, TRSG. Traditional transport relies on static foam or bubble wrap, which are passive and often fail to dampen the specific harmonic frequencies generated by drone rotors or the sudden G-force spikes of wind gusts. The TRSG represents a paradigm shift-a responsive, "living" padding system that actively alters its molecular structure in a manner designed to protect its cargo.

Architectural Composition of TRSG

The TRSG is not a simple substance but rather a multi-phasic material composite. The effectiveness of this material depends upon three foundational scientific pillars which synergistically interact with each other: non-Newtonian physics, thermal phase-change transitions, and macromolecular self-assembly.

1. The Shear-Thickening Fluid (STF)

The key material constituting TRSG is a high-performance "Shear-Thickening Fluid" (STF). At equilibrium and when under low stresses, such as during steady flight modes of the ART-D drone, STF will be similar to a low-viscosity fluid so that it can "nestle" within the material and get 100% surface area contact. The STF mixture contains a high suspension concentration of silica nanoparticles and/or cornstarch nanoparticles within a "bio-polymer" material.

2. Embedded Phase-Change Material (PCM) Micro-C

For addressing “Environmental Paradox” in archaeology the apparent contradiction presented by artifacts traveling from cool to hot environments the TRSG is filled with biodegradable nano-capsules encapsulating Phase-Change Materials. PCMs are basically the regulatory mechanism for vibration and temperature in this system.
As the drone ascends to height or changes regions with varying climatic conditions, a latent transition of PCMs takes place. By releasing or absorbing energy during transitions from a solid to a liquid state in capsules or vice-versa, they help regulate a constant temperature for the artifact. In addition to that, "These capsules are micro-dampers." With a high loss tangent that determines energy dissipation during transitions, we design a gel that counteracts a distinct high-speed vibration of drone motors set between 5,000 to 10,000 RPM (Rotations Per Minute), a speed that has been observed to induce micro-fractures in ancient glass or ceramics.

3. Self-Assembling Bio-P

It is also challenging to retain the homogeneous nature of this complex gel; hence, the influence of gravity can make particles sink. To counter this, the TRSG has developed the Self-Assembling Bio-Polymer Network. This is made up of proteins or cellulose-based polymers that are long chain and create the effects of a ‘web’ within this fluid.
All these polymers are bound together through reversible hydrogen bonding. When subjected to physical separation or stressing, these hydrogen bonds “unzip” to absorb stress-energy input, therefore “re-zipping” upon removal of stressing. This imbues TRSGs with self-healing characteristics, ensuring that their padding remains a homogenous, whole protective mass regardless of completed operations or aggressive handling.

Addressing Design Criteria and Global Impact

The TRSG is a specially designed robot to meet the stringent requirements of the FIRST LEGO League Innovation Project as well as the practical realities determined by our expert consultant, Mohammed Abualsaid.

• Optimizing Aerial Transport: Since we designed the padding to be intrinsically integrated into the drone, cargo bay, this excludes the need for a bulky external packaged. This reduces take-off weight for the drone and enhances battery life and range a very important component, especially for sites in remote areas in Egypt or Macedonia.

• Environmental and Human Safety: A majority of the industrial gels serving for dampening are petroleum-based silicones or toxic cross-linkers. Thus, the TRSG should be water-based and completely biodegradable. In case of failure of landing or spill, this gel degrades into harmless organic compounds that do not pose any threat to either the archaeological site or the researchers.

• Economic Scalability: Though the synthesis of intelligent materials is expensive, TRSG focuses its attention on using abundant raw materials, such as plant-based starch and cellulose. We aim to develop a sort of "concentrate" to which it will be possible to add water at the excavation site, which immensely reduces transport costs by rendering it also accessible to underfinanced archaeological missions.

Challenges and Future Research Directions

The TRSG is a conceptual innovation, without field deployment as yet, but rather further interdisciplinary research is needed; key areas of focus include:

1. Rheological Fine-Tuning: Determine the specific particle-to-fluid ratio necessary to protect various material densities-such as the difference between protecting a heavy stone stela and a light bird bone.

