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THE DIGITAL RESTORATION OF THE HERCULANEUM PAPYRI

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This paper presents a report of the activities so far conducted within the Mellon-funded research project *Digital Restoration of the Herculaneum Papyri* (University of Kentucky).

Keywords: Digital restoration, Photogrammetry, Spectral imaging, 3D models, Metadata

Introduction

While many prognosticators originally forecast the demise of the written word as personal computer and Internet usage grew, the opposite in fact has occurred. Technological advances have instead made it possible for more people to produce, disseminate, preserve, and study written content faster and easier than ever before. From the production of digital copies that can be safely shared and studied, to the use of advanced imaging tools to restore faded texts, to the deployment of AI networks that uncover hidden inaccessible writing, damaged and fragile manuscripts like the Herculaneum papyri are arguably one of the greatest beneficiaries of the technological age.

In particular, the Herculaneum papyri have experienced a true digital renaissance, as technologies like multi-spectral imaging, photogrammetry, micro-CT, and even AI have thrust papyrologists and the blackened, crinkled fragments they study into the modern spotlight.[1] The first hi-tech application to the Herculaneum papyri occurred in the early 2000s, when a team from Brigham Young University applied the power of NASA's multi-spectral earth imaging technology to fragments of opened scrolls.[2] By photographing each fragment under infrared light, the contrast between the charred surface of the papyri and the black ink upon it became much more pronounced. Difficult to read text suddenly became much clearer, and new text appeared on sections believed to be completely blank. Between 1999 and 2005, the BYU team captured more than 30,000 infrared images of the papyri. In the end, almost every fragment from four institutions holding Herculaneum material – the Biblioteca Nazionale in Naples, the Institut de France in Paris, the Bodleian Library at the University of Oxford, and the British Library in London – were included in the project.

While a massive leap forward, MSI technology failed to solve all of the problems associated with the reading of fragmented Herculaneum papyri.[3]

[1] https://scrollprize.org/; I. Sample, *Contest launched to decipher Herculaneum scrolls using 3D X-ray software*, «The Guardian» 2023, March 15 (https://www.theguardian.com/technology/2023/mar/15/contest-decipher-herculaneum-scrolls-3d-x-ray-software); J. Marchant, *Buried by the Ash of Vesuvius, These Scrolls Are Being Read for the First Time in Millennia*, «Smithsonian» 49.04/2018, 40-47, 112-114 (https://www.smithsonianmag.com/history/buried-ash-vesuvius-scrolls-are-being-read-new-xray-technique-180969358/); M. Capone, *Vesuvius Challenge, 250mila dollari per chi decifra i papiri carbonizzati*, «Il Mattino» 2023, March 21 (https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwjR_Pa-rdv_AhWD2qQKHcU2CEUQFnoECBAQAQ&url=https%3A%2F%2Fwww.ilmattino.it%2Fpay%2Fedicola%2Fvesuvio_eruzione_pompei_ercolano_papiri-7298026.html&usg=AOvVaw1dXRD93TQ3pIwU8HMagmIP&opi=89978449).

[2] S.W. Booras-D.R. Seely, *Multispectral Imaging of Herculaneum papyri*, «CErc» 29/1999, 95-100.

[3] See the observations in R. Macfarlane *et alii*, *Update Report on the Use of the Multi-spectral Images of the Herculaneum Papyri*, in J. Frösén-T. Purola-E. Salmenkivi (eds.), *Proceedings of the XXIV International Congress of Papyrology* (Helsinki 2007), 579-586, esp. 584-586; K.E. Piquette, *Illuminating the Herculaneum Papyri: Testing new imaging techniques on unrolled carbonised manuscript fragments*, «Digital Classics Online» 3.2/2017, 80-102 (https://journals.ub.uni-heidelberg.de/index.php/dco/article/view/39417, retrieved June 23, 2023); and R. Janko, *The Herculaneum Library: Some recent developments*, «Estudios Clásicos» 121/2002, 25-41, esp. 28-30.

