EduceLab Research

Multispectral Imaging of Damaged Sacramental Journal Pages: A Preliminary Study (2024)

Ankan Bhattacharyya, C. Seth Parker, and W. Brent Seales. "Multispectral Imaging of Damaged Sacramental Journal Pages: A Preliminary Study". In: *Proceedings of 4th International Conference on Frontiers in Computing and Systems*. Ed. by Dipak Kumar Kole, Shubhajit Roy Chowdhury, Subhadip Basu, Dariusz Plewczynski, and Debotosh Bhattacharjee. Singapore: Springer Nature Singapore, 2024, pp. 659–679. ISBN: 978-981-97-2614-1. DOI: 10.1007/978-981-97-2614-1_47. URL: https://doi.org/10.1007/978-981-97-2614-1_47.

Abstract: Multispectral Imaging (MSI) was used to recover the Archimedes Palimpsest. However, the work did not report to have any ink bleed-through. We develop an MSI pipeline that helps in visualizing the content and the ink bleed-through. As for data, we use damaged pages from the sacramental journal of the Holy Trinity Greek Orthodox Community (HTGOC) Church, situated in New Orleans. During Hurricane Katrina, this church faced destruction leading to damaged sacramental journals, like ink wash-away, ink bleed-through, torn patches of pages, and mold development. In this work, we try to discover any ink signals that show up in a wide spectrum of light, from ultraviolet (UV) to infrared (IR). We also try to study the ink signal response to the different combinations of wavelengths and perform an ablation study that gives us a list of combinations of different spectral bands that generate maximum information about the data. The manuscript reports 12 such combinations after the ablation study, and our data use all the wavelengths to produce ink signals, which are in better contrast in comparison to the images captured under visible light.

Revealing Text from a Still-rolled Herculaneum Papyrus Scroll (PHerc.Paris. 4) (2024)

Federica Nicolardi, Stephen Parsons, Daniel Delattre, Gianluca Del Mastro, Robert L. Fowler, Richard Janko, Tobias Reinhardt, C. Seth Parker, Christy Chapman, and W. Brent Seales. "Revealing Text from a Still-rolled Herculaneum Papyrus Scroll (PHerc.Paris. 4)". In: *Zeitschrift für Papyrologie und Epigraphik* 229 (2024), pp. 1–13. DOI: 11588/959427. URL: https://doi.org/11588/959427.

Abstract: Thanks to a global contest and a groundbreaking interdisciplinary team of computer scientists and papyrologists, complete texts are being revealed from the still-rolled Herculaneum papyrus scrolls for the first time in history. The Vesuvius Challenge, which was launched in March of 2023, brought the best minds in the artificial intelligence (AI) community together with leaders in the virtual unwrapping of damaged manuscripts and experts in the study of Herculaneum papyri to accelerate efforts to discover the scrolls' hidden contents. By October, our team of expert papyrologists who were chosen to adjudicate the contest were reviewing portions of six columns of never-before-seen Greek text from within PHerc.Paris. 4, a completely intact scroll from the collection of the Académie des Inscriptions et Belles-Lettres at the Institut de France. The initial revelation represents the most significant breakthrough in Herculaneum papyrology since their first discovery in 1752 and consequent mechanical opening procedures, warranting this initial publication. This paper describes the technical process that finally — and non-invasively — opened up PHerc.Paris. 4 for reading, discusses the history and features of the scroll, and provides the first diplomatic and literary transcription of the Greek text that was initially revealed.

Flexible Attenuation Fields: Tomographic Reconstruction From Heterogeneous Datasets (2024)

C. Seth Parker. "Flexible Attenuation Fields: Tomographic Reconstruction From Heterogeneous Datasets". PhD thesis. University of Kentucky, 2024. DOI: 10.13023/etd.2024.71. URL: https://doi.org/10.13023/etd.2024.71.

Abstract: Traditional reconstruction methods for X-ray computed tomography (CT) are highly constrained in the variety of input datasets they admit. Many of the imaging settings – the incident energy, field-of-view, effective resolution – remain fixed across projection images, and the only real variance is in the detector's position and orientation with respect to the scene. In contrast, methods for 3D reconstruction of natural scenes are extremely flexible to the geometric and photometric properties of the input datasets, readily accepting and benefiting from images captured under varying lighting conditions, with different cameras, and at disparate points in time and space. Extending CT to support similar degrees of flexibility would significantly enhance what can be learned from tomographic datasets. We propose that traditionally complicated or time-consuming tomographic tasks, such as multi-

resolution and multi-energy analysis, can be more readily achieved with a reconstruction framework which explicitly accepts datasets with varied imaging settings. This work presents a CT reconstruction framework specifically designed for datasets with heterogeneous capture properties which we call Flexible Attenuation Fields (FlexAF). Built on differentiable ray tracing and continuous neural volumes, FlexAF accepts X-ray images captured from any position and orientation in the world coordinate frame, including images which differ in size, resolution, field-of-view, and photometric settings. This method produces reconstructions for regular CT scans which are comparable to those produced by filtered backprojection, demonstrating that additional flexibility does not fundamentally hinder the ability to reconstruct high-quality volumes. Our experiments test the expanded capabilities of FlexAF for addressing challenging reconstruction tasks, including automatic camera calibration and reconstruction of multi-resolution and multi-energy volumes.

Hard-Hearted Scrolls: A Noninvasive Method for Reading the Herculaneum Papyri (2023)

Stephen Parsons. "Hard-Hearted Scrolls: A Noninvasive Method for Reading the Herculaneum Papyri". PhD thesis. University of Kentucky, 2023. DOI: 10.13023/etd.2023.372. URL: https://doi.org/10.13023/etd.2023.372.

Abstract: The Herculaneum scrolls were buried and carbonized by the eruption of Mount Vesuvius in A.D. 79 and represent the only classical library discovered in situ. Charred by the heat of the eruption, the scrolls are extremely fragile. Since their discovery two centuries ago, some scrolls have been physically opened, leading to some textual recovery but also widespread damage. Many other scrolls remain in rolled form, with unknown contents. More recently, various noninvasive methods have been attempted to reveal the hidden contents of these scrolls using advanced imaging. Unfortunately, their complex internal structure and lack of clear ink contrast has prevented these efforts from successfully revealing their contents. This work presents a machine learning-based method to reveal the hidden contents of the Herculaneum scrolls, trained using a novel geometric framework linking 3D X-ray CT images with 2D surface imagery of scroll fragments. The method is verified against known ground truth using scroll fragments with exposed text. Some results are also presented of hidden characters revealed using this method, the first to be revealed noninvasively from this collection. Exten-

sions to the method, generalizing the machine learning component to other multimodal transformations, are presented. These are capable not only of revealing the hidden ink, but also of generating rendered images of scroll interiors as if they were photographed in color prior to their damage two thousand years ago. The application of these methods to other domains is discussed, and an additional chapter discusses the Vesuvius Challenge, a $1,000,000+ open research contest based on the dataset built as a part of this work.

EduceLab-Scrolls: Verifiable Recovery of Text from Herculaneum Papyri using X-ray CT (2023)

Stephen Parsons, C. Seth Parker, Christy Chapman, Mami Hayashida, and W. Brent Seales. *EduceLab-Scrolls: Verifiable Recovery of Text from Herculaneum Papyri using X-ray CT*. 2023. arXiv: `2304.02084 [cs.CV]`.

The X-Ray Micro-CT of a Full Parchment Codex to Recover Hidden Text: Morgan Library M.910, an Early Coptic Acts of the Apostles Manuscript (2022)

Paul C Dilley, Christy Chapman, C Seth Parker, and W Brent Seales. "The X-Ray Micro-CT of a Full Parchment Codex to Recover Hidden Text: Morgan Library M.910, an Early Coptic Acts of the Apostles Manuscript". In: *Manuscript Studies: A Journal of the Schoenberg Institute for Manuscript Studies* 7.1 (2022), pp. 162–174.

Abstract: This article describes the first effort to read inside a damaged codex using X-Ray micro-CT imaging, which has an additional complication beyond most unrolled scrolls, for which the process has been successful: there is writing on both sides. The project is a collaboration between a humanist, a team of computer scientists and engineers, as well as librarians and conservators, to undertake the x-ray micro-CT imaging of codex M.910, a fifth- or sixth-century parchment codex of Acts of the Apostles which is too damaged to open in its current state. The first round of image processing was conducted in December 2017 at the Morgan Library and Museum, and a second round in November 2019; work on restoring the text using machine learning is ongoing, and has already resulted in the identification of some words and phrases. We first describe codex M.910, including the basics of its codicology, and its potential significance for early Christian book culture,

as well as the history of the biblical text. We then provide an overview of the manuscript imaging process, at a level of technical detail intended for a general audience, with the hope of providing a reference for future work in this expanding field of research. The key initial step was the preparation of the manuscript's mount, which had to take into account the necessities of both conservation safety and micro-CT imaging. We also break down the imaging process itself, which was carried out by Skyscan micro-CT scanner, donated for use in this project by Micro Photonics. Finally, we give a brief discussion of the ongoing preliminary data analysis.

Scholarly Editing and AI: Machine Predicted Text and Herculaneum Papyri (2021)

James H. Brusuelas. "Scholarly Editing and AI: Machine Predicted Text and Herculaneum Papyri". In: *magazén* 2.1 (June 2021). DOI: 10.30687/mag/2724-3923/2021/03/002. URL: https://doi.org/10.30687/mag/2724-3923/2021/03/002.

Abstract: In 2016 the Digital Restoration Initiative (DRI) at the University of Kentucky, under the direction of Professor Brent Seales, virtually unrolled a carbonized parchment scroll from Ein Gedi, revealing a copy of Leviticus written in iron gall ink. In 2019 the DRI applied a new machine learning method to reveal a Greek character written in carbon ink from an actual Herculaneum papyrus fragment. Virtual unwrapping of cultural heritage objects is a reality. The application of machine and deep learning methods to enhance difficult-to-detect ink signals in tomography will continue to evolve. This raises an important question. How will the process of editing texts that are 'true-born virtual' (the object can never be opened to verify the results) change to reflect the presence and dependency on AI? This paper produces a theoretical model for how a critical edition of a virtually unwrapped papyrus text must document the role of the machine. It also engages the possible requirements, in terms of Data Science, that this new type of text compels in order to ensure transparency at the level of its 'birth'. Put simply, a new virtual edition model that is a fusion of humanities and science is needed.

