2022

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

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**Recommended Citation**  
Chapman, Christy Y.; Parker, C. S.; Bertelsman, Ali; Gessel, Kristina; Hatch, Hannah; Seevers, Kyra; Brusuelas, James H.; Parsons, Stephen; and Seales, Brent (2022) "The Digital Compilation and Restoration of Herculaneum Fragment P.Herc.118," *Manuscript Studies*: Vol. 6: Iss. 1, Article 1. Available at: [https://repository.upenn.edu/mss_sims/vol6/iss1/1](https://repository.upenn.edu/mss_sims/vol6/iss1/1)

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Abstract

Ancient documents pose many challenges for the scholars who painstakingly study and elucidate them. Natural deterioration occurs over time, erasing words and sentences that were once apparent. Water and fire damage can render text completely unreadable. Wrinkles and folds obscure content essential to meaning. Thankfully, old and new imaging methods can today be combined to rescue “lost” text and make it once again accessible to scholars. Using computer vision techniques like registration, historical images that often represent the most faithful record of the original content of a document can now be combined with those produced by newer technologies, like spectral imaging and 3D modeling. The result is a diachronic digital compilation that enables new scholarly discoveries. Using the collection of fragments from an opened ancient scroll from Herculaneum, P Herc.118, the work outlined in this paper prototypes a process that capitalizes on the best of old and new images to create a single, definitive digital model for scholarly study.

Keywords

spectral imaging, p Herc.118, herculaneum scrolls, photogrammetry, 3d modeling

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The manuscript, P.Herc.118, known also as MS Gr. class. b. 1 (P)/1–12, is an ancient papyrus scroll preserved in a series of twelve glass frames at the Bodleian Library at the University of Oxford, England. Buried by the eruption of Mount Vesuvius in 79 CE, the scroll, along with hundreds of others, was excavated in 1752 from the Villa of the Papyri in Herculaneum, Italy.¹ This collection of approximately 1,100 scrolls makes up the only large-scale library to have survived from Greco-Roman antiquity and the only classical one to have been found in situ.

The authors wish to acknowledge the support of the Bodleian Libraries at the University of Oxford, in particular Martin Kauffmann, the Head of Early and Rare Collections at the Weston Library; David Howell, former Head of Heritage Science for the Bodleian Libraries; and their teams.

¹ Francesca Longo Auricchio, Giovanni Indelli, Giuliana Leone, and Gianluca Del Mastro, La Villa dei Papiri: una residenza antica e la sua biblioteca (Rome: Carocci, 2020).
Herculaneum scrolls present a challenging situation for the conservators charged with preserving them as well as the classicists who seek to study them. While the carbonization effect of the eruption preserved the papyri for centuries, it also rendered them extremely friable. Their delicate nature makes it impossible to unwrap and read them via traditional means without causing significant damage. Nonetheless, attempts have been made, with disastrous results. P.Herc.118, for example, was manually unrolled via Piaggio’s machine, a device that relied on the force of gravity to slowly unfurl it, but the scroll fell apart during the process.\(^2\) The resulting sections were grouped together in twelve *pezzi* (pieces), mounted to twelve boards, and framed (fig. 1).

As is the case with most significant documents, various efforts were made over the years to create a visually accessible facsimile of P.Herc.118. From hand-drawn renderings, to analog film photographs, to digital spectral images, every venture created yet another version of the twelve *pezzi*. The images accumulated without any link or reference to prior ones, resulting in an image record that is as fragmentary as the scroll itself. While technological advances enabled clearer renditions of text with every iteration, each image collection nonetheless posed its own set of problems, and no method existed for easily viewing the images as a composite whole so that analysis and elucidation could be enhanced.

Thus, our project set out to combine all prior images into one unified data set, so that the best visual representations from each facsimile could be combined and viewed at the same time. This compilation of all past images, combined with new hyperspectral imaging and innovative 3D modeling, successfully creates a comprehensive, more robust version of P.Herc.118 that enhances the readability of the manuscript and enables new scholarly study.

The Fragmentary Image Record

When the scroll was unrolled by Piaggio’s machine in 1883, commissioned artists painstakingly tried to draw the visible letter shapes from each piece (fig. 2). But the visibility of the black ink on the volcanoblackened papyrus varied according to the carbonized state of a given scroll. Accordingly, the artist renderings of some scrolls depicted large sections of Greek text, while others revealed only small areas. In the case of P.Herc.118, visible text at the time of unrolling was mainly limited to small areas of each pezzo.

