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

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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.

Keywords: Digital Humanities, Herculaneum Scrolls, Hyperspectral Imaging

1. Introduction

PHerc.118, or the papyri of Herculaneum specimen 118, is an ancient scroll preserved in a series of 12 glass frames at the Bodleian Library in Oxford, England. This manuscript was buried by the eruption of Mount Vesuvius in 79 CE and finally excavated in 1752 from the Villa of the Papyri in Herculaneum, Italy. It is one of more than 1,800 scrolls that make up the only large-scale library to have survived from Greco-Roman antiquity, and it is the only classical one to be found in situ[1]. The content of PHerc.118 is believed to be a Greek philosophical text; however, the fragmentary, blackened condition of the carbonized manuscript makes it extremely difficult to read[2].

  The Herculaneum scrolls present a challenging situation for classicists and conservationists alike. While the carbonization process due to the eruption preserved the papyri for centuries, it also rendered them extremely fragile.

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. PHerc.118, for example, was manually unrolled using a machine that relied on the force of gravity to slowly pull and unfurl the scroll. However, the scroll fell apart during the process, and the resulting sections were grouped together in twelve "pezzos," Italian for "piece," and mounted to twelve boards that were ultimately framed[1].

Over the years, various efforts have been made to create a visually accessible facsimile of the PHerc.118, but the result has been an image record that is as fragmentary as the scroll itself. From hand drawn renderings, to analog film photographs, to digital spectral images, every venture created yet another version of each of the twelve pezzos without any link or reference to prior images. While advances in technology made some of the text clearer with every iteration, each image collection nonetheless posed its own set of problems; and there has been no method for easily viewing the images as a composite whole so that understanding and analysis of the text could be enhanced. Thus, this research set out to combine all prior images into one unified data set, so that the best textual representations from each facsimile could be viewed at once. This compilation of all past images, combined with new hyperspectral imaging and innovative 3D modeling, successfully creates a comprehensive, more robust version of PHerc.118 that enhances the readability of the text and enables new scholarly study.

2. Methodology

This research ultimately relied upon two imaging techniques, hyperspectral imaging and 3D scanning, along with several subsequent digital registration processes to create a comprehensive, unified PHerc.118 image in a three-dimensional space. First, a 3D virtual model was created as a foundation upon which the 1998 photos and the spectral images were then registered. This composite image enables scholars to reap the benefits of spectral imaging while also being able to interact with the manuscript in a 3D space. This allows them to view the geometry of the manuscript and detect layer changes, broken or deformed letters, and warping. The implications of such a model range from aiding scholars in their efforts to discern the document's text to giving the public the ability to explore a model of the manuscript, both without ever putting the physical document at risk. Such a compilation can provide a robust facsimile enabling greater readability and scholarly study than any single version alone.

2.1 Three-Dimensional Modeling

2.1.1 creating a virtual document using photogrammetry

The first step in compositing the various PHerc.118 images is the creation of a virtual model of the document in three-dimensional space. The benefits of having a three-dimensional model versus a two-dimensional photograph are immense for a document like PHerc.118, because it allows functionality such as zooming, rotating, editing, and turning layers on and off. It also gives the user a model that contains information about the shape, distance, and appearance of an object in real time. These tools ultimately allow scholars to dig deeper into the material without ever having to handle the document in its fragile state.

To create this 3D model, the process of photogrammetry was used, which can be defined most simply as a process that estimates the three-dimensional coordinates of surface points using pictures of a physical object taken from different angles. The photogrammetry in this research was achieved using the Artec Space Spider Scanner, a hand-held, industrial scanner used to model physical objects in a virtual space. This particular method of photogrammetry was selected due to the physical constraints of the project - the document itself is too fragile to leave the library in which it is held. Thus, the portability of the hand-held scanner was appropriate for the dataset.