Using METS to Express Digital Provenance for Complex Digital Objects (2021)

Christy Chapman, Seth Parker, Stephen Parsons, and W. Brent Seales. "Us-

ing METS to Express Digital Provenance for Complex Digital Objects". In: *Metadata and Semantic Research*. Ed. by Emmanouel Garoufallou and María-Antonia Ovalle-Perandones. Cham: Springer International Publishing, Mar. 2021, pp. 143–154. ISBN: 978-3-030-71903-6. DOI: 10.1007/978-3-030-71903-6_15.

Abstract: Today's digital libraries consist of much more than simple 2D images of manuscript pages or paintings. Advanced imaging techniques – 3D modeling, spectral photography, and volumetric x-ray, for example – can be applied to all types of cultural objects and can be combined to create complex digital representations comprising many disparate parts. In addition, emergent technologies like virtual unwrapping and artificial intelligence (AI) make it possible to create "born digital" versions of unseen features, such as text and brush strokes, that are "hidden" by damage and therefore lack verifiable analog counterparts. Thus, the need for transparent metadata that describes and depicts the set of algorithmic steps and file combinations used to create such complicated digital representations is crucial. At EduceLab, we create various types of complex digital objects, from virtually unwrapped manuscripts that rely on machine learning tools to create born-digital versions of unseen text, to 3D models that consist of 2D photos, multi- and hyperspectral images, drawings, and 3D meshes. In exploring ways to document the digital provenance chain for these complicated digital representations and then support the dissemination of the metadata in a clear, concise, and organized way, we settled on the use of the Metadata Encoding Transmission Standard (METS). This paper outlines our design to exploit the flexibility and comprehensiveness of METS, particularly its behaviorSec, to meet emerging digital provenance metadata needs.

The Digital Compilation and Restoration of Herculaneum Fragment P.Herc.118 (2021)

Christy Y. Chapman, C. Seth Parker, Ali Bertelsman, Kristina Gessel, Hannah Hatch, Kyra Seevers, James H. Brusuelas, Stephen Parsons, and W. Brent Seales. "The Digital Compilation and Restoration of Herculaneum Fragment P.Herc.118". In: *Manuscript Studies: A Journal of the Schoenberg Institute for Manuscript Studies* 6.1 (2021), pp. 1–32. DOI: 10.1353/mns.2021.0000.

OpenABF (2021)

C. Seth Parker. *OpenABF. A single-header C++ library of angle-based flattening algorithms*. Comp. software. Jan. 2021. DOI: 10.5281/zenodo.4483858. URL: https://doi.org/10.5281/zenodo.4483858.

Volume Cartographer (2021)

C. Seth Parker, Kristina Gessel, Stephen Parsons, Jacob Chappell, Bruno Athie Teruel, Nikki Bentley, Ali Bertelsman, John Broadbent, Sydney Chapman, Abigail Coleman, Chao Du, Callie Gardella, Nick Graczyk, Hannah Hatch, Lula Hogg, Sean Karlage, Tam Nguyen, James Pack, David Pennington, Allison Revers, Mike Roup, Michael Royal, Kyra Seevers, Melissa Shankle, Raiffa Syamil, Ryan Taber, and JP Posma. *Volume Cartographer. A cross-platform C++ library and toolkit for the recovery and restoration of damaged cultural artifacts*. Comp. software. Mar. 2021. DOI: 10.5281/zenodo.4604881. URL: https://doi.org/10.5281/zenodo.4604881.

Machine Learning Infrastructure on the Frontier of Virtual Unwrapping (2021)

Stephen Parsons, Jacob Chappell, C. Seth Parker, and W. Brent Seales. "Machine Learning Infrastructure on the Frontier of Virtual Unwrapping". In: *Proceedings of International Symposium on Grids & Clouds 2021 (ISCG2021)*. Academia Sinica Computing Centre (ASGC), Taipei, Taiwan (Online): Proceedings of Science, Mar. 2021, p. 15. DOI: 10.22323/1.378.0015.

Abstract: Virtual unwrapping is a software pipeline for the noninvasive recovery of texts inside damaged manuscripts via the analysis of three dimensional tomographic data, typically X-ray micro-CT. Recent advancements to the virtual unwrapping pipeline include the use of trained models to perform the "texturing" phase, where the content written upon a surface is extracted from the 3D volume and projected onto a surface mesh representing that page. Trained models are critical for their ability to discern subtle changes that indicate the presence or absence of writing at a given point on the surface. The unique datasets and computational pipeline required to train and make use of these models make it a challenge to develop succinct, reliable, and reproducible research infrastructure. This paper presents our response to that challenge and outlines our framework designed to support the on-

going development of machine learning models to advance the capability of virtual unwrapping. Our approach is designed on the principles of visualization, automation, data access, metadata, and consistent benchmarks.

Towards Automating Volumetric Segmentation for Virtual Unwrapping (2020)

Kristina Gessel, Stephen Parsons, Clifford Parker, and William Seales. "Towards Automating Volumetric Segmentation for Virtual Unwrapping". In: *Proceedings of the 25th International Conference on Cultural Heritage and New Technologies 2020.* Ed. by Wolfgang Börner, Hendrik Rohland, Christina Kral-Börner, and Lina Karner. Nov. 2020.

Structured Metadata Engine and Graph Objects Library (2020)

C. Seth Parker. *Structured Metadata Engine and Graph Objects Library.* Comp. software. Oct. 2020. DOI: 10.5281/zenodo.4134987. URL: https://doi.org/10.5281/zenodo.4134987.

Deep Learning for More Expressive Virtual Unwrapping (2020)

Stephen Parsons, Kristina Gessel, Clifford Parker, and William Seales. "Deep Learning for More Expressive Virtual Unwrapping". In: *Proceedings of the 25th International Conference on Cultural Heritage and New Technologies 2020.* Ed. by Wolfgang Börner, Hendrik Rohland, Christina Kral-Börner, and Lina Karner. Nov. 2020, pp. 203–207. DOI: 10.11588/propylaeum.1045.c14501. URL: https://doi.org/10.11588/propylaeum.1045.c14501.

Unbending light: new computational methods for the correction of 3D effects in scanning XRF (2019)

Monica Ganio, Stephen Parsons, Seth Parker, Marie Svoboda, Brent Seales, and Catherine Schmidt Patterson. "Unbending light: new computational methods for the correction of 3D effects in scanning XRF". In: *Optics for Arts, Architecture, and Archaeology VII.* Conference Proceedings of SPIE

Volume 11058. 2019. DOI: 10.1117/12.2525038. URL: https://doi.org/10.1117/12.2525038.

Abstract: Scanning macro-X-ray fluorescence (XRF) spectroscopy on works of art provides researchers with rich data sets containing information about material composition and technique of material use in a compelling visual format in the form of element-specific distribution maps. Collection these maps, however, typically assumes a two dimensional object, and few works of art are truly flat. Small nuances in elemental intensity may be introduced into element distribution maps by surface topography. The inability to confidently ascribe a change in signal intensity to actual elemental composition versus topographically-induced variance, therefore, presents a challenge, particularly when attempting to identify markers of artists' techniques, compare several objects, or overlay/register images from scanning XRF with those from other imaging modalities. This paper introduces a new methodology for post-processing scanning XRF data sets to correct for elemental intensity variations as a function of topography. The method augments the acquired XRF data based on a three-dimensional reconstruction of an object and a set of elemental intensity/distance response functions. These response functions act as a calibrated guide for modifying the intensity map based on depth variation. The geometry-based parameters of local surface shape (curvature), distance of the XRF detector from the surface, region of intersection of the incident fluorescence beam with the surface, and the orientation of the incident beam with respect to the surface normal, are each accounted for in the calibration phase as a large set of pre-acquired examples. This provides a mechanism for capturing and understanding the anticipated variations in the macro-XRF data, interpolating the examples in order to smoothly estimate variations, and applying those variations as corrections to macro-XRF data collected on non-planar surfaces. Macro-XRF variation as a function of the geometry is explained, with an emphasis on understanding the parameters that induce the most severe errors in the XRF estimates. The representational framework for collecting, storing, and summarizing calibration data over a large number of scans is discussed, followed by several proof of concept examples.

From invisibility to readability: Recovering the ink of Herculaneum (2019)

Clifford Seth Parker, Stephen Parsons, Jack Bandy, Christy Chapman, Fred-

erik Coppens, and William Brent Seales. "From invisibility to readability: Recovering the ink of Herculaneum". In: *PLOS ONE* 14.5 (May 2019), pp. 1–17. DOI: 10.1371/journal.pone.0215775. URL: https://doi.org/10.1371/journal.pone.0215775.

Abstract: The noninvasive digital restoration of ancient texts written in carbon black ink and hidden inside artifacts has proven elusive, even with advanced imaging techniques like x-ray-based micro-computed tomography (micro-CT). This paper identifies a crucial mistaken assumption: that micro-CT data fails to capture any information representing the presence of carbon ink. Instead, we show new experiments indicating a subtle but detectable signature from carbon ink in micro-CT. We demonstrate a new computational approach that captures, enhances, and makes visible the characteristic signature created by carbon ink in micro-CT. This previously "unseen" evidence of carbon inks, which can now successfully be made visible, is a discovery that can lead directly to the noninvasive digital recovery of the lost texts of Herculaneum.

Revealing "Invisible" Signals in CT with Machine Learning (2019)

Stephen Parsons, C. Seth Parker, Frederik Coppens, and W. Brent Seales. "Revealing "Invisible" Signals in CT with Machine Learning". In: *Bruker Micro-CT User Meeting*. Abstract Book. Mechelen, Belgium, June 2019, pp. 20–22.

Abstract: The analysis of complex tomographic data presents a number of challenges. Numerous approaches and tools are available to overcome many of these hurdles for various kinds of datasets. These primarily rely on the visualization of the CT scan data, sometimes augmented by basic filtering operations. The resulting intuition implies that signals or features which are present in a visualization are present in the data, while other signals are not. Recently, the usage of neural networks has been widely used to learn subtle and complex patterns that may not be clearly present to a human observer. We present a technique based on Convolutional Neural Networks (CNNs) to learn and reveal the presence of signals in CT data previously thought to be "invisible" in CT.