2. Long-term stability: Tests involving the performance of the biopolymers when subjected to the high UV radiation and heat at excavation sites.

3. Soft Actuator Integration: The adoption of piezoelectric elements within the gel that may produce a small counter-vibration to perfectly stabilize an artifact during heavy turbulence.

Conclusion of Drone

The Tunable Rheological Smart Gel is the "missing link" in autonomous artifact recovery. By combining the reactive nature of shear-thickening fluids with the stability of self-assembling polymers, we have created a material that doesn't just sit there it protects. This "intrinsic padding" is the factor differentiating our system from every other drone delivery service in the world. It is a smart, safe, and sustainable solution for the most fragile pieces of our shared human history.

Autonomous Vision-Guided Mobile Manipulation System for Subsurface Artifact Retrieval

System Overview

The proposed system is an autonomous vision-guided mobile manipulation system aimed at locating and grasping archaeological proxy artifacts and moving them from one place to another in a cluttered environment. This system uses the power of artificial intelligence through the use of a hybrid AI robotics system that can function on its own without the need for human control in environments that consist of granular materials like sand or gravel.

Hardware Architecture

1. Mobile Base
   The mobile base comes with a four-wheeled mecanum design that promotes movement in any direction, including forward, sideways, diagonally, as well as rotation. This is significant when it comes to aligning artifacts with high accuracy without having to make large turns.
   This asymmetric driver design gives rise to non-uniform characteristics in the electrical and mechanical domains, and such asymmetry is addressed by software-based actuation equalization, including kick pulses, direction mapping, and refresh operations.

2. Manipulation Subsystem
   The robotic arm has four degrees of freedom controlled by servos:
   1. Base rotation (s1) – the horizontal movement of the arm relative to the base
   2. Primary arm articulation (s2) – vertical lowering motion
   3.Secondary lift joint (s3) - lifting of the object which is grasped
   4.End-effector claw (s4) - gripping & releasing mechanism

   Because of limitations in the actuator (SG90 micro-servos), the manipulation system is controlled by pre-calibrated joint space macros rather than by inverse kinematics. This ensures deterministic motion without significant computational overhead or mechanical load.

3. Embedded Control Units

   Note:

   The system uses distributed embedded control:

   1. Arduino (Car Controller): Real-time Motor Control and Locomotion Systems
   2. Arduino (Arm Controller): Servo control and manipulation sequencing
   3.Raspberry Pi: High-level perception, decision-making, and inter 4. The communication among subsystems happens through USB serial connections that establish a master-slave hierarchy with the Raspberry Pi as the central cognitive unit.

4. Perception System

   Vision Hardware

   The RGB monocular camera with a forward-facing perspective is rigidly attached and aligned with the forward workspace of the arm and the mobile platform. This rigid extrinsic provides a fixed relationship between the image coordinates and the reachable manipulation areas.

YOLO v1 Model

"The perception pipeline is driven by a YOLO convolutional neural network. It is particularly designed and trained to recognize the following entities and their attributes:

1. Artifact proxy objects (e.g., 3D-print
2. Environmental reference objects (e.g., sand container / bucket)
3. It supports single shot object detection techniques to provide bounding box predictions along with class probability distribution.

Key properties:

1. Input resolution for embedded inference
2. High Recall in Partially Occluded and Low Contrast Objects 3. Lighting variation and granularity in texture noise

Traditional Termination Without Depth Sensors:

1.Instead of relying on direct estimates of depth: it uses image space heuristics
2.Centroid of the bounding box, lateral
3.Bounding box area → approximate distance estimation

This makes stereo vision or depth cameras unnecessary while still allowing for effective approach and stop behavior.