One of the acknowledged shortcomings of the existing MSI images is the lack of scale or metric information. Precise measurements are needed to estimate circumferences and «reconstruct» a scroll from its fragmented parts. Another issue is the lack of surface shape detail. The holes and jagged edges caused by the physical unwrapping make it difficult to determine on which layer of papyrus a particular letter or series of letters appears, and the two-dimensional images of multi-spectral photography cannot distinguish between layers or even sometimes between holes and letters. Scholars must therefore physically engage with the actual papyri by tilting the fragment and moving it left to right, forward and backward under raking light and a high-powered microscope.[4] Finally, changes in the technologies and procedures used during the project resulted in datasets with inconsistent properties. The images vary significantly in terms of field-of-view, spatial resolution, exposure settings, and available spectral bands. While this variability was intentional in order to maximize the image quality for each fragment individually, it complicates the process of drawing comparisons across the collection as a whole. The inconsistencies in the MSI data due to required stitching of subregions as well as naming conventions and other practical workflow and metadata structuring were also a by-product of the groundbreaking digitization.

But with the march of time comes advances in technology and the new solutions they offer. In 2022, a team led by computer science professor W. Brent Seales from EduceLab at the University of Kentucky set out to apply the latest technologies to the reading of the Herculaneum papyrus fragments. With the improvements in spectral imaging – lighting arrangements, resolution improvements, lens quality – came the opportunity to capture more than just the photometric qualities of the papyrus. The Seales team was able to capture consistent spectral images – single shots of entire *cornici* without the need for stitching – at a larger number of spectral bands (16 in total, which also produced calibrated RGB images). But more than the spectral response, the team also used a photogrammetry system to build 3D depictions of the surface shape. The new spectral images will be aligned with these 3D models to create a highly legible digital version of each papyrus fragment. For the first time, text illuminated by infrared light will be seen along with the shape of the papyrus surface. Funded by the Andrew Mellon Foundation, the project will result in a complete digital library of all Herculaneum papyrus fragments accompanied by a thorough collection of linked open metadata.

Technical Setup

Beginning in the fall of 2022, spectral images were acquired using a MegaVision multispectral imaging system equipped with a 50 megapixel E7 camera back (Fig. 1), UV-IR apochromatic lens, and four UV-IR LED light panels (Fig. 2).

[4] For an overview of the means and practices to study the Herculaneum papyri, see R. Janko, *How to Read and Reconstruct a Herculaneum Papyrus*, in B. Crostini-G. Iversen-B.M. Jensen (eds.), *Ars Edendi Lecture Series* IV (Stockholm 2016), 117-161 (http://dx.doi.org/10.16993/baj.f. License: CC-BY 4.0, retrieved June 23, 2023).

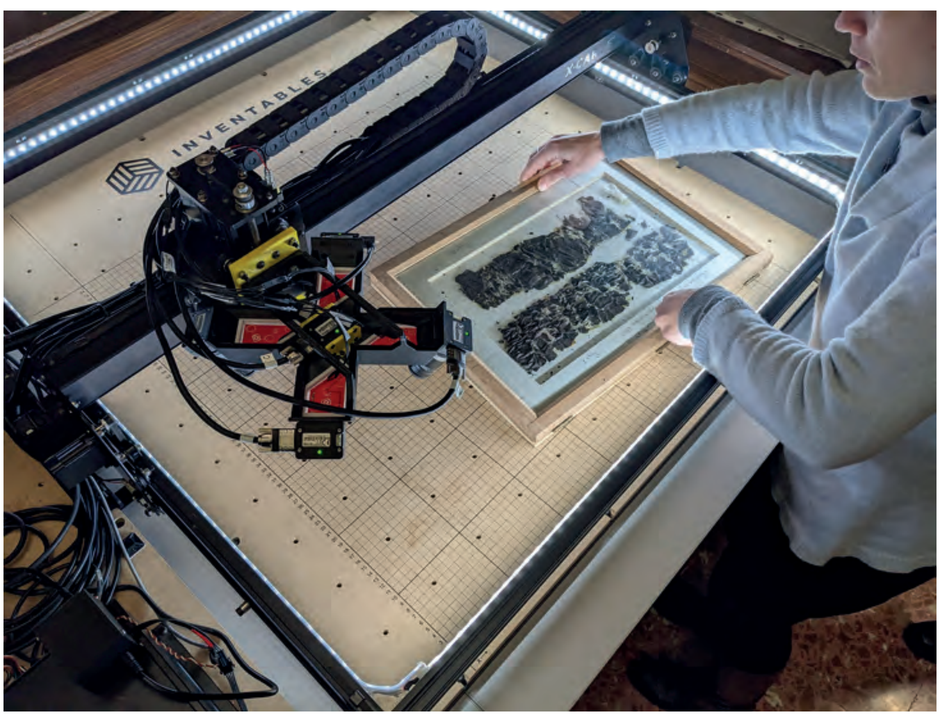
Fig. 1. Multispectral imaging system: 50 megapixel E7 camera back