Making Fragile Artifacts Interactive: The 3D and Hyperspectral Imaging Of PHerc. 118 (2019)

Kyra Seevers, Kristina Gessel, Alix Bertelsman, and Hannah Hatch. "Making Fragile Artifacts Interactive: The 3D and Hyperspectral Imaging Of PHerc. 118". In: *2019 NCUR* (2019).

Abstract: In the year 79 CE, the infamous eruption of Mt. Vesuvius buried Pompeii and its neighboring city of Herculaneum in pyroclastic ash. The resulting carbonization of the entire town provided a rare preservation of the past, including several hundred Greek and Latin scrolls found in a villa believed to have belonged to the family of Julius Caesar. While the scrolls managed to survive intact, the carbonization rendered them brittle and incapable of being opened by hand without causing significant damage. This research focused on the recovery of illegible text from one of these documents, PHerc. 118. This scroll, a casualty of the forced unrolling processes common in the 19th century, lies fragmented and mounted in 12 wooden trays, known as "pezzos," at the Bodleian Library of Oxford University. This research implemented a five-step process for analyzing all 12 of the PHerc. 118 pezzos: 3D and hyperspectral data capture; Point-cloud registration of the 3D model; Texture reordering and registration of the 3D model; Registration of hyperspectral images to the 3D model; Creation of a composite image from the unified data sets of PHerc 118. Users are now able to access PHerc 118 in a 3D virtual environment with the ability to rotate, zoom and even edit the virtual document without posing any harm to the physical artifact. This innovative tool allows scholars and conservationists to not only view and interpret new text but provides the general populous access to rare and fragile documents. While issues with scanning technologies and 3D editing software limited this research, future work would include more complete hyperspectral image sets, more computationally efficient mesh editing software, and the creation of an automated landmark registration process.

Enhanced CT Analysis Using Volume Flattening (2017)

C. Seth Parker and W. Brent Seales. "Enhanced CT Analysis Using Volume Flattening". In: *Bruker Micro-CT User Meeting*. Abstract Book. Brussels, Belgium, June 2017, pp. 15–16.

Abstract: Systematic analysis of complex CT scan data can be very difficult. Volumetric rendering is effective, but analysis is viewpoint dependent and

locating features of interest in 3D can be difficult. In such circumstances, a simplification of the dataset into a flattened representation can help drive analysis. We present a technique for volumetric flattening and resampling as part of our Virtual Unwrapping pipeline and discuss how this technique can be used in areas other than document preservation.

The St. Chad Gospels: Diachronic Manuscript Registration and Visualization (2017)

Stephen Parsons, C. Seth Parker, and W. Brent Seales. "The St. Chad Gospels: Diachronic Manuscript Registration and Visualization". In: *Manuscript Studies: A Journal of the Schoenberg Institute for Manuscript Studies* 2.2 (2017), pp. 483–498. DOI: 10.1353/mns.2017.0022.

4.1.1.7 Virtual Unwrapping: A Computational Approach for Reading Damaged Manuscripts (2017)

W. Brent Seales, C. Seth Parker, and Christy Chapman. "4.1.1.7 Virtual Unwrapping: A Computational Approach for Reading Damaged Manuscripts". In: *Textual History of the Bible*. Ed. by Armin Lange. Vol. 4. 2017. Chap. 1.1.7. DOI: 10.1163/2452-4107_thb_COM_225869. URL: http://dx.doi.org/10.1163/2452-4107_thb_COM_225869.

Reading the Invisible Library: A Retrospective (2017)

W.B. Seales. "Reading the Invisible Library: A Retrospective". In: *Modern Alchemy: New Technology for Museum Collections*. Ed. by Carl Brune and Caroline Foutch. Gilcrease Museum. Tulsa, OK, 2017.

Description: Coherent recounting of development of virtual unwrapping.

Reading the Invisible Library (2016)

C. Seth Parker, W. Brent Seales, and Gregory Heyworth. "Reading the Invisible Library". In: *Bruker Micro-CT User Meeting*. Abstract Book. Mondorf-les-Bains, Luxembourg, May 2016, pp. 58–59.

Abstract: With age, many of humanity's most important written works have become decayed, faded, and too fragile to touch and read. While computer imaging techniques are commonly used to digitally preserve and share readable texts, electronically capturing the writing locked away in ancient, deteriorated, and easily damaged manuscripts is an entirely different challenge. The computational framework and software described in this work opens up – for the first time – irreparably damaged manuscripts for scholarly textual analysis. Our computational framework and set of available tools enables the digital analysis of the interior of damaged manuscripts and leads directly to the detection and restoration of text previously considered lost. We use as examples two Medieval books from a collection of manuscripts owned by the Médiathèque l'Apostrophe in Chartres, France. This collection was severely damaged by fire and water during an Allied air raid in World War II, leaving many manuscripts in a state thought to be unrecoverable. We demonstrate that the recovery of text from these books is not only possible, but that text sufficient for scholarly analysis can be extracted within an hour after volumetric reconstruction.

Quantitative Distortion Analysis of Flattening Applied to the Scroll from En-Gedi (2016)

Clifford Seth Parker, William Brent Seales, and Pnina Shor. "Quantitative Distortion Analysis of Flattening Applied to the Scroll from En-Gedi". In: *Art & Archaeology, 2nd International Conference*. 2016. arXiv: 2007.15551 [cs.CV].

Abstract: Non-invasive volumetric imaging can now capture the internal structure and detailed evidence of ink-based writing from within the confines of damaged and deteriorated manuscripts that cannot be physically opened. As demonstrated recently on the En-Gedi scroll, our "virtual unwrapping" software pipeline enables the recovery of substantial ink-based text from damaged artifacts at a quality high enough for serious critical textual analysis. However, the quality of the resulting images is defined by the subjective evaluation of scholars, and a choice of specific algorithms and parameters must be available at each stage in the pipeline in order to maximize the output quality.

From damage to discovery via virtual unwrapping: Reading the scroll from En-Gedi (2016)

William Brent Seales, Clifford Seth Parker, Michael Segal, Emanuel Tov, Pnina Shor, and Yosef Porath. "From damage to discovery via virtual unwrapping: Reading the scroll from En-Gedi". In: *Science Advances* 2.9 (2016). DOI: 10.1126/sciadv.1601247. eprint: http://advances.sciencemag.org/content/2/9/e1601247.full.pdf. URL: http://advances.sciencemag.org/content/2/9/e1601247.

Description: Virtual unwrapping is the composite result of segmentation, texturing, and flattening. Segmentation is piecewise. After flattening, the merging and the visualization stages occur. In this article, one process for merging has been adopted. Texture merging is the alignment of texture images from small segmentations to generate a composite master view. This introduce distortion because textures have been flattened independently and don't have consistent overlap. Mesh merging refers to a more precise recalculation of the merge step by using the piecewise meshes to generate a single mesh representing the whole surface which can then be flattened. Each of these three processes are sequential and depend on the output from the last step. Texturing and flattening are dependent on the mesh creation from the segmentation stage. So, the pipeline is tightly coupled and can lead to unexpected results if one of the segmentation and/or texturing fails.

Abstract: Computer imaging techniques are commonly used to preserve and share readable manuscripts, but capturing writing locked away in ancient, deteriorated documents poses an entirely different challenge. This software pipeline—referred to as "virtual unwrapping"—allows textual artifacts to be read completely and noninvasively. The systematic digital analysis of the extremely fragile En-Gedi scroll (the oldest Pentateuchal scroll in Hebrew outside of the Dead Sea Scrolls) reveals the writing hidden on its untouchable, disintegrating sheets. Our approach for recovering substantial ink-based text from a damaged object results in readable columns at such high quality that serious critical textual analysis can occur. Hence, this work creates a new pathway for subsequent textual discoveries buried within the confines of damaged materials.

An Early Leviticus Scroll from En-Gedi: Preliminary Publication (2016)

Michael Segal, Emanuel Tov, William Brent Seales, Clifford Seth Parker, Pnina Shor, and Yosef Porath. "An Early Leviticus Scroll from En-Gedi: Preliminary Publication". In: *Textus* 26.1 (2016), pp. 29–58. DOI: 10.1163/2589255X-02601004.

Virtual unrolling of carbonized Herculaneum scrolls: Research Status (2007–2012) (2013)

W Brent Seales and Daniel Delattre. "Virtual unrolling of carbonized Herculaneum scrolls: Research Status (2007–2012)". In: *Cronache Ercolanesi* 43 (2013), pp. 191–208.

Description: In-depth summary of team's work on Herculaneum scrolls through 2012.

Asset digitization: moving beyond facsimile (2012)

W Brent Seales and Steve Crossan. "Asset digitization: moving beyond facsimile". In: *SIGGRAPH Asia 2012 Technical Briefs*. ACM. 2012, p. 32.

Analysis of Herculaneum papyri with x-ray computed tomography (2011)

W Brent Seales, J Griffioen, R Baumann, and M Field. "Analysis of Herculaneum papyri with x-ray computed tomography". In: *International Conference on nondestructive investigations and microanalysis for the diagnostics and conservation of cultural and environmental heritage*. 2011.

Description: Overview of work on Paris Herculaneum scrolls.

Virtual conservation: Experience with micro-CT and manuscripts (2010)

WB Seales, J Griffioen, and D Jacobs. "Virtual conservation: Experience with micro-CT and manuscripts". In: *EIKONOPOIIA: Digital Imaging of*

Ancient Textual Heritage, Proceedings of the International Conference (Nov. 28–29, 2010). Helsinki, 2010.

Description: Summary of work on virtual unwrapping to date. This conference was the first discussion of the application of Phase Contrast Tomography as a possible approach. Internal reports had been produced the prior year.
Performed elemental analysis of PHerc. Paris 2 fragments 96 and 126: "calcium and trace quantities of aluminum, magnesium, strontium and lead are the elements that discriminate between the ink in the Herculaneum fragments and the papyrus alone." Not success using this knowledge to create ink contrast in tomography.

Robust registration of manuscript images (2009)

Ryan Baumann and W Brent Seales. "Robust registration of manuscript images". In: *Proceedings of the 9th ACM/IEEE-CS joint conference on Digital libraries*. 2009, pp. 263–266.

Abstract: In this paper we present an application of image registration techniques to the specific domain of manuscript images. We show the application of this technique to images of the Venetus A, a 10th century manuscript of Homer's Iliad. The same algorithm is used to register images of the MS across time (including photographs separated by over a century), as well as across imaging modalities.