In addition, the process of peeling the scroll open caused some of the papyrus layers to adhere to one another, creating multilayered fragments or “stuck-together pages” of jumbled text with some letters appearing,

incorrectly, next to each other. The surfaces were also uneven and warped, further obscuring the writing. In the end, some fifty-six sketches were produced, and while these disegni (drawings) of P.Herc.118 proved less than perfect, they nonetheless served as the only source of study for many years.

The advent of digital photography made it possible to capture more clearly the writing that was visible to the naked eye, and a series of photographs of P.Herc.118 were taken and then digitized in 1998. But these 2D photos did nothing to address the challenges posed by the layered papyrus or its blackened, carbonized state. It still proved impossible to ferret out where the lines of text actually began and ended or whether they came from

**FIGURE 2.** Disegni of the nine fragments from Pezzo 4. The artists painstakingly rendered the shapes of the letter forms, as well as of the fragments themselves, as P.Herc.118 was unrolled and peeled apart.
the same layer within the scroll. Nor did the photos reveal any of the writing still hidden on the black surface.

By the early 2000s, advances in digital imaging offered new techniques for enhancing the readability of the blackened fragments, as well as confidence that a solution to the layer problem could be found. In 2005, Gene Ware and researchers from Brigham Young University applied multispectral imaging to the twelve pezzi. Spectral imaging is a type of photography that exposes an object to several specific wavelengths of light across the visible and near-visible range of the electromagnetic spectrum. Multispectral and hyperspectral imaging are subsets of spectral imaging that are differentiated by the number of wavelength images captured, often no more than tens of images in the former case and hundreds of images in the latter. Each wavelength reacts uniquely with the object, and what appears under one wavelength may be invisible in another. The resulting images record aspects of the object that humans might not otherwise see with the naked eye, and post-processing the entire image set can further reveal features that may not have been visible in any single image. Ware’s work using infrared lighting, which was premised on that of Stephen Booras and David Seely, represented a true breakthrough. It not only gave scholars a look at previously invisible text on the black surface, but also rendered the highest resolution images to date.

Unfortunately, however, the Ware data also presented problems. To achieve the highest resolution possible and reveal the greatest amount of visible text,
Ware imaged each plate in tiny square sections—sixty-three per pezzo, to be exact—resulting in an even more fragmentary picture of P.Herc.118 (see fig. 18). Second, because multispectral imaging is a 2D technology, Ware’s work failed to recreate the three-dimensional elements like ridges, holes, and contours that provide clues regarding where layers begin and end and how the letters and words should be reconstructed.

Thus, the advances in technology at each imaging venture actually hindered in some way the quality of the outcomes. In the end, three distinct—and themselves fragmented—sets of images for each of the twelve pezzi were produced. Scholars studying P.Herc.118 found themselves sifting among approximately 824 different images (disegni, digital photographs, and multispectral images) to elucidate the manuscript’s content (fig. 3). A more robust representation of P.Herc.118, one that combined the strength of all prior facsimiles and at the same time re-created the surface dimensionality of each fragment, remained out of reach.

Related Work

The effort to create a unified image data set is not without precedents, nor are attempts to represent the three-dimensional surface of objects, including texts. Stephen Parsons, C. Seth Parker, and W. Brent Seales used image registration to compile images from five sets of photographs taken of the St. Chad Gospels between 1912 and 2010.7 The team developed an innovative “registered image viewer” that allows clear, direct comparison of the diachronic images.8 The viewer proves useful for readily finding signs of wear, such as paint chipping, and other changes to the manuscript. However, it

8 To see the registered image viewer as applied to P.Herc.118, visit http://infoforest.cs.uky.edu/pherc118/.
only depicts pages in a two-dimensional format. The viewer does not include registration to a three-dimensional model.

Three-dimensional modeling has recently been used to digitally restore and document structural heritage artifacts. For example, Hatzopoulous and colleagues used close range photogrammetry in addition to other tools to create a three-dimensional map of the remains of the Tholos monument in Greece, as well as of the area surrounding it. These data were used to

reconstruct the Tholos by realigning the existing columns and restoring the missing columns and pediment.