Fig. 2. Multispectral imaging system: UV-IR LED light panels

In total, 16 unique spectral bands were captured from wavelengths 420 nm to 1050 nm. An additional 17th spectral image was captured at 1050 nm and was intentionally overexposed to emphasize the visible ink contrast. While this image was not used in any of our post-processing steps, it was a useful «preview» image for the imaging team during the project. As ultraviolet illumination produced neither reflective nor fluorescent contrast on the Herculaneum fragments, UV spectral bands in the 365 nm to 400 nm range were not included in the imaging set. For each captured spectral band, the MegaVision capture

software automatically produced a raw grayscale image, a flatfielded grayscale image, and a gamma-corrected preview image. For every tray, we additionally saved one CIELAB-encoded «true color» image derived from the set of visible spectrum bands.
To ensure the spectral images were not contaminated by the room's working lights, a blackout tent was constructed to house the spectral camera, lights, and samples during image capture (Fig. 3). The camera was statically mounted to an overhead truss at a fixed distance from the imaging plane so that the largest *cornici* were fully captured in a single field-of-view. This setup resulted in an image spatial resolution of approximately 360 ppi.

Fig. 3. Multispectral imaging system: blackout tent



To capture the 3D surface of each fragment, we designed a photogrammetry imaging system specifically for the Herculaneum papyri. As the name suggests, photogrammetry is a method that uses multiple photographs of an object to reconstruct its 3D shape. The photographs are taken from multiple viewing positions, and special software converts the differences between these views into 3D shape information. Our system consists of a motorized camera head of five cameras which sweeps above the surface of the *cornice*, capturing images of each location from five different viewing angles (Figs. 4 and 5).

Fig. 4. Photogrammetry system: detail

For the Herculaneum imaging, the views captured at each position were illuminated by integrated white LED lights which run the perimeter of the system. Additionally, a single down-facing image was captured using infrared (940 nm) LEDs attached to the camera head. The 5 megapixel grayscale cameras were positioned approximately 10 cm from the fragment's surface, resulting in an image spatial resolution of 580 ppi. To ensure a complete 3D reconstruction for the whole surface, 168 capture positions with overlapping fields-of-view were acquired to produce 1008 images per *cornice*.