Lire sans détruire les papyrus carbonisés d'Herculanum (2009)

Brent Seales. "Lire sans détruire les papyrus carbonisés d'Herculanum". In: *Comptes rendus des séances de l'Académie des Inscriptions et Belles-Lettres* 153.153 (2009), pp. 907–923. eprint: `https://www.persee.fr/doc/crai_0065-0536_2009_num_153_2_92557`.

Description: Report to the Institut de France on findings from the first ever volumetric scan of an intact scroll. First reporting of the discovery of lead in the ink (and not the papyrus).

The use of micro-ct in the study of archaeological artifacts (2008)

Ryan Baumann, Dorothy Carr Porter, and W Brent Seales. "The use of micro-ct in the study of archaeological artifacts". In: *9th International Conference on NDT of Art*. 2008, pp. 1–9. eprint: `https://www.ndt.net/article/art2008/papers/244Seales.pdf`.

Description: Recovery of internal layers from 15th century Ecclesiastes binding (Univ. of Michigan).

Restoring 2D content from distorted documents (2007)

Michael S Brown, Mingxuan Sun, Ruigang Yang, Lin Yun, and W Brent Seales. "Restoring 2D content from distorted documents". In: *Pattern Analysis and Machine Intelligence, IEEE Transactions on* 29.11 (2007), pp. 1904–1916.

Description: Prior work to virtual unwrapping flattening stage. Conformal mapping and image intensity restoration.

Physically-based digital restoration using volumetric scanning (2007)

Yun Lin. "Physically-based digital restoration using volumetric scanning". PhD thesis. University of Kentucky, 2007. ISBN: 978-0-549-43331-6.

Description: The first, complete virtual unwrapping paper. Addresses scanning, segmentation, filtering, and flattening in some form.

Abstract: Digitization has become critical to preservation, dissemination and even restoration of damaged artifacts of cultural history. There are a number of priceless documents of cultural heritage that are preserved in museums and libraries with content that is still difficult for modern scholars to see. Their opaque surfaces in rolled or folded forms, such as scrolls and bound manuscripts, prevent their content from being accessed. Physical unwrapping is usually not considered as a solution due to its destructive nature, especially for the aged and damaged materials that are in fragile condition. This thesis develops a general approach for building a readable image of an opaque, rolled or folded document from a non-destructive volumetric scan. We use a custom high-resolution Computed Tomography (CT) scan to solve the problem of opaque document acquisition, based on an extensive analysis

of the important issues specifically related to this application. The post-processing problem is framed by localizing, constructing and manipulating a texture image induced by a surface embedded in a 3D voxel space. Algorithms are developed to localize the surface present in a scan, construct a texture map that reproduces the ink on the surface, and parameterize the convoluted surface over a 2D domain that enables a complete reading. The "virtual unwrapping", based on simulation of mass-spring system dynamics that is found on classical mechanics, preserves geometric features, such as angles and lengths, thus minimizes the distortion of text. For preliminary testing and empirical analysis of the restoration method, we conduct a series of simulation experiments based on a CT scanner simulator. Satisfactory experimental results on replica scrolls and a real 15th manuscript from the University of Michigan's Library promise feasibility of this method. The content of the ancient manuscript revealed by our method is confirmed by posterior physical manipulation, which permanently altered the object. This research presents novel contributions that are expected to benefit the scholarship that studies human history and culture. The vision is to apply the proposed method ultimately to precious documents and allow complete analysis of them while enforcing continued physical preservation.

Opaque document imaging: Building images of inaccessible texts (2005)

Yun Lin and W Brent Seales. "Opaque document imaging: Building images of inaccessible texts". In: *Computer Vision, 2005. ICCV 2005. Tenth IEEE International Conference on*. Vol. 1. IEEE. 2005, pp. 662–669.

Description: Application of Lin's thesis to example objects.

Geometric and photometric restoration of distorted documents (2005)

Mingxuan Sun, Ruigang Yang, Yun Lin, George Landon, Brent Seales, and Michael S Brown. "Geometric and photometric restoration of distorted documents". In: *Tenth IEEE International Conference on Computer Vision (ICCV'05) Volume 1*. Vol. 2. Oct. 2005, 1117–1123 Vol. 2. DOI: 10.1109/ICCV.2005.106.

Abstract: We present a system to restore the 2D content printed on distorted documents. Our system works by acquiring a 3D scan of the document's surface together with a high-resolution image. Using the 3D surface information and the 2D image, we can ameliorate unwanted surface distortion and effects from non-uniform illumination. Our system can process arbitrary geometric distortions, not requiring any pre-assumed parametric models for the document's geometry. The illumination correction uses the 3D shape to distinguish content edges from illumination edges to recover the 2D content's reflectance image while making no assumptions about light sources and their positions. Results are shown for real objects, demonstrating a complete framework capable of restoring geometric and photometric artifacts on distorted documents.

Image restoration of arbitrarily warped documents (2004)

Michael S Brown and W Brent Seales. "Image restoration of arbitrarily warped documents". In: *Pattern Analysis and Machine Intelligence, IEEE Transactions on* 26.10 (2004), pp. 1295–1306.

Description: Prior work to complete virtual unwrapping flattening stage. Mass-spring particle system applied to 3D models of manuscripts in order to deskew manuscript images.

Digital restoration using volumetric scanning (2004)

W Brent Seales and Yun Lin. "Digital restoration using volumetric scanning". In: *Digital Libraries, 2004. Proceedings of the 2004 Joint ACM/IEEE Conference on*. IEEE. 2004, pp. 117–124.

Description: Early work linking document flattening, volumetric imaging via micro-CT, and complete virtual unwrapping.

Digital restoration: Principles and approaches (2003)

W Brent Seales and Y Lin. "Digital restoration: Principles and approaches". In: *Proceedings of DELOS/NSF Workshop on Multimedia in Digital Libraries*. 2003.

Description: First paper on "digital restoration," outlining principles and promoting the idea of imaging using non-invasive, volumetric techniques such as tomography.

Key quote:

If one allows that a volumetric imaging method can be applied to the case of the closed scroll, we believe it is possible from that point onward to develop a physically-based model that can "unroll" the material, "flatten" it and potentially provide a reading of text that may be on the surface of the object. The idea of providing a reading of a text that was previously inaccessible and potentially even unknown is very exciting, and it may be less far-fetched than it seems.

The digital atheneum: new techniques for restoring and preserving old documents. (2000)

W Brent Seales, James Griffioen, and Kevin Kiernan. "The digital atheneum: new techniques for restoring and preserving old documents." In: *Computers in Libraries* 20.2 (2000), pp. 26–30.

Description: Reports on "restoration framework" and the importance of 3D acquisition for manuscript pages, applied with manuscripts in the Cotton collection at the British Library.

The Digital Atheneum-restoring damaged manuscripts (1999)

W Brent Seales, James Griffioen, and Kevin Kiernan. "The Digital Atheneum-restoring damaged manuscripts". In: *RLG DigiNews* 3.6 (1999), p. 15.

Description: First paper on restoration using 3D acquisition of manuscript pages and then flattening – the precursor to "unwrapping."

Object recognition in compressed imagery (1998)

W Brent Seales, Cheng J Yuan, Wei Hu, and Matthew D Cutts. "Object recognition in compressed imagery". In: *Image and Vision Computing* 16.5 (1998), pp. 337–352.

Abstract: Image-based applications can save time and space by operating on compressed data. The problem is that most mid- and high-level image operations, such as object recognition, are formulated as sequences of operations in the image domain. Such methods need direct access to pixel information as a starting point, but the pixel information in a compressed image stream is not immediately accessible. In this paper we show how to perform object recognition directly on compressed images (JPEG) and index frames from video streams (MPEG I-frames) without recovering explicit pixel information. The approach uses eigenvectors constructed from compressed image data. Our performance results show that a five-fold speedup can be gained by using compressed data.

Virtual Unwrapping

Advanced Microspatially Offset Raman Spectroscopy for Noninvasive Imaging of Concealed Texts and Figures Using Raman Signal, Fluorescence Emission, and Overall Spectral Intensity (2024)

Alessandra Botteon, Marc Vermeulen, Laura Cristina, Silvia Bruni, Pavel Matousek, Costanza Miliani, Marco Realini, Lora Angelova, and Claudia Conti. "Advanced Microspatially Offset Raman Spectroscopy for Noninvasive Imaging of Concealed Texts and Figures Using Raman Signal, Fluorescence Emission, and Overall Spectral Intensity". In: *Analytical Chemistry* (2024). PMID: 38456422. DOI: 10.1021/acs.analchem.3c05249. eprint: https://doi.org/10.1021/acs.analchem.3c05249. URL: https://doi.org/10.1021/acs.analchem.3c05249.

Abstract: This study explores the possibility of using microspatially offset Raman spectroscopy (micro-SORS) imaging to reconstruct noninvasively letters and figures hidden by opaque layers. Micro-SORS experiments were conducted on mockup samples that mimic real situations encountered in the cultural heritage field, such as sealed letters with inaccessible text and original documents. Subsurface images were obtained using both the characteristic Raman bands of the hidden compounds and their different optical properties from the remaining matrix. In the latter case, contrast obtained through observing a difference in the overall spectral intensity and fluorescence profile rather than any specific Raman bands were used to track the images within the hidden layer. This approach opens new prospects for the use of micro-SORS in heritage science, with applications in the field that include the study of objects covered by opaque overlayers not only through

their Raman signatures but also through differences in their optical properties (e.g., fluorescence emission, absorption).

Fully Automatic Virtual Unwrapping Method for Documents Imaged by X-Ray Tomography (2024)

Petr Kulagin, Dmitry Polevoy, Marina Chukalina, Dmitry Nikolaev, and Vladimir V. Arlazarov. "Fully Automatic Virtual Unwrapping Method for Documents Imaged by X-Ray Tomography". In: *Document Analysis and Recognition - ICDAR 2024*. Ed. by Elisa H. Barney Smith, Marcus Liwicki, and Liangrui Peng. Cham: Springer Nature Switzerland, Sept. 2024, pp. 233–250. ISBN: 978-3-031-70543-4. DOI: 10.1007/978-3-031-70543-4_14. URL: https://doi.org/10.1007/978-3-031-70543-4_14.