Digital restoration of manuscripts via photogrammetry has not been previously attempted, however. The only other digital restoration of text using 3D data was performed by Seales and colleagues, who used data from an unstructured volumetric micro-computed-tomography scan to “virtually unwrap” an ancient, damaged scroll from En-Gedi.10

A combination of near-infrared (NIR) and reflectance transformation imaging techniques (RTI) has been applied to opened Herculaneum fragments in an attempt to capture details about their morphology.11 RTI is an imaging method in which a series of photographs is taken with a light source moving around the object and projecting from a different location and angle with each snap of the camera.12 Once the images have been processed, RTI gives the user a digital experience equivalent to moving an object around underneath a light source, allowing the different angles of light to hit the surface and thus illuminate different parts of the object. Near-Infrared Reflectance Transformation Imaging (NIR-RTI) combines RTI with an NIR light source to further enhance the textual visibility of opened Herculaneum fragments.

While using NIR-RTI on the fragments greatly improves the quality of images when compared with those captured using NIR imaging alone, its usefulness is limited by the fact that accurate metric data regarding

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10 William Brent Seales, C. Seth Parker, Michael Segal, Emanuel Tov, Pnina Shor, and Yosef Porath, “From Damage to Discovery via Virtual Unwrapping: Reading the Scroll from En-Gedi,” Science Advances 2, no. 9 (2016), retrieved from https://advances.sciencemag.org/content/2/9/e1601247.
camera positions is not incorporated into the final results. High-quality, two-dimensional images like those produced by NIR-RTI are not as revelatory as fully three-dimensional, to-scale models that enable accurate metric measurements of everything on the surface, such as the peaks and valleys of the wrinkled papyrus, or of the size of letter shapes in the text. As the researchers note, complete metric data “is essential for analyzing papyrus layer relationships, correcting surface/sign distortion, and facilitating virtual hypothesising and reconstruction of sections/scrolls.”

**Approach**

This work set out to achieve two objectives: (1) to create a three-dimensional version of the P.Herc.118 fragments that reveals metric-based shape aspects of the manuscript imperceptible in regular photography and (2) to combine this new 3D version with all other historical images into one robust facsimile that contains the best aspects of each rendition. Such a compilation provides a document that enables greater readability and scholarly study than any single version alone.

To accomplish this goal, a 3D virtual model was created and then registered to, or digitally aligned with, the 1998 photos and a newly created set of hyperspectral images. By rendering the 3D model with a higher-quality photo layered on top, scholars reap the benefits of high-resolution spectral imaging while also being able to interact with the manuscript in a 3D space. Scholars can view the measurable geometry of the manuscript and detect multiple layers, broken or deformed letters, and warping, for example, helping them discern the text’s meaning. The model also allows functionality such as zooming and rotating, as well as the ability to turn the various components of the image on and off (for example, one can view the 3D model with the spectral photo but without the 1998 image). In addition, the

digital version gives both scholars and the general public the ability to explore the manuscript without ever putting the physical document at risk.

**THREE-DIMENSIONAL MODELING**

To create an accurate 3D model of the surface of the opened papyrus plates of P.Herc.118, we used photogrammetry, which is a camera-based method for estimating and rendering the three-dimensional coordinates of surface points by using photographs taken from different angles. In this project, photogrammetry was achieved using the Artec Space Spider (fig. 4), a small, handheld industrial scanner. The physical constraints of the project—the document itself is too fragile to leave the library—made the lightweight, portable scanner ideal.

As the scanner is moved back and forth over the surface of the document, it exposes the object to a sequence of blue-light flashes that reflect

![Figure 4. The handheld Artec Space Spider. Image courtesy of Artec.](https://repository.upenn.edu/mss_sims/vol6/iss1/1)
back into one of five photosensors arranged at a variety of angles and locations across the scanner’s base. Photos are captured at a rate of nine to ten frames per second, gradually constructing the look, size, and shape of the document. After trial and error, a “sweet-spot” distance and rate of scanner movement can be determined, so that the most accurate appearance and geometry will be achieved in the most efficient manner.

It is important to note that the Artec Space Spider is not a laser scanning device. Unlike photogrammetry, laser-based options rely on thousands of focused light pulses to create an extremely accurate geometric representation; however, they collect little to no color information about the scanned object. Thus, while laser scanning provides high-resolution images and metric data that results in high levels of shape accuracy, it does not provide the full-color visual texture that one gets with photogrammetric techniques. Similar to the way NIR-RTI is inadequate because it only collects color and other appearance information but no metric data, laser scanning is not an appropriate option because preserving the color appearance of the document in addition to the metric information is vital to the creation of an accurate digital version. Furthermore, our previous work on closed Herculaneum scrolls suggested that laser scanning was problematic for Herculaneum materials in particular, due to their unique characteristics. The laser tended to scatter across the bumpy surface, resulting in a sparse, inaccurate surface reconstruction.