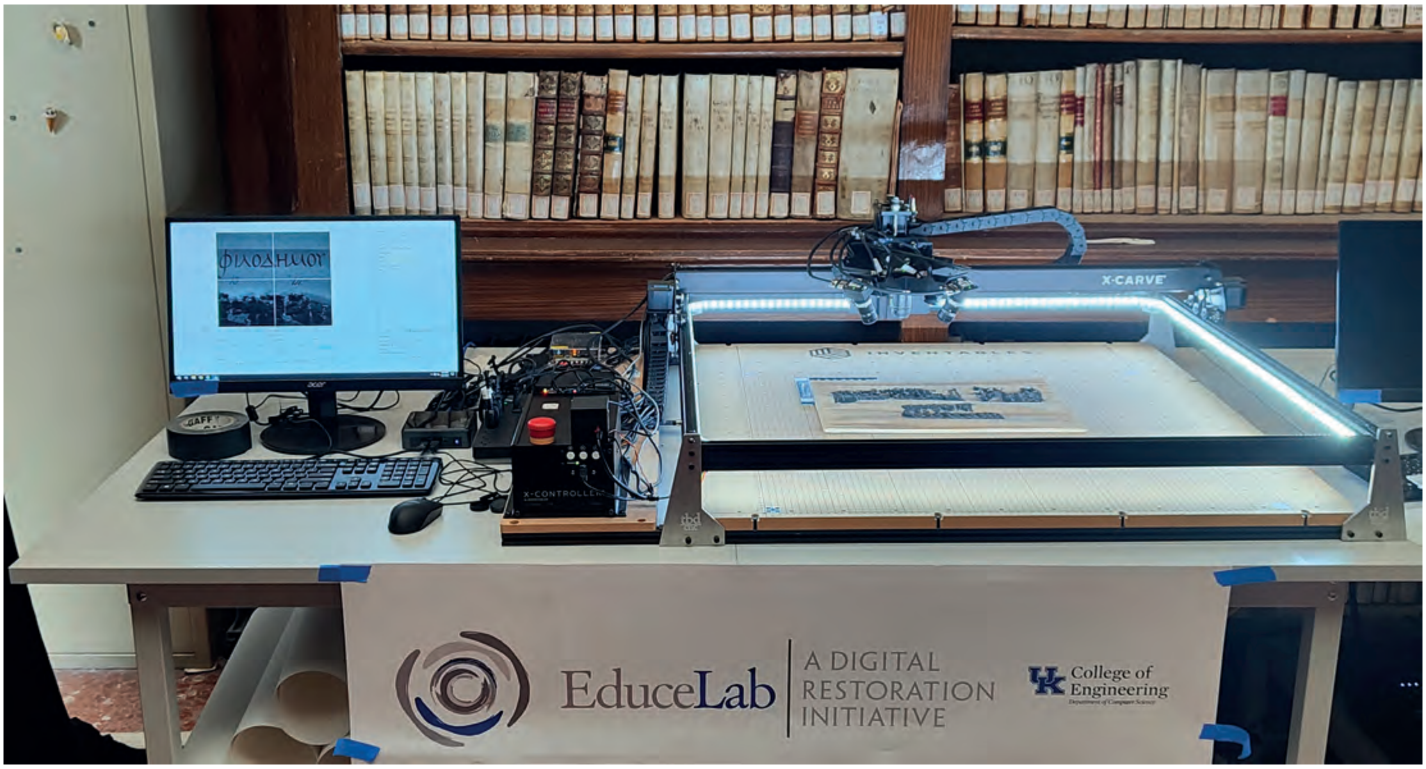


Fig. 5. Photogrammetry system

To maintain consistent sample positioning across all datasets, a 3D printed «sample square» was mounted to the imaging table of each system. This square provides known scale and orientation markers which are used during post-processing to align and calibrate the images captured across the spectral and photogrammetry systems. Additionally, each *cornice* was assigned a unique ID number (UUID) during imaging which was printed as a QR code and placed in a special slot on the sample square. As this UUID is embedded in the image metadata and is visible in the captured images as a QR code, the UUID provides an easy way to link the object to the data and metadata capture during this project.

Local team and workflow process

In addition to the Kentucky EduceLab team, the Project involves a local papyrological team that oversees all the activities taking place in the Officina dei Papiri. Managed by Federica Nicolardi, the team includes one PostDoc scholar, Marzia D'Angelo, and four PhD candidates, Alessia Lavorante, Maria

Chiara Robustelli, Claudio Vergara, and Rossella Villa, all of whom have been working on projects dealing with Herculaneum papyri and have familiarity with the collection and the material preserved in the Officina. The local team also benefits from the collaboration and advice of the Kentucky team, the Centro Internazionale per lo Studio dei Papiri Ercolanesi 'Marcello Gigante', and major experts in the field, namely Professors Gianluca Del Mastro and Roger Macfarlane.