Abstract: The study of historical documents faces challenges due to aging, particularly when rolled or folded, risking damage during unfolding. While computer tomography enables 3D digital replicas, direct examination is inconvenient. To facilitate content analysis, various virtual unfolding methods have been proposed. We present a groundbreaking, fully automated system for virtual unfolding/unrolling, employing a neural network to generate a binary document mask and perform skeletonization on 2D sections of the 3D volume. Additional algorithms address artifacts, false loops, branching, and discontinuities. Introducing a unified coordinate system for skeletal sections allows the generation of an unfolded document image. Performance is assessed on the CT-OCR-2022 dataset, utilizing a novel criterion for geometric distortion evaluation. Enriched with marker coordinates, the dataset facilitates future algorithm assessments. Accompanying source codes for the proposed algorithms and evaluation criterion are publicly available.

A Geometric Feature-Based Algorithm for the Virtual Reading of Closed Historical Manuscripts (2023)

Rosa Brancaccio, Fauzia Albertin, Marco Seracini, Matteo Bettuzzi, and Maria Pia Morigi. "A Geometric Feature-Based Algorithm for the Virtual Reading of Closed Historical Manuscripts". In: *Journal of Imaging* 9.10 (Oct. 2023). ISSN: 2313-433X. DOI: 10.3390/jimaging9100230. URL: https://www.mdpi.com/2313-433X/9/10/230.

Abstract: X-ray Computed Tomography (CT), a commonly used technique in a wide variety of research fields, nowadays represents a unique and powerful procedure to discover, reveal and preserve a fundamental part of our patrimony: ancient handwritten documents. For modern and well-preserved ones, traditional document scanning systems are suitable for their correct digitization, and, consequently, for their preservation; however, the digitization of ancient, fragile and damaged manuscripts is still a formidable challenge for conservators. The X-ray tomographic approach has already proven its effectiveness in data acquisition, but the algorithmic steps from tomographic images to real page-by-page extraction and reading are still a difficult undertaking. In this work, we propose a new procedure for the segmentation of single pages from the 3D tomographic data of closed historical manuscripts, based on geometric features and flood fill methods. The achieved results prove the capability of the methodology in segmenting the different pages recorded starting from the whole CT acquired volume.

Using computed tomography to recover hidden medieval fragments beneath early modern leather bindings, first results (2023)

J Eric Ensley, Katherine H Tachau, Susan A Walsh, Honghai Zhang, Giselle Simon, Laura Moser, Jarron Atha, Paul Dilley, Eric A Hoffman, and Milan Sonka. "Using computed tomography to recover hidden medieval fragments beneath early modern leather bindings, first results". In: *Heritage Science* 11.1 (2023), p. 82. DOI: 10.1186/s40494-023-00912-9. URL: https://doi.org/10.1186/s40494-023-00912-9.

Abstract: Medieval bindings fragments have become increasingly interesting to Humanities researchers as sources for the textual and material history of medieval Europeans. Later book binders used these discarded and repurposed pieces of earlier medieval manuscripts to reinforce the structures of other manuscripts and printed books. That many of these fragments are contained within and obscured by decorative bindings that cannot be dismantled ethically has limited their discovery and description. Although previous attempts to recover these texts using IRT and MA-XRF scanning have been successful, the extensive time required to scan a single book, and the need to modify or create specialized IRT or MA-XRF equipment for this method are drawbacks. Our research proposes and tests the capabilities of medical CT scanning technologies (commonly available at research univer-

sity medical schools) for making visible and legible these fragments hidden under leather bindings. Our research team identified three sixteenth-century printed codices in our university libraries that were evidently bound in tawed leather by one workshop. The damaged cover of one of these three had revealed medieval manuscript fragments on the book spine; this codex served as a control for testing the other two volumes to see if they, too, contain fragments. The use of a medical CT scanner proved successful in visualizing interior book-spine structures and some letterforms, but not all of the text was made visible. The partial success of CT-scanning points to the value of further experimentation, given the relatively wide availability of medical imaging technologies, with their potential for short, non-destructive, 3D imaging times.

From tomographic reconstruction to automatic text recognition: the next frontier task for the artificial intelligence (2023)

D. V. Polevoy, P. A. Kulagin, A. S. Ingacheva, Zh. V. Soldatova, M. V. Chukalina, D. P. Nikolaev, and V. V. Arlazarov. "From tomographic reconstruction to automatic text recognition: the next frontier task for the artificial intelligence". In: *Fifteenth International Conference on Machine Vision (ICMV 2022)*. Ed. by Wolfgang Osten, Dmitry P. Nikolaev, and Jianhong (Jessica) Zhou. Vol. 12701. International Society for Optics and Photonics. SPIE, 2023, 127010P. DOI: 10.1117/12.2680132. URL: https://doi.org/10.1117/12.2680132.

Abstract: Virtual unrolling or unfolding, digital unwrapping, flattening or unfurling – all these terms are used to describe the process of surface straightening of a tomographically reconstructed digital object. For many objects of historical heritage, tomography is the only way to obtain a hidden image of the original object without its destruction. Digital flattening is no longer considered a unique met hodology. It being applied by many research group, but AI-based methods are used insignificantly in such projects, despite the amazing success of AI in computer vision, in particular optical text recognition. It can be explained by the fact that the success of AI depends on large, broad and high quality datasets, but there are very few published CT-based datasets relevant to the task of digital flattening. Accumulation of a sufficient amount of data necessary for training models is a key point for the next technological breakthrough. In this paper, we present open and cumulative dataset CT-OCR-2022. Dataset includes 6 packages data for different model

objects that help to enrich tomographic solutions and to train machine learning models. Each package contains optically scanned image of model objects, 400 measured X-ray projections, 2687 CT-reconstructed cross-sections of 3D reconstructed image, segmentation markups. We believe that CT-OCR-2022 dataset will serve as a benchmark for reconstructed object digital flattening and recognition systems, and that it will prove invaluable for advancement of the field of CT-reconstruction, symbols analysis and recognition. The data presented are openly available in Zenodo at doi:10.5281/zenodo.7123495 and linked repositories.

Volumetric Fast Fourier Convolution for Detecting Ink on the Carbonized Herculaneum Papyri (2023)

Fabio Quattrini, Vittorio Pippi, Silvia Cascianelli, and Rita Cucchiara. *Volumetric Fast Fourier Convolution for Detecting Ink on the Carbonized Herculaneum Papyri*. 2023. arXiv: 2308.05070 [cs.CV]. URL: https://arxiv.org/abs/2308.05070.

Abstract: Recent advancements in Digital Document Restoration (DDR) have led to significant breakthroughs in analyzing highly damaged written artifacts. Among those, there has been an increasing interest in applying Artificial Intelligence techniques for virtually unwrapping and automatically detecting ink on the Herculaneum papyri collection. This collection consists of carbonized scrolls and fragments of documents, which have been digitized via X-ray tomography to allow the development of ad-hoc deep learning-based DDR solutions. In this work, we propose a modification of the Fast Fourier Convolution operator for volumetric data and apply it in a segmentation architecture for ink detection on the challenging Herculaneum papyri, demonstrating its suitability via deep experimental analysis. To encourage the research on this task and the application of the proposed operator to other tasks involving volumetric data, we will release our implementation this https URL.

Terahertz Identification of Characters Written in Iron-Gall Ink on Stacked Paper (2023)

Haolian Shi, Leor Jacobi, Alexandre Locquet, and DS Citrin. "Terahertz Identification of Characters Written in Iron-Gall Ink on Stacked Paper". In:

IMEKO TC4 International Conference on Metrology for Archaeology and Cultural Heritage. IMEKO. Oct. 2023. DOI: 10.21014/tc4-ARC-2023.106.

Abstract: Iron-gall ink has been widely used ink in the production of documents and artworks since the fifth century C.E. Terahertz imaging is used to read characters written in such ink on stacked sheets of paper. Several contrast mechanisms including maximum/minimum of the reflected terahertz signal, signature frequency, Gaussian mixture model, and short-time Fourier transform are tested to compare the image quality of the buried text. The results show that the short-time Fourier transform mechanism outperforms other contrast mechanism and has the ability to extract clear images of buried text within paper stacks.

X-ray tomography for manuscripts (2022)

Fauzia Albertin. "X-ray tomography for manuscripts". In: *Umanistica Digitale* 12 (2022), pp. 39–64.

Abstract: This review presents the studies and the results achieved in the framework of the "Virtual X-ray Reading – VXR" project devoted to X-ray tomography for manuscripts. The project started in 2014 at École Polytechnique Fédérale de Lausanne (EPFL, Switzerland) and was part of the ambitious "Venice Time Machine" project. VXR aimed to test the feasibility and develop an alternate digitization technique for ancient manuscripts based on X-ray tomography. Research and technology made considerable progress in increasing the speed and the safety of the traditional digitization process of ancient collections, but, despite this, imaging of ancient, fragile, or un-opened documents remains a formidable challenge. Thanks to the high penetration of X-rays, using X-ray tomography, the acquisition of a 3D – tomographic – volume is possible even without opening the document. The X-ray contrast necessary for the readability is linked to the chemical composition of the ancient inks, such as the high X-ray absorption of the iron gall inks mainly used for centuries in Europe. In this review, I present the studies conducted to develop this technology, from the investigations on the ink chemistry to the imaging feasibility tests performed using extensive centralized facilities such as synchrotrons and the imaging of a 200-pages manuscript book the tomography of a 14th Venetian sealed last wills.

Deep learning for terahertz image denoising in nondestructive historical document analysis (2022)

Balaka Dutta, Konstantin Root, Ingrid Ullmann, Fabian Wagner, Martin Mayr, Mathias Seuret, Mareike Thies, Daniel Stromer, Vincent Christlein, Jan Schür, et al. "Deep learning for terahertz image denoising in nondestructive historical document analysis". In: *Scientific Reports* 12.1 (Dec. 2022), pp. 1–11. DOI: 10.1038/s41598-022-26957-7. URL: https://doi.org/10.1038/s41598-022-26957-7.