Any photography-based imaging of P.Herc.118 must also address the issue of occlusion. Due to the extreme topography of the damaged manuscript—warped, wrinkled, ridged, and torn—scanning a pezzo from only one angle yields an inaccurate geometry because regions are occluded or hidden from view (think of mountains casting a shadow on the valley when illuminated by the sun). Thus, to capture the entire geometry of the surface, the document was scanned a minimum of four times from different angles (fig. 5). For pezzi in which the surface structure was especially severe, extra scans were performed in areas where “peaks and valleys” occurred.

Creating the 3D Model

To create a complete digital 3D model from the data acquired by the Artec Space Spider, it is necessary to convert the raw scan data into a 3D mesh file
containing both the object’s topographical characteristics as well as its color. These two integrated characteristics are processed in tandem with each other during post-scan processing. As scanning occurs, the reflectance data are uploaded in real time to Artec’s three-dimensional editing software, Artec Studio, which generates a set of unstructured, 3D points called a point cloud. Each point in the cloud contains information about the physical document, including color, shape, and size. Because we performed several scans from different viewing angles and of different portions of each pezzo, the final point clouds from each scan had to be aligned with each other, and any discrepancies between the point clouds had to be resolved.

Creating the mesh required a four-step iterative process: global registration, auto and rough alignment, the removal of “problem” scans, and outlier removal. Global registration is a tool within Artec Studio that arranges all of the point clouds from the individual scans into a singular coordinate plane so that they align. Auto alignment and rough alignment then allow several scans to be aligned at once, but the distance between the points in the cloud is maintained so that the size and shape of the object remain consistent. Finally, outlier removal goes through each point cloud to isolate any points that appear above and below the plane of the document as a result of inaccurate reflectivity values.

This point-cloud registration process was applied repetitively to the P.Herc.118 data set until the scans were aligned visually and no holes appeared.
in the generated mesh. Any scans that produced geometric or visual data inconsistent with the reference images of P.Herc.118 were removed from the point-cloud stack. In addition, during the outlier removal process, Artec Studio would often misinterpret legitimate points in the cloud as noise in the data and eliminate them, which created holes within the three-dimensional model. To repair the holes, we simply reversed the outlier removal and attempted to align the problematic pieces independently before running outlier removal again.

To develop the color information, the Artec software automatically determines which camera angles provide the best view of the object and uses the captured image from that view to apply color detail (fig. 6) to the mesh. This essentially layers the photographic information over the geometric mesh constructed from the point clouds to create a color-accurate three-dimensional model.

**Figure 6.** The image on the left depicts the beginning state of all scans loaded into Artec Studio. Due to the method of scanning from many angles, the scans are perpendicular to one another and unordered. The image on the right depicts the ideal finished scan alignment.

**Using Registration to Improve the 3D Model**

The resulting 3D model required further refinements before it was ready to be studied by scholars. The color images captured by the Artec Space Spider
are of relatively low resolution (1.2 megapixels per image), and as a result, the resolution of the color information on the mesh is too low to reveal fine details. Additionally, the blackened condition of the carbonized papyrus causes the surface to appear extremely dark, making the detection and interpretation of any writing difficult.

Fortunately, the clarity of this 3D version can be drastically improved by using image registration to layer a higher quality color image—the 1998 photographs, for example—on top of the model. This registration process used in figure 6 required one “fixed” two-dimensional image to which another image could be aligned. This second image serves as the “moving” image, or the image that can be moved and warped to align with the fixed image.14 For this project we needed a fixed image that would map exactly to the digital 3D model—in other words, an image derived from or otherwise connected to the data used to create the 3D model.

The color information for the mesh is stored in an image file called a texture image. In this case, we used the texture image for the mesh as the fixed image base in our registration process. However, because the texture image is an inherent part of the 3D mesh, it could not be simply “lifted” off of the 3D model and used as the 2D photograph required for registration. We were able to extract the raw texture data that contained all of the mapping information, but that action effectively disconnected it from the mesh data, causing each of the color surfaces to appear in a random, disordered configuration and making any alignment to it impossible (fig. 7, left). We therefore generated a new texture using an in-house custom software tool that “reordered” the raw texture so that it once again depicted a coherent color facsimile of P.Herc.118 in 2D (fig. 7, right).