Project activity has been divided into different phases requiring different approaches depending on the typology of material being dealt with (Fig. 6):

1. Imaging the «regular» *cornici* (November 2022-March 2023). The first phase of the imaging process involved the vast majority of the collection, i.e. over 2800 *cornici*, each of which includes an individual board carrying one or more papyrus pieces. Each board was imaged as an individual item (approximately spectral scanning area of 47 cm x 32 cm; photogrammetry scanning area of 53 cm x 39 cm).
2. Imaging the *scorze* (March-April 2023). Following the remounting carried out in 2000,[5] the *scorze* are (mostly) individually glued to Japanese paper fixed to conservation paperboard. One *cornice* usually preserves two or more items, which were imaged individually obtaining multiple scans for each *cornice*.
3. Remounting and imaging the Oslo *cornici* (scheduled November 2023-). During the survey of the collection carried out as a preliminary step (September-October 2022) to defining timeline and workflow of the activities, a major concern emerged regarding the condition of material stored in the *mobili osloensi* 1-10. More than 300 *cornici* stored in these cabinets preserve papyrus fragments, small and medium-sized, glued on Japanese paper sheets as a result of being opened with the so-called Oslo method.[6] These pieces have never been fixed on cardboard and, being loose and very light, they move freely around in the metal *cornici*. In its current state of preservation, the material is less stable than scholars would like in order to promote more frequent handling. Project activities presented the perfect opportunity to reconsider the storage of this material and secure it by mounting the Japanese paper sheets on backing boards. This procedure, which was used for fixing the *scorze* to conservation paperboard in 2000,[7] is safe and risk-free for the ancient material, as it does not require direct intervention on papyrus fragments, but rather on the Japanese paper. Thanks to the support of the Director of the Library, Maria Iannotti, and Giovanni Bova, in charge of the Officina dei Papiri, it was possible to receive technical advice and support by the Istituto Centrale per la Patologia degli Archivi e del Libro (ICPAL). Remounting, which will follow the instructions provided by the ICPAL, will allow imaging of this material without risks.
4. Imaging «special» items (May-November 2023). During the preliminary survey of the collection, some items were identified as requiring special attention and specific adjustments. This material includes: wooden *cornici* which do not allow the board carrying the papyri to be extracted; papyrus pieces stored between two pieces of glass, as a result of Fackelmann's intervention;[8] and *PHerc.* 1672, whose non-standard length will allow only spectral imaging subject to special adjustment.

[5] K. Kleve-M. Capasso-G. Del Mastro, *Nuova sistemazione delle scorze*, «CErc» 30/2000, 245 f. and Iid., *Nuova sistemazione delle scorze (2000)*, «CErc» 31/2001, 143.

[6] K. Kleve *et alii*, *Three technical guides to the Papyri of Herculaneum. How to unroll. How to remove Sovrapposti. How to take Pictures*, «CErc» 21/1991, 111-124; see also the reports published in «CErc» 19/1989, 22/1992, 24/1994-30/2000.

[7] See n. 5.

[8] A. Fackelmann, *The Restoration of Herculaneum Papyri and Other Recent Finds*, «BICS» 17/1970, 144-147.

5. Imaging the *cassetti* (May-June 2023). The project offered the opportunity to capture for the first time spectral images of the *cassetti*, which contain unopened scrolls and fragments of scrolls. Infrared light is a key aid for identifying handwriting in fragments that, due to their state of conservation, cannot be examined under a microscope.
6. Digitizing historical photographs (May-September 2023). With the goal of gathering all existing image data in addition to creating new images, the project will also digitize historical analog photographs and negatives stored at the Officina.