Abstract: Historical documents contain essential information about the past, including places, people, or events. Many of these valuable cultural artifacts cannot be further examined due to aging or external influences, as they are too fragile to be opened or turned over, so their rich contents remain hidden. Terahertz (THz) imaging is a nondestructive 3D imaging technique that can be used to reveal the hidden contents without damaging the documents. As noise or imaging artifacts are predominantly present in reconstructed images processed by standard THz reconstruction algorithms, this work intends to improve THz image quality with deep learning. To overcome the data scarcity problem in training a supervised deep learning model, an unsupervised deep learning network (CycleGAN) is first applied to generate paired noisy THz images from clean images (clean images are generated by a handwriting generator). With such synthetic noisy-to-clean paired images, a supervised deep learning model using Pix2pixGAN is trained, which is effective to enhance real noisy THz images. After Pix2pixGAN denoising, 99% characters written on one-side of the Xuan paper can be clearly recognized, while 61% characters written on one-side of the standard paper are sufficiently recognized. The average perceptual indices of Pix2pixGAN processed images are 16.83, which is very close to the average perceptual index 16.19 of clean handwriting images. Our work has important value for THz-imaging-based nondestructive historical document analysis.

High-precision page information extraction from 3D scanned booklets using physics-informed neural network (2022)

Zhongjiang Han, Jiarui Ou, and Koji Koyamada. "High-precision page information extraction from 3D scanned booklets using physics-informed neural network". In: *Journal of Visualization* (2022), pp. 1–15.

Abstract: X-ray-based computerized tomography scans are used to analyze page information in closed booklets noninvasively. An important task is to extract the page information. Previously, the Laplace equation was used to calculate the page number field and extract the page information as an iso-surface. However, this technique cannot extract the page information properly. To solve this problem and improve the accuracy of the extracted page information, we propose a page information extraction method using a physics-informed neural network. The proposed method employs a structural similarity measure—often used in image processing research—to numerically evaluate the appropriateness of the page extraction. New history booklet is used to verify the effectiveness of this method in addition to the conventional booklet data.

The Ghosts of Bindings Past: Micro-Computed X-Ray Tomography for the Study of Bookbinding (2022)

JD Sargan, Jessica J Lockhart, Andrew J Nelson, DL Meert-Williston, and Alexandra Gillespie. "The Ghosts of Bindings Past: Micro-Computed X-Ray Tomography for the Study of Bookbinding". In: *Digital Philology: A Journal of Medieval Cultures* 11.1 (2022), pp. 142–173.

Abstract: This essay describes the results of a new application of micro-computed X-ray tomography (µCT) to conduct nondestructive investigations of the binding structures of premodern books. This application addresses a twofold challenge in the study of historic bindings and their construction. Few premodern books survive in their original bindings. Moreover, until recently, when books were rebound, the original structures were rarely documented, and the remains were usually discarded. Where original bindings do remain in situ, much of their structure is, by design, hidden. Particulars of construction may be surmised; but without destructive disbinding, little can be proven. µCT enables an exploratory, multilinear approach to codicological investigations that makes bindings accessible in the form of tractable volumetric data.

Virtual unrolling technology based on terahertz computed tomography (2022)

Tianyi Wang, Kejia Wang, Kaigang Zou, Sishi Shen, Yongqiang Yang, Mengting Zhang, Zhengang Yang, and Jinsong Liu. "Virtual unrolling technology

based on terahertz computed tomography". In: *Optics and Lasers in Engineering* 151 (2022), p. 106924. ISSN: 0143-8166. DOI: https://doi.org/10.1016/j.optlaseng.2021.106924. URL: https://www.sciencedirect.com/science/article/pii/S0143816621003936.

Abstract: Due to the shape diversity and the occlusion problem, non-invasive inspection of cultural relic with special-shaped structures has always been the bottleneck of the existing imaging technology. We propose a virtual unrolling technique that can extract content from structures similar to folded paper and scroll, exploiting the three-dimensional imaging capability provided by terahertz computed tomography (THz CT). The method performs THz CT imaging on the object and obtains several slice images of its cross section. Considering the morphological properties of the slice image, the cross-sectional profile of the object is obtained by an improved single-pixel ridgeline extraction algorithm after suppressing the severe metal artifact on the slice images with our segmentation and inpainting-based scheme. And then a match-graft approach based on dynamic exemplar (MGDE) is developed to stitch lines of different layers into the final image. To illustrate, the occluding text content is successfully extracted from a mimic oil painting scroll samples with a thickness of sub-wavelength level. The method makes it possible for THz non-destructive inspection of similar structure that widely exist in industry, security, and especially heritage conservation.

Revealing the Nature of Black Pigments Used on Ancient Egyptian Papyri from Champollion Collection (2021)

Pierre-Olivier Autran, Catherine Dejoie, Pierre Bordet, Jean-Louis Hodeau, Caroline Dugand, Maëva Gervason, Michel Anne, and Pauline Martinetto. "Revealing the Nature of Black Pigments Used on Ancient Egyptian Papyri from Champollion Collection". In: *Analytical Chemistry* 93.2 (2021), pp. 1135–1142. DOI: 10.1021/acs.analchem.0c04178. eprint: https://doi.org/10.1021/acs.analchem.0c04178. URL: https://doi.org/10.1021/acs.analchem.0c04178.

Abstract: Although numerous papyri from ancient Egypt have been collected and preserved over the centuries, the recipe used to prepare black inks was only reported in manuscripts from the late Greco-Roman period. Black inks were mostly obtained after mixing carbon black with a binder agent and water. In previous studies performed on black inks apposed on papyri from ancient Egypt, additional chemical elements such as lead, iron, or copper

were also identified, and the resulting chemical contrast with the papyrus support was used to virtually decrypt highly degraded or rolled papyri. Combining a series of synchrotron-based techniques with Raman spectroscopy and scanning electron microscopy, we investigated 10 papyri fragments from J.-F. Champollion's private collection. For each fragment, the carbon-black pigment found in the ink is identified as flame carbon (lampblack or soot). Using X-ray diffraction computed tomography, we show that the diffraction signal of the carbon-based pigment itself can be isolated. As a result, a contrast with the papyrus support is obtained, even in the absence of a specific chemical element in the ink. This is opening up new opportunities to decipher words written millennia ago, as part of our Cultural Heritage.

Revisiting the Jerash Silver Scroll: a new visual data analysis approach (2021)

Daniel Baum, Felix Herter, John Møller Larsen, Achim Lichtenberger, and Rubina Raja. "Revisiting the Jerash Silver Scroll: a new visual data analysis approach". In: *Digital Applications in Archaeology and Cultural Heritage* (2021), e00186. ISSN: 2212-0548. DOI: https://doi.org/10.1016/j.daach.2021.e00186. URL: https://www.sciencedirect.com/science/article/pii/S2212054821000151.

Abstract: This article revisits a complexly folded silver scroll excavated in Jerash, Jordan in 2014 that was digitally examined in 2015. In this article we apply, examine and discuss a new virtual unfolding technique that results in a clearer image of the scroll's 17 lines of writing. We also compare it to the earlier unfolding and discuss progress in general analytical tools. We publish the original and the new images as well as the unfolded volume data open access in order to make these available to researchers interested in optimising unfolding processes of various complexly folded materials.

Unlocking history through automated virtual unfolding of sealed documents imaged by X-ray microtomography (2021)

Jana Dambrogio, Amanda Ghassaei, Daniel Starza Smith, Holly Jackson, Martin L. Demaine, Graham Davis, David Mills, Rebekah Ahrendt, Nadine Akkerman, David van der Linden, and Erik D. Demaine. "Unlocking history through automated virtual unfolding of sealed documents imaged by X-ray microtomography". In: *Nature Communications* 12.1 (Mar. 2021), p. 1184.

ISSN: 2041-1723. DOI: 10.1038/s41467-021-21326-w. URL: https://doi.org/10.1038/s41467-021-21326-w.

Abstract: Computational flattening algorithms have been successfully applied to X-ray microtomography scans of damaged historical documents, but have so far been limited to scrolls, books, and documents with one or two folds. The challenge tackled here is to reconstruct the intricate folds, tucks, and slits of unopened letters secured shut with "letterlocking," a practice—systematized in this paper—which underpinned global communications security for centuries before modern envelopes. We present a fully automatic computational approach for reconstructing and virtually unfolding volumetric scans of a locked letter with complex internal folding, producing legible images of the letter's contents and crease pattern while preserving letterlocking evidence. We demonstrate our method on four letterpackets from Renaissance Europe, reading the contents of one unopened letter for the first time. Using the results of virtual unfolding, we situate our findings within a novel letterlocking categorization chart based on our study of 250,000 historical letters.

A computational platform for the virtual unfolding of Herculaneum Papyri (2021)

Sara Stabile, Francesca Palermo, Inna Bukreeva, Daniela Mele, Vincenzo Formoso, Roberto Bartolino, and Alessia Cedola. "A computational platform for the virtual unfolding of Herculaneum Papyri". In: *Scientific Reports* 11.1 (2021), pp. 1–11.

Abstract: Ancient Herculaneum papyrus scrolls, hopelessly charred in the 79 A.D. Vesuvius eruption, contain valuable writings of the Greek philosophers of the day, including works of the Epicurean Philodemus. X-ray phase contrast tomography has recently begun unlocking their secrets. However, only small portions of the text hidden inside the scroll have been recover. One of the challenging tasks in Herculaneum papyri investigation is their virtual unfolding because of their highly complicated structure and three-dimensional arrangement. Although this procedure is feasible, problems in segmentation and flattening hinder the unrolling of a large portion of papyrus. We propose a computational platform for the virtual unfolding procedure, and we show the results of its application on two Herculaneum papyrus fragments. This work paves the way to a comprehensive survey and to further interpretation of larger portions of text hidden inside the carbonized Herculaneum papyri.

Virtual unwrapping of the BISPEGATA amulet, a multiple folded medieval lead amulet, by using neutron tomography (2021)

Birgit Wilster-Hansen, David C. Mannes, Karen L. Holmqvist, Kristine Ødeby, and Hartmut Kutzke. "Virtual unwrapping of the BISPEGATA amulet, a multiple folded medieval lead amulet, by using neutron tomography". In: *Archaeometry* (Nov. 2021). DOI: https://doi.org/10.1111/arcm.12734. eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/arcm.12734. URL: https://onlinelibrary.wiley.com/doi/abs/10.1111/arcm.12734.