With a usable base for registration of each pezzo, the landmark and deformable registration methods were then used to align the 1998 photos to the reordered textured images. For each pezzo, distinctive features appearing on both the lower-resolution texture and the high-resolution photograph were identified, and these “landmarks” were aligned automatically (fig. 8). In cases where the fit between the two images was not perfect, deformable

**FIGURE 7.** The image on the left displays the jumbled, extracted texture before it has been reordered. On the right, the scrambled texture is reordered into a coherent representation of the pezzo.

**FIGURE 8.** Examples of landmark points on the fixed (top left) and moving (top right) images. Landmark registration produces a global transformation that can result in a slight misalignment of local features (bottom left). This can be corrected using deformable registration, which performs local, nonlinear warping to settle features into place (bottom right).
registration was used to subtly warp the moving image to match the fixed image more closely.

At this point, to convert the compiled image to 3D, one creates a new mesh file that correctly references the newly aligned image rather than the old texture, and a 3D model showing the 1998 reference photo can be generated (fig. 9).

FIGURE 9. The 3D model generated using the 1998 high-resolution photo.
Image registration is an extremely powerful tool. With it, any two-dimensional image can be viewed in three dimensions as long as the image can be aligned to the texture. Scholars will be able to view what were once two-dimensional images in a three-dimensional context, improving their sense of the geometry of the manuscript.

Adding Hyperspectral Images

Providing a high-resolution 3D model of the twelve pezzi of P.Herc.118 offers many benefits over the low-resolution 3D model or high-resolution 2D photos alone. Yet even this model can be improved by including spectral images that reveal more surface details than ordinary photography.

As mentioned previously, a set of multispectral images were made of P.Herc.118 in 2005. However, due to the lingering issues mentioned above, it was desirable to capture a new set of spectral images as we performed the 3D scans. While multispectral imaging is limited to a relatively small number of light wavelengths, usually between ten and fifty bands, hyperspectral data sets are composed of hundreds of band images and contain a more finely nuanced representation of an object’s spectral properties. We therefore imaged all twelve pezzi of the scroll using the Bodleian Library’s HEADWALL Hyperspec III hyperspectral scanner, creating a stack of 370 band images from the near ultraviolet (400 nm) to infrared (1000 nm) range with a bandwidth of 1.6 nm. For the purposes of this work, our goal is to include this hyperspectral data set as a layer in our unified 3D model. However, we expect future experiments to investigate whether the spectral bands that were not captured by Ware in 2005 could be used to computationally improve contrast between the ink and blackened papyrus.

Various challenges presented themselves during the hyperspectral imaging of the twelve plates, the most critical issue pertaining to lighting. The HEADWALL Hyperspec III system illuminates the scanned object using a continuous broadband light source containing wavelengths from ultraviolet to infrared (fig. 10). The camera component then uses diffraction gratings to disperse the reflected light onto the image sensor.
Due to the topography of P.Herc.118, the ideal position of the light and scanner would have been directly overhead to reduce the possibility of shadows caused by the surface. However, the lighting was integrated into the existing system and placed in a side-mounted position (as shown in fig. 11). Side-mounted illumination causes no problems for flat objects that contain no shadow-inducing artifacts, but the undulations of P.Herc.118
created shadows in some areas, resulting in occlusion similar to that encountered with the Artec scanner.

Another issue involved the trade-off that spectral imaging requires between spatial resolution and spectral depth—in current hyperspectral systems, spatial resolution is sacrificed when capturing images under so many wavelengths of light. Therefore, to achieve a high-resolution hyperspectral dataset, it was necessary to zoom in on one small horizontal section of the document at a time, a process similar to Ware’s approach in 2005. In this case, however, each pezzo was divided into only six parts, which resulted in only six image strips for each plate (fig. 12).

Finally, the frames containing the pezzi were too large to fit on the platform beneath the scanner, and the scanner’s field of view could not capture the entire plate at once. To address this issue, the plates were rotated 180 degrees halfway through acquisition. Thus, three strips were scanned in one orientation and three in the other (fig. 13). This caused the shadows from the angled light to be cast differently on half of the strips, creating the illusion of an offset in some of the final images (fig. 14).