Fig. 6. Examples of different material from the Herculaneum collection. Top from left to right: *PHerc*. 1012, cr 10 (*cornice*); *PHerc.* 410 (*scorza*); *PHerc*. 18, cr 10 (wooden *cornice*). Bottom from left to right: *PHerc.* 1433, cr 1 (between two pieces of glass); *cassetto* 63; *PHerc.* 353, cr 3 (negative). ©EduceLab-University of Kentucky-Biblioteca Nazionale, Napoli

At the time of imaging, appropriate basic metadata was simultaneously gathered for each papyrus object: each digital item was labeled with a unique reference ID, the *cornice* number, the type of support (board, bare wood, modern conservation paperboard, Japanese paper …), and paperboard color (if applicable). Other metadata were added later using the fundamental base represented by the information recorded in the online catalog of the Herculaneum papyri *Chartes*.[9] Elements that can help track down *PHerc*. numbers pertaining to the same scroll and to keep track of any changes in numbering within the collection have been carefully considered. Particular attention has been given to miscellaneous *cornici*, where papyri stored under the same inventory number belong to different original scrolls.

[9] We are very grateful to Gianluca Del Mastro for allowing us to use this huge amount of data he collected.

Results

The two photogrammetry systems have allowed two people to work simultaneously each day in a fluid and safe workflow. Collaboration of the Library staff was crucial: we are very grateful to the Director of the Officina dei Papiri Ercolanesi, Giovanni Bova, and his staff, Sabina Battista, Elena Carrelli, Erminia Criscuolo, Rossella D'Amore, Simone Falba, Sara Graus, Ciro Marotta, Lucia Teano. Our gratitude also goes to Fabrizio Diozzi and Daniela Bacca.

Scanning «regular» *cornici* and *scorze* produced spectral images and photogrammetry of around 3,000 items, to which the approximately 350 newly restored Oslo trays will soon be added. Post-processing of the image data will generate the following for each papyrus fragment:

- A set of spectral derivative images (*i.e*. enhancements).
- A photogrammetric 3D reconstruction.
- An alignment of the spectral images to the resulting 3D models.
- Web-friendly versions of the above for quick search and review to help users avoid unnecessarily downloading massive raw images of the wrong papyri.

While all post-processing steps were prototyped prior to the launch of the project, a constant state of improvement occurred as we captured and learned from the real data. This includes improvements to quality and efficiency.

Moreover, a key contribution of the project will be to include clear statements of digital provenance for each of the digital images. Various software pipelines, each consisting of multiple computational processes, are applied to the data during the image post-processing described in the above steps. Pipelines include Segmentation, Stitching, Register 3D, and Register 2D; while examples of discrete computational operations within these pipelines include Reorganize Texture, Affine Registration, and Combine Transforms, to name just a few. As a result, throughout this project we have been sensitive to the admonitions of The London Charter, a set of principles designed to «ensure that digital heritage visualization is, and is seen to be, at least as intellectually and technically rigorous as longer established cultural heritage and communication methods».[10]

In 2006, a group of concerned international scholars met in London to discuss their growing disquietude over the use of «computer-based visualizations», such as those generated by this project, in the study of cultural heritage. They feared that – thanks to the use of computer graphics in entertainment – the academic integrity of scholarly outcomes based on digitally rendered images would be called into question. Commercial productions were known to take «creative license» when depicting historical artifacts or events for entertainment purposes, and the expert panel rightly questioned how anyone could «distinguish between scientifically valid communication and fantastic, video-game display?».[11]

As the New Introduction to the London Charter points out:

> «No matter how thoughtfully a research question is posed in relation to the existing field of knowledge, how painstakingly available sources are researched and interpreted, how discerningly or creatively an argument is elaborated visually, *to the viewer, a finished image alone does not reveal the process by which it was created* … Such visualizations, solipsistically adrift in cyberspace, can only slip, unremarked, through the continuum of scholarly discourse. *The empirical opacity*

[10] H. Denard, *A New Introduction to the London Charter*, in A. Bentkowska-Kafel–D. Baker–H. Denard (eds.), *Paradata and Transparency in Virtual Heritage* (Ashgate 2012), 57-71, esp. 59.

[11] R. Beacham-H. Denard-F. Niccolucci, *An Introduction to the London Chart* (2009), https://londoncharter.org/old-introduction.html (retrieved June 23, 2023).