It is important to note that the Artec Space Spider Scanner is not a laser scanning device. Like photogrammetry, laser scanning relies on thousands of focused light pulses to create an extremely accurate geometric representation; however, laser-based options collect little to no color context for the appearance of the scanned object. Thus, while laser scanning can provide high levels of shape accuracy and resolution, it cannot provide the photorealistic visual texture supplied by photogrammetric techniques. Because preserving the photorealistic appearance of the document within the 3D model is vital to this research, laser scanning was not an appropriate option.

2.1.3 special considerations in scanning pherc.118

To achieve the most accurate three-dimensional representation of PHerc.118, it was necessary to consider the issue of occlusion. Due to the extreme topology of the damaged manuscript (warped, wrinkled, ridged, and torn), scanning the document from a single angle would produce an artifact in the geometry, whereupon one portion of the document would hide, or occlude, another region from view, similar to mountains casting a shadow on the valley when illuminated by the sun. Thus, in order to ensure that the entire geometry of the surface was captured, the document was scanned a minimum of four times. While tilting the scanner 45 degrees, the manuscript was scanned first from a position facing the document head on and then from the right side. The plate was then rotated 180 degrees ("turned upside down,") and the same process was repeated. For plates in which the surface structure was especially severe, extra scans were performed in areas where "peaks and valleys" occurred (Figure 1).
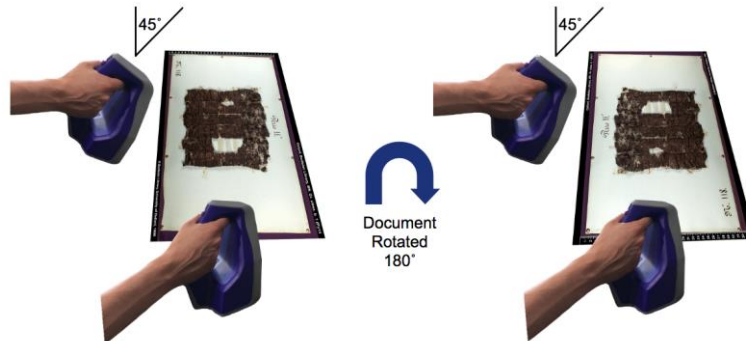

Figure 1. The figure above depicts the methods by which the twelve PHerc. 118 plates were scanned using the Artec Scanner. Held at a 45° angle from the vertical, each plate was scanned at 0° and 90° and then rotated 180° and scanned twice more. Any spots of apparent occlusion were scanned again to provide a complete data set.

2.1.4 creating the three-dimensional model

Once scanning is complete, the creation of the digital 3D model involves two primary steps: generating the 3D mesh frame and then overlaying it with the color texture. Both of these steps rely on the editing of point clouds generated by the various scans. As scanning occurs, the collected data is uploaded in real-time to Artec's three-dimensional editing software, Artec Studio. From the directional vectors captured, results are generated in the form of a point cloud that exists in the Artec Studio environment. Each point cloud represents a single scan, and each point cloud is a separate entity that can be edited, added, or removed. The four-step scanning process generated point clouds representative of the entire PHerc. 118 plate. However, in regions where occlusion required additional scans, the point clouds only represent a small portion of the entire plate. Also, due to the nature of scanning the plates from both a 0 degree and 90 degree angle, the point clouds were arranged perpendicularly to one another. Taking multiple scans from different angles resulted in a three-dimensional model in Artec Studio that was jumbled and required editing to be representative of the original physical object. It is the editing of this point cloud that ultimately constructs an appropriate mesh and texture that comprises a three-dimensional model (Figure 2).
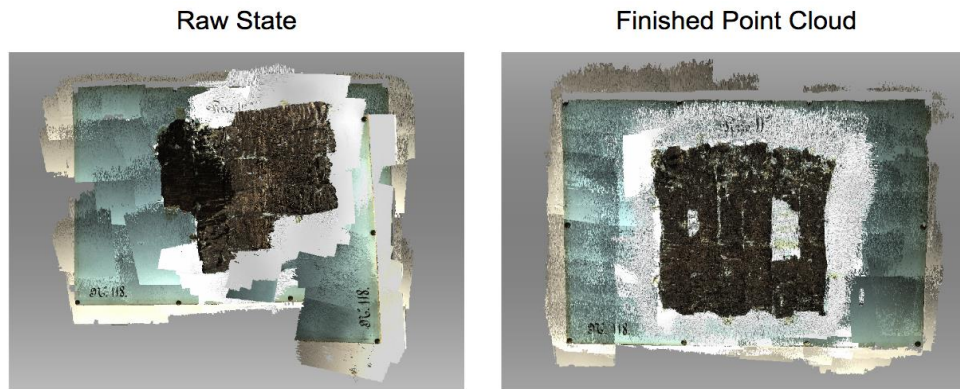
Raw State   Finished Point Cloud