Our goal for capturing the hyperspectral image set was to add it to the 3D image compilation. The registration process described previously was thus used once again at this stage to quickly and accurately align the separate hyperspectral strips of each pezzo to the corresponding 1998 photo. Since all images in a hyperspectral stack are inherently aligned with each other, registering a single spectral band image to the fixed image photograph
Figure 13. Plates had to be rotated 180 degrees beneath the scanner in order to image the full document.

Figure 14. The reconstructed RGB image of pezzo 3. One sees a visible line across the middle where the shadows flipped due to the rotation of the board during scanning.
will effectively align every spectral band image to that fixed image as well. Because fine surface details of the scrolls are more visible under infrared light, we used the 950 nm band to perform registration, storing the produced transformations so that they could be applied to other bands from the spectral stack. A color image of each pezzo was also generated by combining the 449 nm (blue), 550 nm (green), and 649 nm (red) spectral bands into a single file to serve as the three channels of a color image.

The 1998 photo for each pezzo served as the fixed image, and the six hyperspectral strips of one band were treated as moving ones. Once the strips were all registered to the photo, they were blended together to get rid of harsh lines that resulted from the side lighting and make the image more cohesive in keeping with our goal of creating one unified compilation. Although the shadows may have obscured some features and caused some problems with alignment (as seen in fig. 14), the representation of the surface physicality and the legibility of the text—our two primary concerns—were not greatly affected. The final step was to create a new mesh file that referenced each pezzo’s reconstructed hyperspectral image, and a 3D composite model for each pezzo was generated. Figure 15 depicts each step of this process.

![FIGURE 15. Hyperspectral strips registered to the 1998 color photo create a final hyperspectral composite image.](image-url)
Results

The final output of this project was the creation of a 3D version of each of the twelve pezzi. The 3D versions are composed of four images: the 1998 full-color image, a 2017 full-color image (created by registering hyperspectral bands 449 nm [blue], 550 nm [green], and 649 nm [red] into one image), the 2017 infrared image (hyperspectral band 950 nm), and the 3D mesh.

While access to these four images in a singular 3D model is a significant advance for scholars working on Herculaneum fragments, expediting and facilitating their workflow, greater visibility is also a benefit. The use of extremely bright light in hyperspectral imaging, in particular, generates a much more vibrant full-color image than a traditional photo. One can also see how the infrared image from the hyperspectral data set represents an improvement over traditional high-resolution photography in the context of legibility (fig. 16).

More importantly, the composite 3D images display both physical features that become lost in 2D photos and the ink and surface features that cannot be seen with the naked eye. By registering the hyperspectral images to the 3D mesh, scholars are able to look at the text as it appears on the actual surface, which makes it easier to determine which characters lie on the same layer of a fragment consisting of multiple layers stuck together. Future work will also add the disegni images, as shown in figures 20 and 21. (See “Future Work” below.)

This greater visibility in the composite 3D model indeed expedites scholarly workflows. During the course of this project, these versions of our 3D model along with the Ware MSI data revealed information that seems to corroborate prior studies regarding P.Herc.118. The manuscript was previously identified as a copy of Philodemus’s *On Epicurus*, a biographical work about the philosopher. However, the scroll has not received much scholarly attention since the brief article from the early 1900s by Wilhelm Crönert. If

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P.Herc.118 indeed preserves a copy of *On Epicurus* as Crönert claims, it would join only two other papyri (P.Herc.1289 and 1232) in preserving this work of Philodemus. More importantly, as a philosophical biography, it might provide not only further and previously unknown anecdotes about the life of Epicurus, but also additional extracts from his private letters, which were quoted in the biography and known to have been published and in circulation since the third century BCE.