Abstract: In recent decades, computed tomography (CT) combined with suitable image processing software has become a valuable tool to enable the reading of texts written on scrolls, which are fragile, damaged, or fused together, without physically unwrapping them. X-ray based computer tomography has successfully been used on scrolls made of soft materials such as papyrus and parchment. Although in few cases inscriptions on thin metal plates that have been rolled up and worn as amulets have been deciphered by using a high energy X-ray source, the readability of writings on of metal scrolls is limited by the high attenuation factor of this type of material. In this paper, we present for the first time the use of neutron tomography as an alternative to X-ray tomography for studying hidden inscriptions on folded metal objects. It is shown that the method overcomes the limitations of X-ray tomography caused by high attenuation of X-rays in lead objects. The inscription on the medieval Bispegata amulet, unearthed during excavations in Oslo's Old Town, has been read by using neutron tomography combined with VG Studio software. The amulet was made up of a thin lead sheet with an inscribed text, folded together into a rectangle. The inscription was runic, containing words of religious and magic meaning.

Virtual unfolding of folded papyri (2020)

Heinz-Eberhard Mahnke, Tobias Arlt, Daniel Baum, Hans-Christian Hege, Felix Herter, Norbert Lindow, Ingo Manke, Tzulia Siopi, Eve Menei, Marc Etienne, and Verena Lepper. "Virtual unfolding of folded papyri". In: *Journal of Cultural Heritage* 41 (2020), pp. 264–269. ISSN: 1296-2074. DOI: 10.1016/j.culher.2019.07.007. URL: https://www.sciencedirect.com/science/article/pii/S1296207419301670.

Abstract: The historical importance of ancient manuscripts is unique since they provide information about the heritage of ancient cultures. Often texts are hidden in rolled or folded documents. Due to recent improvements in sensitivity and resolution, spectacular disclosures of rolled hidden texts were possible by X-ray tomography. However, revealing text on folded manuscripts is even more challenging. Manual unfolding is often too risky in view of the fragile condition of fragments, as it can lead to the total loss of the document. X-ray tomography allows for virtual unfolding and enables non-destructive access to hidden texts. We have recently demonstrated the procedure and tested unfolding algorithms on a mockup sample. Here, we present results on unfolding ancient papyrus packages from the papyrus collection of the Musée du Louvre, among them objects folded along approximately orthogonal folding lines. In one of the packages, the first identification of a word was achieved, the Coptic word for "Lord".

4D imaging of lithium-batteries using correlative neutron and X-ray tomography with a virtual unrolling technique (2020)

Ralf F Ziesche, Tobias Arlt, Donal P Finegan, Thomas MM Heenan, Alessandro Tengattini, Daniel Baum, Nikolay Kardjilov, Henning Markötter, Ingo Manke, Winfried Kockelmann, et al. "4D imaging of lithium-batteries using correlative neutron and X-ray tomography with a virtual unrolling technique". In: *Nature Communications* 11.1 (2020), pp. 1–11.

Abstract: The temporally and spatially resolved tracking of lithium intercalation and electrode degradation processes are crucial for detecting and understanding performance losses during the operation of lithium-batteries. Here, high-throughput X-ray computed tomography has enabled the identification of mechanical degradation processes in a commercial Li/MnO_2 primary battery and the indirect tracking of lithium diffusion; furthermore, complementary neutron computed tomography has identified the direct lithium diffusion process and the electrode wetting by the electrolyte. Virtual electrode unrolling techniques provide a deeper view inside the electrode layers and are used to detect minor fluctuations which are difficult to observe using conventional three dimensional rendering tools. Moreover, the 'unrolling' provides a platform for correlating multi-modal image data which is expected to find wider application in battery science and engineering to study diverse effects e.g. electrode degradation or lithium diffusion blocking during battery cycling.

Placental Flattening via Volumetric Parameterization (2019)

S. Mazdak Abulnaga, Esra Abaci Turk, Mikhail Bessmeltsev, P. Ellen Grant, Justin Solomon, and Polina Golland. "Placental Flattening via Volumetric Parameterization". In: *Medical Image Computing and Computer Assisted Intervention – MICCAI 2019*. 2019, pp. 39–47. DOI: 10.1007/978-3-030-32251-9_5. URL: https://doi.org/10.1007/978-3-030-32251-9_5.

Virtual cleaning and unwrapping of non-invasively digitized soiled bamboo scrolls (2019)

Daniel Stromer, Vincent Christlein, Xiaolin Huang, Patrick Zippert, Tino Hausotte, and Andreas Maier. "Virtual cleaning and unwrapping of non-invasively digitized soiled bamboo scrolls". In: *Scientific reports* 9.1 (2019), p. 2311.

Description: Use of custom segmentation to handle vertical bamboo slats, and texturing step to texture based on carved surfaces. High quality reconstruction of original text and drawings.

An assessment of multimodal imaging of subsurface text in mummy cartonnage using surrogate papyrus phantoms (2018)

Adam Gibson, Kathryn E Piquette, Uwe Bergmann, William Christens-Barry, Graham Davis, Marco Endrizzi, Shuting Fan, Sina Farsiu, Anthony Fitzgerald, Jennifer Griffiths, et al. "An assessment of multimodal imaging of subsurface text in mummy cartonnage using surrogate papyrus phantoms". In: *Heritage Science* 6.1 (2018), p. 7.

Description: To date, the most thorough exploration of the relationship between ink chemistry and imaging technique. Explores MSI, transillumination, optical coherence tomography, micro-CT, XRF spectroscopy and imaging, x-ray phase contrast imaging, and terahertz imaging.

Robust Virtual Unrolling of Historical Parchment XMT Images (2018)

Chang Liu, Paul L Rosin, Yu-Kun Lai, and Weiduo Hu. "Robust Virtual

Unrolling of Historical Parchment XMT Images". In: *IEEE Transactions on Image Processing* 27.4 (2018), pp. 1914–1926.

Description: Modified graph cut method for segmenting layers from scrolls. Primarily a segmentation paper.

Abstract: We develop a framework to virtually unroll fragile historical parchment scrolls, which cannot be physically unfolded via a sequence of X-ray tomographic slices, thus providing easy access to those parchments whose contents have remained hidden for centuries. The first step is to produce a topologically correct segmentation, which is challenging as the parchment layers vary significantly in thickness, contain substantial interior textures and can often stick together in places. For this purpose, our method starts with linking the broken layers in a slice using the topological structure propagated from its previous processed slice. To ensure topological correctness, we identify fused regions by detecting junction sections, and then match them using global optimization efficiently solved by the blossom algorithm, taking into account the shape energy of curves separating fused layers. The fused layers are then separated using as-parallel-as-possible curves connecting junction section pairs. To flatten the segmented parchment, pixels in different frames need to be put into alignment. This is achieved via a dynamic programming-based global optimization, which minimizes the total matching distances and penalizes stretches. Eventually, the text of the parchment is revealed by ink projection. We demonstrate the effectiveness of our approach using challenging real-world data sets, including the water damaged fifteenth century Bressingham scroll.

Virtual Recovery of Content from X-Ray Micro-Tomography Scans of Damaged Historic Scrolls (2018)

Paul L Rosin, Yu-Kun Lai, Chang Liu, Graham R Davis, David Mills, Gary Tuson, and Yuki Russell. "Virtual Recovery of Content from X-Ray Micro-Tomography Scans of Damaged Historic Scrolls". In: *Scientific reports* 8.1 (2018), p. 11901.

Description: Rethinking of Liu 2018's segmentation approach to account for certain segmentation challenges.

Non-destructive Digitization of Soiled Historical Chinese Bamboo Scrolls (2018)

Daniel Stromer, Vincent Christlein, Andreas Maier, Patrick Zippert, Eric Helmecke, Tino Hausotte, and Xiaolin Huang. "Non-destructive Digitization of Soiled Historical Chinese Bamboo Scrolls". In: *2018 13th IAPR International Workshop on Document Analysis Systems (DAS)*. IEEE. 2018, pp. 55–60.

Description: Virtual unwrapping application. Segments volume into subvolumes by hand and performs planar intersection for texturing. No flattening required because each individual piece is already roughly planar. Applied to (proxy) slatted bamboo scroll.

Browsing through sealed historical manuscripts by using 3-D computed tomography with low-brilliance X-ray sources (2018)

Daniel Stromer, Vincent Christlein, Christine Martindale, Patrick Zippert, Eric Haltenberger, Tino Hausotte, and Andreas Maier. "Browsing through sealed historical manuscripts by using 3-D computed tomography with low-brilliance X-ray sources". In: *Scientific reports* 8.1 (2018). Data available for download here: `https://www5.cs.fau.de/research/data/bamboo-scroll-dataset/`, pp. 1–10. DOI: `10.1038/s41598-018-33685-4`. URL: `https://doi.org/10.1038/s41598-018-33685-4`.

Abstract: Severely damaged historical documents are extremely fragile. In many cases, their secrets remain concealed beneath their cover. Recently, non-invasive digitization approaches based on 3-D scanning have demonstrated the ability to recover single pages or letters without the need to open the manuscripts. This can even be achieved using conventional micro-CTs without the need for synchrotron hardware. However, not all manuscripts may be suited for such techniques due to their material and X-ray properties. In order to recommend which manuscripts and which inks are best suited for such a process, we investigate six inks that were commonly used in ancient times: malachite, three types of iron gall, Tyrian purple, and buckthorn. Image contrast is explored over the complete pipeline, from the X-ray CT scan and page extraction to the virtual flattening of the page image. We demonstrate, that all inks containing metallic particles are visible in the output, a decrease of the X-ray energy enhances the readability, and that the visibility highly depends on the X-ray attenuation of the ink's metallic

ingredients and their concentration. Based on these observations, we give recommendations on how to select the appropriate imaging parameters.

Uncovering the hidden content of layered documents by means of photoacoustic imaging (2018)

George J Tserevelakis, Margarita Tsagkaraki, Panagiotis Siozos, and Giannis Zacharakis. "Uncovering the hidden content of layered documents by means of photoacoustic imaging". In: *Strain* (2018), e12289.

Description: Photoacoustic detection of carbon ink signals. Uses time domain information to help estimate layer and ink position. Setup requires immersion of object in water tank.

Revealing hidden text in rolled and folded papyri (2017)

Daniel Baum, Norbert Lindow, Hans-Christian Hege, Verena Lepper, Tzulia Siopi, Frank Kutz, Kristin Mahlow, and Heinz-Eberhard Mahnke. "Revealing hidden text in rolled and folded papyri". In: *Applied Physics A* 123.3 (2017), p. 171.

Description: Segmentation algorithm based on iterative volume warping to get it into "good" state. Attempt at novel flattening algorithm.