Figure 2. The image on the left depicts the beginning state of all scans loaded into Artec Studio. Due to the method of scanning from a variety of angles, the scans are perpendicular to one another and appear to be jumbled. The image on the right depicts the ideal finished scan alignment.

In Artec Studio, the point cloud can be compared to the childhood game of connect-the-dots (Figure 3). Each point contains information about the physical document, including color and shape information, but these dots have not yet been "connected" or registered. Point cloud alignment is the process of arranging these data points in a meaningful way, such that they are no longer jumbled. Once the point cloud alignment process occurs, an appropriate mesh and texture will be created. The mesh in Artec Studio is simply like drawing the lines between the dots in connect-the-dots in order to give the random points its ultimate shape. Thus, the mesh represents the overall shape or geometry of PHerc.118. Texture, on the other hand, which is created in the next step, is like coloring in your connect-the-dot creation in order to make the object appear more lifelike than the simple straight lines connecting the dots. Thus, the texture created in Artec Studio represents the way PHerc.118 appears in the physical world, and this texture is layered this over the geometric mesh to create a color-accurate three-dimensional model.

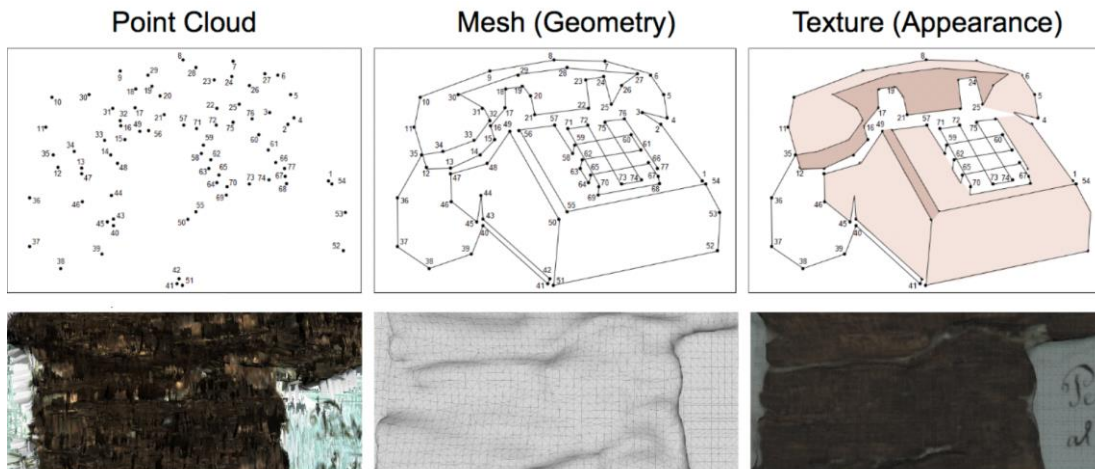Point Cloud   Mesh (Geometry)   Texture (Appearance)