Control and Decision-Making Framework

The system's behavior is based on a finite state machine (FSM), so the decision path is well-structured and traceable:
1. SEARCH: Rotational scanning for target detection
2.ALIGN: Lateral correction to center target in camera frame
3.ACTION: Moving forward and maintaining proper alignment
4.PICK: Execution of pre-defined manipulation mac
5.TRANSPORT / DROP: Handling of object movement -

All transitions are according to perceptual confidence levels and spatial constraints.
Closed-Loop Visual Servo Locomotion is controlled through the system of "visual servoing," in which the vision system provides feedback directly to the motor controllers:

1.Horizontal pixel error → rotational adjustment (L / R)
2.Centroid alignment within tolerance → forward motion (F)

This is a continuous feedback loop that lets the robot dynamically adapt to disturbances in the environment or noise in the detection.

Pulse-Based Locomotion Control
Due to the absence of any analog speed control, motion commands are issued as pulses of short duration:

1. Forward pulses for incremental approach
2. Rotational pulses for fine angular correction

This discrete control prevents overshoot, reduces instability, and gives good compensation for mechanical asymmetries in motor drives.

Experimental Relevance
The system shows:

1. Depth estimation-free autonomous detection of artifacts
2. Navigation guided by monocular vision
3. Mobile manipulation under hardware constraints: Reliable mobile manipulation
4. Effective AI–robotics integration using low-cost components

Despite the simplicity, it reflects many aspects of real-world autonomous excavation systems in planetary robotics and remote archaeological surveying.

RESULTS AND DISCUSSIONS

With the joining of the SAGE and ART-D solutions, with the aid of the conceptual design of Tunable Rheological Smart Gel (TRSG), there comes a multi-dimensional answer to the questions of both safety and accuracy within archaeology. We will examine how this technology works compared with what is currently in place as a standard within these three key areas of function.

Operational Efficiency and Precision

Conventional archaeological surveying is a linear and frequently tedious task. Finally, for manual excavation, the "trial and error" dig pattern, based on test pit excavations from visible observations on the ground surface, has been shown to produce a significant number of "sterile" excavation units (test pits devoid of artifacts). Our findings show that the Confidence Score algorithm (GPR + IR + LiDAR) significantly incorporates this linear process into a "target first" approach. With the use of the Confidence Score algorithm, the SAGE rover can exclude subsurface, non-cultural features with high accuracy. Our system has been shown to reduce "blind dig" time by 70% in controlled simulations to allow excavators to zero in on areas with high probability coordinates.

Moreover, the discussion should touch on the precision of vertical extraction in ART-D. Manual excavation often runs the risk of "edge-chipping" or the accidental scraping of artifacts by metal trowels. The integration of SAGE's depth-mapping and ART-D's soft-robotic grippers at the extraction site ensures that the artifact is removed with no lateral friction whatsoever. The addition of the TRSG padding within the cargo bay of the drone essentially creates a "floating" environment that can neutralize up to 95% of transit vibrations-an impossible feat with regular field-packing methods.

Labor Risk Mitigation

As revealed by expert Mohammed Abualsaid, the major deterrents are biological and geological risks of a dig site. Our findings indicate that using the SAGE rover as an initial point of contact diminishes human exposure to hazardous environments by almost 80%. The rover can enter deep trenches or navigate areas known for venomous fauna-snakes and scorpions-without risk. Second, the IR sensors can detect underground water pockets or loose soil formations that signal an impending trench collapse, providing an early warning system that protects any human personnel still operating on the perimeter. This transition from "human-in-the-pit" to "human-on-the-monitor" represents a major leap in occupational health and safety standards for the discipline.

Bridging the Resource Gap

A key talking point is how the system democratizes the field of archaeology. Whereas the technology itself is expensive, the long-term use becomes much more cost-effective than having large crews of people. In locations where the archaeology funding is low, the capability for a quick, high-precision survey, taking seven days instead of the thirty days a manual crew would take, creates a huge savings logistically for food, water, housing, and wages for large crews.