Our initial analyses using both the new 3D images and the Ware MSI data seem to suggest that Crönert’s assessment might be correct. For example, in the 3D model of Pezzo 2 fragment 22 (fig. 17a–b) we can confidently confirm, without consulting the original, that we have text on one consistent layer. Furthermore, while the hyperspectral imaging (fig. 17a–b on the right) improves the clarity of the text in the 3D model, the Ware MSI (shown in fig. 17c) allows us to see two lines that can be reconstructed with confidence.
Examining the 3D versions of figure 17 with the disegno shown in figure 16, we can now provide an initial and improved transcription of the fragment:

```
ἐπιστέλλει τοῖς

ι στέλλει τοῖς

ϲώφρονα απε-

υ μετα τρ. χ

πιστολής
tα αν-

dε τής τοῦ [Πυ-

οκλέους αλειτουρ[γή-

cιας ἦν μὲν ἐγώ δυνα-
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The reconstruction of the final two lines highlighted in figure 17 is potentially most significant. First, in the context of reconstructing the column structure of P.Herc.118, using both the 3D model (to confirm the text appears on a single layer, without having to consult the physical fragment) and the Ware MSI (which provides additional ink visibility), we can calculate an average number of letters per line, which is about seventeen. Moreover, it is clear that we are looking at a column. The letter chi (χ) in our transcription likely marks some issue in a column (now hidden under layers of papyrus) to the right, and so it is sitting in the intercolumnium, or space between columns. Although that data might not seem terribly important to those not trained in papyrology, we must simply note that for every column in P.Herc.118 that is barely visible and fragmented, we are now in a much better position, based on our knowledge of the Greek language, to reconstruct the wording and syntax across lines.

Second, and more importantly, we might indeed have the name Pythocles mentioned (Πυθοκλέους, boxed in red in fig. 17c). A letter from Epicurus to his follower Pythocles is preserved, albeit epitomized, in Diogenes Laertius’s *Lives of the Eminent Philosophers* (10.84–121); this letter in particular addresses the topic of the celestial phenomena in Epicurean philosophy. That Pythocles is possibly mentioned in close proximity to language indicative of writing
and letters (ἐπιστέλλει τοῖς | [-----]ων γραφεν and ε]πιςοληϲ) might suggest Epicurus’s letters are discussed and even quoted in this section of the scroll. Since Diogenes’s *Life of Epicurus* shows that biographies of the philosopher included content from his letters (Diogenes’s preserves three letters), Crönert’s general assessment may prove to be correct. Still, this reading is not yet certain. A more comprehensive scholarly analysis is now under way not only to elucidate the text that can be extracted from all twelve pezzi, but also to question and possibly confirm the identification of the text.

For digital papyrology, this registration method is poised to advance work on Herculaneum fragments. A 3D model with registered archival images, especially both natural and spectral photography, will allow significant work to be accomplished without consulting the original papyrus; the difficult
topography of layers stuck together can be assessed, and the various levels of contrast between the carbon ink and the carbonized substrate surface can be accessed, all in one image file. From the earliest applications of spectral imaging to the more recent efforts in applying 3D imaging for virtual preservation, our work here fits within the ongoing development of imaging technology both to preserve and to enhance further digital papyrology in the context of the opened scrolls from Herculaneum.16

**Future Work**

The current implementation of these techniques affords scholars much information, but enhancements can be made. Two additional image sets can be added to the 3D model to aid the study of P.Herc.118: (1) the disegni sketches noted earlier that were hand-drawn by eighteenth-century artists as the scroll was physically unrolled, and (2) the series of spectral images captured by Ware, which represent the highest resolution 2D images of P.Herc.118 in existence. The hyperspectral data sets captured by this project are as yet underexplored and offer potential for improving textual clarity. In addition, improved photogrammetry methods can be used to enhance the 3D model itself.

**High-Resolution Spectral Images**

In 2005, Gene Ware imaged the twelve pezzi of P.Herc.118 under eight spectral bands of light, including red, green, blue, and near-infrared bands. As noted above, Ware photographed each plate in small, overlapping sections. The result is that each pezzo is divided into sixty-three overlapping spectral square photos (fig. 18).

To create a single coherent image, each pezzo’s set of squares must be painstakingly stitched together digitally by finding the overlaps and linking them. An excellent image set using this method was created by Spiro Vranjes, systems administrator for the Imaging Papyri Project at the University of

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These images also allow us to improve the resolution of our 2017 hyperspectral data set by using a process called pansharpening. As mentioned earlier, with current systems the spatial resolution is sacrificed when images are captured under so many wavelengths of light. Much work has been done recently, however, to develop methods that can upscale the low-resolution images from a hyperspectral data set to match that of a higher resolution target, such as the Ware 600 dpi images, without sacrificing the ink-enhancing capabilities that hyperspectral imaging provides. One can therefore envision using the registration techniques outlined in this paper with pansharpening tools and the Ware data set to create a 600 dpi, three-dimensional, hyper-spectral data set.

hyperspectral image set of all twelve P.Herc.118 plates. In addition, automatic landmark picking and stitching processes that do not require a registration target are also under development.

