A Multimodal Computational Imaging Pipeline for the Recovery of Weathered and Erased Stone Inscriptions

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1 Abstract

Ancient stone inscriptions are among the most important primary sources for classical studies, ancient history and public memory. Their legibility, however, is frequently compromised by natural weathering of the stone substrate, by deliberate erasure in antiquity (most commonly for political reasons), and by post-antique secondary use of the material. Standard photography regularly fails to capture the shallow depth of worn carvings, since the human eye and a conventional camera sensor are easily misled by the stone's colour, texture, and surface damage. While optical measurement techniques such as laser scanning have occasionally been explored in related fields (Chambers, 1992; Powers et al., 2005; Dong et al., 2022), and multispectral imaging has proven effective for other inscription types such as ostraka (Faigenbaum-Golovin et al., 2017), no established computational imaging methodology exists for epigraphy (Seales and Chapman, 2023; Kumar, 2024). This is attributable to two interrelated constraints: most advanced methods require controlled laboratory conditions and substantial financial resources, while stone inscriptions are almost invariably immovable objects, embedded in walls, scattered across landscapes, or housed in regional museums and depots, so that it is always the researcher who must travel to the stone.

This research presents a portable, field-deployable computational imaging pipeline that addresses these constraints by combining multiple complementary capture techniques with a suite of computer vision algorithms into an integrated, reproducible workflow. The pipeline is designed for the documentation and analysis of Roman and Greek stone inscriptions, though its methods are applicable to carved stone surfaces more broadly. In the capture stage, several imaging modalities are employed. Grazing light photography illuminates the stone surface at an oblique angle, casting shadows that accentuate the relief of even shallow carvings. Reflectance Transformation Imaging (RTI), which has demonstrated its value in epigraphy (Miles et al., 2018; Tanrıöver, 2020; Greaves et al., 2020) and adjacent fields such as historical archaeology and the study of temple graffiti (Frood and Howley, 2014; Díaz-Guardamino et al., 2015; Mytum and Peterson, 2018), captures the same surface under illumination from multiple systematically varied directions, producing a set of images from which the micro-topography of the carved surface can be computationally reconstructed. A parallel set of images is acquired under ultraviolet light, prioritising the blue and green spectral response to maximise the detection of mineral and organic traces within letter grooves that are invisible under normal lighting conditions. Depending on the material properties and condition of the individual inscription, near-infrared photography is additionally employed to reveal subsurface contrasts and features that neither visible light nor UV can capture.

The computational processing begins with a robust image registration step that ensures all photographs in a capture session are precisely co-registered despite the substantial illumination differences between frames. The aligned image stacks are then fused using multi-resolution blending techniques that preserve fine surface detail while suppressing sensor noise. The core of the pipeline is an exploratory enhancement stage in which a diverse set of computational techniques is applied to the fused image data in order to identify which combination of methods yields the best legibility for a given inscription. The underlying rationale is that different types of surface degradation respond to different analytical approaches, and no single method is universally optimal (cf. Jayanthi and Maheswari, 2024, on the comparative effectiveness of pre-processing methods for ancient script images

on stone). The pipeline therefore generates a range of outputs: relief-oriented representations derived from principal component analysis and photometric stereo estimation isolate the geometry of the carved surface from the albedo of the stone; morphological operators at multiple scales detect carved grooves and raised features of varying depth and width; illumination-normalisation techniques compensate for uneven weathering and difficult lighting conditions in the field; directional filters exploit the shadow structure inherent in the grazing light technique to enhance edges aligned with specific stroke orientations; and multi-scale edge detection highlights fine letter contours. These individual outputs are also composited into combined result images. Where both visible-light, Infrared and UV data are available, cross-modality fusion and false-colour composites map the differential response of the surface to different wavelength ranges.

The entire pipeline runs on a laptop and requires only inexpensive, easily transportable equipment: a digital camera, portable directional lighting, a UV light source, the portable RTI and a processing computer. This portability has been validated through field deployments at museums, depots, and open-air sites. The structured, machine-readable outputs produced by the pipeline also open pathways toward future integration of machine learning models for automated character recognition, text reconstruction, and the systematic analysis of large epigraphic corpora.

The contribution of this project to computational humanities is threefold. First, it proposes a structured multimodal data representation for carved stone inscriptions, a source type that has so far resisted standardised digital capture in the field. Second, it develops and evaluates a computational method specifically tailored to the humanities problem of recovering textual information from degraded physical surfaces, where the systematic exploration and combination of multiple imaging and analysis techniques proves more informative than any single approach in isolation. Third, it demonstrates the application of computer vision and image analysis techniques to the classics domain in which such methods have not yet been systematically employed.

Disclosure

During the preparation of this work the authors used DeepL Write (2026, DeepL SE, Cologne, Germany) for structuring and styling the text. After using this tool, the authors have reviewed and edited the content as necessary and take full responsibility for the content of the publication.

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