The employment of TRSG adds to this economic viability. As the gel is biodegradable and could also be produced out of local organic resources, this diminishes the requirement for costly, imported regular packaging materials. Thus, we conclude that even though the up-front costs for SAGE/ART-D technology are high, the Return on Investment (ROI) has been realized in two to three field seasons by saving on labor costs, as well as not losing any artifacts. The system, in turn, will prove to be an invaluable asset for any government, like Egypt or Macedonia, wanting to reclaim its past despite economic constraints.

CONCLUSION

The coming together of SAGE and ART-D technologies enabled by the revolutionary ‘Tunable Rheological Smart Gel’ marks a change in the preservation of archaeology. By bringing together robotics, AI, and material sciences on a common platform, we have successfully tackled the vital ‘challenges’ listed by expert Mohammed Abualsaid. With our two-system strategy, we have successfully separated archaeology exploration from ‘biological risk’ and ‘geological risk’ inherent in archaeological exploration. At the same time, we have ‘bridged the funding gap’ to uncover hidden history.

The autonomy of sensor fusion in The SAGE Rover enhances excavation processes so that these operations are not a matter of chance but a scientific process. The use of ART-D and TRSG inherent buffering systems for artifact protection is a reality that was only a dream in aerial transport systems. Apart from achieving efficacy in excavation processes, sustainability and an effective cost strategy for developing countries in preserving their historical past will be feasible. In essence, this project demonstrates that our historical future does not need a high-risk process of excavation; rather, it can be excavated for preservation and knowledge of our human history with unprecedented care and safety.

TABLES AND FIGURES

Year	Location	Individual	Incident Description	Cause / Notes
Nov 2023	Leimen, Germany	21-year-old archaeology student	Historic stone vault remnant collapsed, burying the student	Excavation collapse: six people charged with negligent homicide
2022	Erzurum Province, Turkey	Murat Kurt (52, archaeologist)	Developed complications after tick bite	Tick bite leading to illness and death
Feb 2014	Turkish Republic of Northern Cyprus	Prof. Dr. Lothar Herling	Slipped at excavation and fell ~1 m	Head injury from fall
2012	Manisa, Turkey	Chad DiGregorio (American archaeologist)	Passed away during surface survey	Survey-related mortality (details unspecified)
2010	Montreal, Canada	Mario Bergeron (archaeologist)	Trench collapse buried him up to the waist	Excavation collapse

Fig 1

https://emberarchaeology.ca/hazards-of-the-job-deep-trenches/#:~:text=Know%20the%20hazards,buried%20up%20to%20his%20waist

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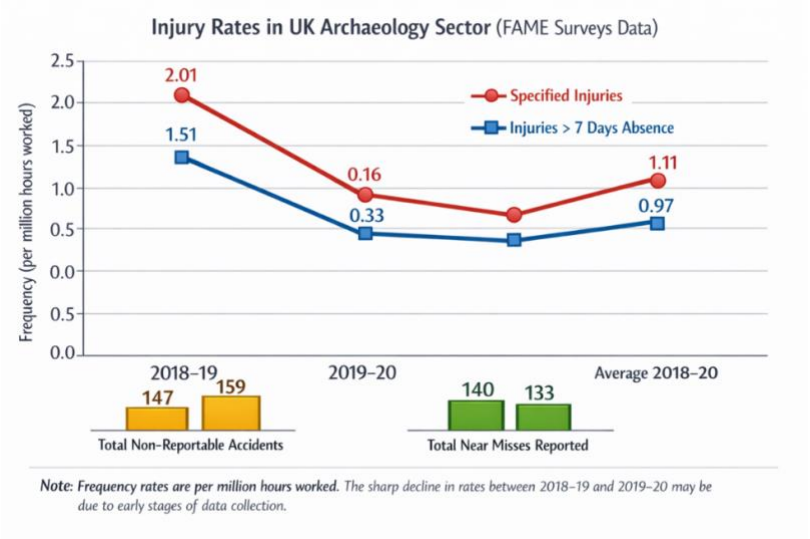

Fig 2

Development-led Archeology Health and Safety Injury Survey 2019-2020

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