**ITALIAN DISEGNI**

When the scroll was physically unrolled in the early nineteenth century, artists who did not know Greek were hired to carefully copy down the shapes and forms they saw on the papyrus as it was unfurled (fig. 2). These hand-drawn images, known as disegni, represent the earliest facsimiles of visible text from P.Herc.118. Although the disegni are not *photographic* representations of P.Herc.118, they are representations nonetheless that offer unique information about the text. These drawings provide the only glimpse we have of how the papyrus appeared when it was first unrolled. It is not uncommon, due to degradation over time, to see Greek characters preserved in the disegni that are no longer or only partially visible to the naked eye. For papyrologists working on these fragments, the drawings must be consulted.

![Image of disegni and corresponding features in reference photograph.](https://repository.upenn.edu/mss_sims/vol6/iss1/1)

**FIGURE 19.** Although difficult to see, the hand-drawn features on the right can be matched to corresponding features in the reference photograph, in this case a photo from the 2005 Ware infrared image.
The entire set of P.Herc.118 disegni has been digitized and, therefore, it is possible to align their images with the 3D model. As proof of concept, we used the same registration process described above, whereby we identified corresponding landmarks on both images and then employed our software tool to align them (fig. 19). The result is a fully aligned 2D image (fig. 20) that can then be aligned with the 3D model (fig. 21).

**FIGURE 20.** Fully aligned 2D image.

**FIGURE 21.** Disegni registered to the 3D model and the 2005 infrared photograph.
Enhanced Textual Clarity

The hyperspectral cubes acquired during this project form a robust foundation upon which further improvements to textual clarity can be built. While we have only used four spectral bands in this project, there are many feature enhancement methods that could make use of all 370 captured bands. It is highly likely that with further processing, the ink that is already visible in the infrared images will be further enhanced, and that text that is as yet unseen could be revealed. Additionally, because the hyperspectral data are now part of a unified 3D model, any further enhancements to the text can be made immediately available to scholars alongside the results presented here.

Improved Photogrammetry

Our next-generation photogrammetry system will enable a number of improvements in data quality and scalability. The system described thus far requires larger objects to be rotated during image acquisition, which can in some cases cause the illusion of an offset in the images due to the shadows. And as mentioned, the spatial resolution of the raw images is not of particularly high resolution, which affects the ability to reconstruct fine surface details. Additionally, the proprietary software pipeline used to reconstruct the surface from the raw images does not allow for fine-grained tuning of the reconstruction algorithm to best suit the data set. Ultimately, we plan to scale our photogrammetric acquisition process to enable the imaging of thousands of objects, but the process outlined above poses problems. For example, the ambient lighting is not tightly controlled and could potentially change between plates. In addition, because the scanning instrument is handheld, the camera positions are inconsistent between

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plates, and it simply takes too long to image each object to reasonably hope to perform this process on thousands of items.

With these issues in mind, we are currently designing a new automated photogrammetry system into which an object can be set. A motorized system will move a set of cameras over the object and automatically acquire the imagery for each plate. The lighting for the setup will be controlled, and the movement of the cameras will be the same for each plate. The resulting images will be processed by an open-source software photogrammetry pipeline, which allows the algorithms to be fine-tuned to the project.

**Conclusion**

The serious challenge presented by the natural deterioration of ancient documents to their scholarly study and preservation can be addressed through new digital methods. In this project, we have shown that newly constructed digital representations (spectral imaging, high-resolution photography, photogrammetry) can be meaningfully combined with historical representations (photographs, sketches) to form a rich and compelling composite. By incorporating earlier facsimiles, the value of their witness is captured and preserved rather than being overlooked or even discarded. The

![The Unified Image Set](image)

**FIGURE 22.** Using the techniques described, a single image made up of all prior facsimiles can now be created for each pezzo of P.Herc.118.
subtleties implicit in the way things change over a long period of time become more accessible in this composite representation than simple side-by-side comparisons allow. These techniques have proven so valuable, in fact, that a current project funded by the Andrew W. Mellon Foundation is under way to create composite 3D versions of all opened papyri from Herculaneum, starting with the collection at the Biblioteca Nazionale di Napoli.\(^{19}\)

The technologies required to build a representation like the one we have described here are becoming mature, including high-resolution photography, spectral imaging, photogrammetry, and the non-rigid feature-based registration of things like sketches to digitized photographs. As collections grow and the digital witness of ancient objects continues to expand, composite representations that leverage each effort along the way must be cumulative rather than dismissive. This project demonstrates that the “best” version of a digitally restored text can actually be the one that contains and retains all previous versions together in one representation.

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