> *of the synchronous image, then, is the crisis that threatens to isolate visualizations from meaningful disciplinary dialogue*».[12]

Obviously, our goal for these digitally rendered images of Herculaneum papyri is that they enable many significant scholarly outcomes. Therefore, in addition to capturing traditional descriptive metadata for each papyrus fragment, we are developing methods to document the digital provenance chain for the digital images of the Herculaneum papyri and then disseminate that metadata in a clear, concise, and organized way that enables investigations of those processes. For example, a scholar may want to see the «big picture» of how the complete collection of registered compilations was created; or they may want to understand the specific parameters used to align the various images in the creation of one particular 3D papyrus fragment. To accomplish this goal, we will use the Metadata Encoding Transmission Standard (METS),[13] a comprehensive container that can enumerate various types of files; show how they are interconnected and work together to create a complex digital object; and provide all of the relevant metadata for each file, either embedded within the document itself or linked to a location outside of the document. Each digital image of the Herculaneum papyri can thus be accompanied by a METS file that lists all its composite image files, along with all of the intermediate files and data transformations that occurred «behind the scenes» to create the 3D object. In addition, METS provides a powerful design tool for creating all kinds of interpretive operations, such as displaying and visualizing the digital provenance chain of any given digital object.

Challenges

The size of the Herculaneum fragment collection poses the greatest challenge to our digitization and cataloging efforts. Imaging more than 3000 objects at a consistently high quality requires efficient workflows, robust hardware, thorough quality controls, and well-defined operating procedures when failures and errors inevitably occur. This situation becomes more complicated with an international research team, where the imaging and development teams work with a six-hour time differential. Efficient, asynchronous workflows proved to be the most important component for the successful completion of this project.

To achieve our goal of digitizing the entire collection in one year (including setup, teardown, and unforeseen delays), our workflow target was to image 50-60 *cornici* per day, or about one *cornice* every 5-6 minutes. While spectral imaging took less than one minute per *cornice*, photogrammetry capture times of 6-7 minutes per *cornice* proved the biggest obstacle to our schedule. By deploying two photogrammetry systems, however, we were able to increase our capture rate to two *cornici* every 7-8 minutes.

The total amount of raw data captured for every *cornice* was approximately 14 GB, or 50 TBs for the entire collection. When fully operational, we produced 2-3 TBs of data every four days. To ensure against data loss due to unexpected hardware failure, our data management workflow was designed so that at least two copies of the previous weeks' data was available at any given time. First, our three imaging systems captured directly to external solid state harddrives (SSDs). At the end of each week, these drives were removed from the systems

[12] Denard, *A New Introduction* cit., 60.

[13] http://www.loc.gov/standards/mets/.

and three new drives were used for the next week's imaging. The data on the first set of drives was then transferred to an on-site data server equipped with enough storage for the entire project. At regular intervals, the storage server initiated a transfer of any newly copied data to a remote server located at the University of Kentucky. Once the data was backed up to both the on-site and remote servers, the SSDs were cleared and reused for imaging in subsequent weeks. To minimize the possibility of data loss through this workflow, we used the Rclone utility for all backup operations as it automatically identifies file transfer failures and initiates problematic transfers immediately.

Conclusions

For scholars studying the Herculaneum papyri, with its unique structures of folds, fractures, corrugations, and hollows, three-dimensionality has been a long time *desideratum*. Meeting high standards in terms of resolution, accuracy, and consistency, the new corpus of 3D images will greatly facilitate remote work on the collection, as it will allow for an experience similar to that of studying papyri under a microscope but one that is absolutely non-invasive and risk-free. In the past, such efforts as trying to trace a letter in a fold or on a heavily corrugated surface would require the board to be severely angled under the microscope. But it is imperative that this practice be avoided, as it can overstress the papyrus, facilitating the detachment and falling away of stray or barely attached fragments. Three-dimensional images finally offer the ability to virtually tilt papyrus boards, take accurate measurements, and examine recurring damages (*danni solidali*) in an absolutely non-invasive and risk-free manner.