Browsing Through Closed Books: Evaluation of Preprocessing Methods for Page Extraction of a 3-D CT Book Volume (2017)

Daniel Stromer, Vincent Christlein, Tobias Schön, Wolfgang Holub, and Andreas Maier. "Browsing Through Closed Books: Evaluation of Preprocessing Methods for Page Extraction of a 3-D CT Book Volume". In: *IOP Conference Series: Materials Science and Engineering*. Vol. 229. 1. IOP Publishing. 2017, p. 012005.

Description: Examination of existing image thresholding techniques for layer segmentation. Layers are roughly planar.

X-ray computed tomography for virtually unrolling damaged papyri (2016)

Dario Allegra, Enrico Ciliberto, Paolo Ciliberto, Giuseppe Petrillo, Filippo Stanco, and Claudia Trombatore. "X-ray computed tomography for virtually unrolling damaged papyri". In: *Applied Physics A* 122.3 (2016), p. 256.

Description: Medical CT scan of proxy scroll. Uses a 64-multi-detector Optima CT660 scan. First, a scan proof was performed on unrolled papyrus. Then the papyrus was rolled and scanned. Selection of good papyrus slice using two criteria. One criteria being lower number of overlapping sheets, in the best case no overlaps. Second criteria being the spiral paths detected through a raw segmentation. A good slice is selected using morphological operator (skeletonization and branch-points detection), Otsu thresholding, and gamma transformation (gamma=2.0). For slice reconstruction, manually find the first and final points and then apply a weighted 3x3 neighbor mask to detect slices and reconstruct the missing path between the slices using the highest intensity value using contrast stretched method. The pixels of the visited points are saved in a vector. The final stage is virtual unrolling. For each coordinate. the pixels of maximum intensity along the direction of the gradient is chosen. The result is tested on a single roll of 259 slices. A bad slice with overlap is also tested for the result section. Original unrolled version and the virtually unrolled version are compared in the result section. Overlapping sheet issue is not solved in the paper.

Abstract: The regular format for ancient works of literature was the papyrus roll. Recently many efforts to perform virtual restoration of this archeological artifact have been done. In fact the case of ancient rolled papyrus is very intriguing. Old papyruses are the substrates of very important historical information, probably being the use of papyrus dated to the Pre-Dynastic Period. Papyrus degradation is often very hard so that physical unrolling is sometime absolutely impossible. In this paper, authors describe their effort in setting a new virtual restoration methodology based on software manipulation of X-ray tomographic images. A realistic model, obtained by painting a hieroglyph inscription of Thutmosis III on a papyrus substrate made by the original method described by Plinius the Elder and by pigments and binders compatible with the Egyptian use (ochers with natural glue), was made for the X-ray investigation. A GE Optima 660 64 slice was used to obtain a stack of tomographic slices of the rolled model. Each slice appears as spiral. The intensity variations along the cross-sectional result from ink on the papyrus. The files were elaborated with original software, written

by the use of MATLAB high-level language, and the final result was quite similar to the radiography of the physically unrolled sheet.

Virtual unrolling and deciphering of Herculaneum papyri by X-ray phase-contrast tomography (2016)

I Bukreeva, A Mittone, A Bravin, G Festa, M Alessandrelli, P Coan, V Formoso, RG Agostino, M Giocondo, F Ciuchi, et al. "Virtual unrolling and deciphering of Herculaneum papyri by X-ray phase-contrast tomography". In: *Scientific reports* 6 (2016), p. 27227.

Description: Phase contrast micro-CT applied to Herculaneum papyri. Essentially the same type of results as Mocella, Brun, Ferrero, and Delattre, "Revealing letters in rolled Herculaneum papyri by X-ray phase-contrast imaging".

Recovering historical film footage by processing microtomographic images (2016)

Chang Liu, Paul L Rosin, Yu-Kun Lai, Graham R Davis, David Mills, and Charles Norton. "Recovering historical film footage by processing microtomographic images". In: *Digital Heritage. Progress in Cultural Heritage: Documentation, Preservation, and Protection: 6th International Conference, EuroMed 2016, Nicosia, Cyprus, October 31–November 5, 2016, Proceedings, Part I 6*. Springer. 2016, pp. 219–231.

Abstract: 1960s film was typically printed on tri-acetate film base. If not preserved properly, such material breaks down at a chemical level, which is a non-stoppable process that permanently fuses the film so that it essentially becomes a lump of solid plastic. Recently, some precious films, such as the only known copy of the earliest surviving episode of 'The Morecambe and Wise Show' have been discovered, but they are in poor condition. They will eventually turn into a pool of sticky liquid and be gone forever. In this paper, as proof of concept, we use X-ray microtomography to provide 3D imaging of a test film of similar vintage, and propose an automatic method to extract footage from it.

Revealing text in a complexly rolled silver scroll from Jerash with computed tomography and advanced imaging software (2015)

Gry Hoffmann Barfod, John Møller Larsen, Achim Lichtenberger, and Rubina Raja. "Revealing text in a complexly rolled silver scroll from Jerash with computed tomography and advanced imaging software". In: *Scientific reports* 5 (2015), p. 17765.

Description: The work aims to virtually unfold irregularly folded and heavily deformed inscribed metal sheets (silver) from Jerash, Jordan. This work demonstrates detection of morphological writing signal (i.e. etching) using high-resolution CT scans. During the scan, the sample is mounted under vacuum in epoxy, sectioned, and polished. Unwrapping is performed using VGStudioMax 3 Beta by drawing a polyline ROI on the slices of the reconstruction. This ROI selection is created manually using a 3D draw tool and can be flattened to a plane. The result shows 1-8 lines of the content of one scroll. The result infers that the original container was made of lead with tin and tin-copper alloy decorations but that the iron oxide likely is a secondary feature deposited later from percolating groundwater. The scroll was protected in a sealed case which had cracks due to corrosion and there are sediments in it. Flattening is not done. It considered small longitudinal segments of the scroll to display each lines. Some lines are also broken into two parts, namely, upper and lower segments. When there is physical contact between the metal sheets, the unrolling can be time-consuming and results in "scratches". The metal is generally silver, but the study shows that there are other metals also present, namely: Lead, Copper, Iron, Bismuth, Samarium, Tin. This is revealed by backscattered electron imaging on the resulting scroll.

Abstract: Throughout Antiquity magical amulets written on papyri, lead and silver were used for apotropaic reasons. While papyri often can be unrolled and deciphered, metal scrolls, usually very thin and tightly rolled up, cannot easily be unrolled without damaging the metal. This leaves us with unreadable results due to the damage done or with the decision not to unroll the scroll. The texts vary greatly and tell us about the cultural environment and local as well as individual practices at a variety of locations across the Mediterranean. Here we present the methodology and the results of the digital unfolding of a silver sheet from Jerash in Jordan from the mid-8th century CE. The scroll was inscribed with 17 lines in presumed pseudo-Arabic as well as some magical signs. The successful unfolding shows that it

is possible to digitally unfold complexly folded scrolls, but that it requires a combination of the know-how of the software and linguistic knowledge.

Revealing letters in rolled Herculaneum papyri by X-ray phase-contrast imaging (2015)

Vito Mocella, Emmanuel Brun, Claudio Ferrero, and Daniel Delattre. "Revealing letters in rolled Herculaneum papyri by X-ray phase-contrast imaging". In: *Nature communications* 6 (2015).

Description: X-ray computed tomography (XCT) is used on samples of 2 of out of 6 Herculaneum Scrolls. One of these samples are unrolled and another is rolled. They used an 'unrolling' operation conducted by the Oslo method in Naples in 1986–1987 and showing several superposed layers of papyrus. The phase-contrast CT was imaged at ESRF on beamline ID17 with FReLoN detector. There is no stage for virtual unwrapping.
One of the challenges was to resolve several layers of the innermost windings of the scroll. The authors claim to have resolved this issue of ink detection using fluorescent x-ray techniques with traces of lead.

Abstract: Hundreds of papyrus rolls, buried by the eruption of Mount Vesuvius in 79 AD and belonging to the only library passed on from Antiquity, were discovered 260 years ago at Herculaneum. These carbonized papyri are extremely fragile and are inevitably damaged or destroyed in the process of trying to open them to read their contents. In recent years, new imaging tech- niques have been developed to read the texts without unwrapping the rolls. Until now, specialists have been unable to view the carbon-based ink of these papyri, even when they could penetrate the different layers of their spiral structure. Here for the first time, we show that X-ray phase-contrast tomography can reveal various letters hidden inside the precious papyri without unrolling them. This attempt opens up new opportunities to read many Herculaneum papyri, which are still rolled up, thus enhancing our knowledge of ancient Greek literature and philosophy.

Virtual unrolling and information recovery from scanned scrolled historical documents (2014)

Oksana Samko, Yu-Kun Lai, David Marshall, and Paul L Rosin. "Virtual

unrolling and information recovery from scanned scrolled historical documents". In: *Pattern Recognition* 47.1 (2014), pp. 248–259.

Description: Application of a graph cut method for roll segmentation.

Area-preserving flattening maps of 3D ultrasound carotid arteries images (2008)

Bernard Chiu, Micaela Egger, David J Spence, Grace Parraga, and Aaron Fenster. "Area-preserving flattening maps of 3D ultrasound carotid arteries images". In: *Medical image analysis* 12.6 (2008), pp. 676–688.

Flattening maps for the visualization of multibranched vessels (2005)

Lei Zhu, Steven Haker, and Allen Tannenbaum. "Flattening maps for the visualization of multibranched vessels". In: *IEEE Transactions on Medical Imaging* 24.2 (2005), pp. 191–198.

Robust and objective decomposition and mapping of bifurcating vessels (2004)

Luca Antiga and David A Steinman. "Robust and objective decomposition and mapping of bifurcating vessels". In: *IEEE transactions on medical imaging* 23.6 (2004), pp. 704–713.

Nonlinear virtual colon unfolding (2001)

AV Vilanova Bartroli, Rainer Wegenkittl, Andreas Konig, and Eduard Groller. "Nonlinear virtual colon unfolding". In: *Proceedings Visualization, 2001. VIS'01.* IEEE. 2001, pp. 411–579.

Nondistorting flattening maps and the 3-D visualization of colon CT images (2000)

S Halier, Sigurd Angenent, A Tannenbaurn, and Ron Kikinis. "Nondistorting flattening maps and the 3-D visualization of colon CT images". In: *IEEE Transactions on Medical Imaging* 19.7 (2000), pp. 665–670.