In addition to improving the readability of the text, the new 3D models will also – and for the first time – facilitate preliminary and preparatory operations to digitally reconstruct the rolls. The infrared imaging technique proves extremely useful for enhancing the contrast between ink and the papyrus surface, yet it tends to flatten the three-dimensional features and thus make it difficult to identify circumferences (*volute*). It is reasonable to think that the material analysis of pieces will be carried out seamlessly on the new images (Fig. 7).

The three-dimensional approach is hoped to aid in the identification of multiple layers (*sovrapposti* and *sottoposti*) and pave the way for their automated detection through the use of AI, moving in the direction of a 3D virtual restoration of the Herculaneum papyri.

The thorough collection of metadata, as well as of facsimiles and pre-existing photographs to be aligned with the new images, will allow to consult the material needed to study and publish a papyrus more quickly, easily, and at the same time and place.

Ultimately, the results of the project will provide clear and easy-to-use tools for anyone seeking a general overview on the collection of the Herculaneum papyri, but at the same time specific and comprehensive resources for in-depth study by papyrologists. The outcomes will not only be a point of arrival, but aim to become a point of departure for further developments and innovative perspectives.

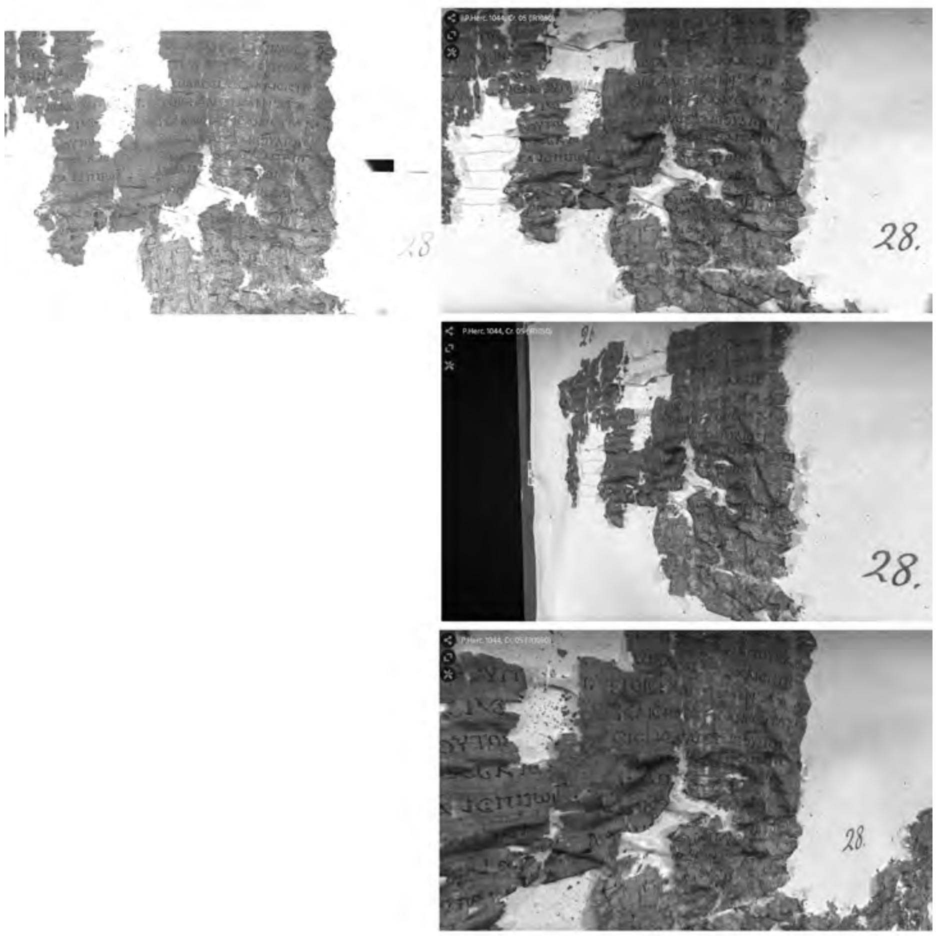


Fig. 7. *PHerc.* 1044, cr 5, detail: BYU NIR image (left); EduceLab/Kentucky 3D model from different perspectives (right)

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