Figure 3. The images in the top row depict the concepts of point clouds, mesh, and texture using the childhood game of connect-the-dots. The images below enumerate the concepts within the 3D visualization of PHerc. 118. Puzzle from William Armstrong, *Brain Trainer,* 2011, Web, http://williamarmstrong.com/brain/childL2.html

Creating an accurate mesh and texture in Artec Studio requires a four-step iterative process: Global Registration, Auto and Rough Alignment, Removing "Problem" Scans, and Outlier Removal. Essentially, this process involves using both tools found in Artec Studio and manual alignment to arrange the point clouds themselves, rather than the individual points, in order to create a singular, cohesive model. Only once this cohesive point cloud is obtained can an accurate mesh and texture be output from the software.

In brief, this research utilized photogrammetry to create a virtual model of the fragile PHerc.118 manuscript, such that it can be analyzed in greater depth without harm to the physical object. Using the Artec Space Spider Scanner, a

point cloud of data was generated and subsequently manipulated to create our final three-dimensional model of each plate of the document. The model was then exported and prepared for the next phase of research whereupon the texture was refined and enhanced to make the models even more useful to scholars.

2.2 Registration

The Artec Spider 3D scanner is designed to create a morphologically correct virtual model of an object; it is not, unfortunately, capable of rendering high resolution photographic images of the object's surface. It does an excellent job of capturing the shape of an object, and it does a decent job of capturing some color information. However, the 3D model that results from the process described above lacks the fine details that high resolution, 2D color photography can provide. Therefore, a second step in the methodology that layers a high-resolution color photograph of each plate on top of its 3D model is necessary. This step is further referred to as the process of registration.

Key to this 2D to 3D alignment is the texture image created in Artec Studio. Before any image can be registered to the texture, the texture must go through a process called reordering. When the Artec Spider Scanner is acquiring data, it is encoding and creating the mesh. During this process, it applies segments of color which end up making the texture appear in a seemingly random order. The texture may be incomprehensible to a human. However, the scanner is able to put the 'pieces' of the texture in the right order so that, when viewed on the 3D model, it accurately represents the manuscript that was scanned. It is impossible to align any image to this kind of texture. Reordering the texture creates an image that will allow the alignment of other images to it, and the registration process may begin (Figure 4).
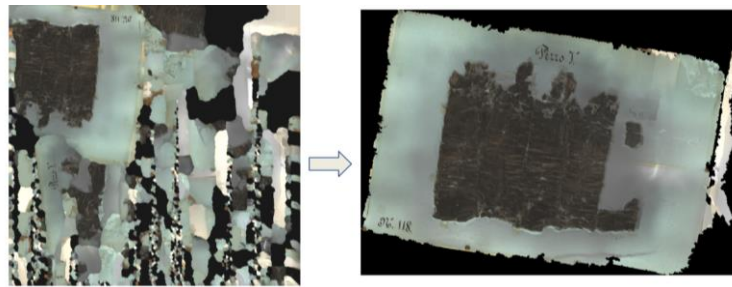

Figure 4. The scrambled texture is reordered into a coherent texture in preparation for the registration process.

2.2.1 how registration improves the model

Improvements can be made to the three-dimensional model, the texture in particular. This texture generated in Artec Studio (see Section 2.1) gives us an idea of the coloring of the manuscript, but factors such as the darkness of the manuscript caused the texture to appear very dark. Additionally, the texture image is too low-resolution to see any fine detail. This makes any writing extremely difficult to detect.

Figure 5. Some text is visible in high-resolution photos (left), whereas the Artec texture image (right) is too dark.

While the texture may not be very useful for scholarly analysis, it proves to be useful for other reasons. Note that the texture is a two-dimensional image that is mapped to a three-dimensional surface to show the coloration of the manuscript. The texture maps exactly to the mesh of the three-dimensional model (Figure 6). Because of this mapping, the texture is the key to accurately aligning other images of the plates to the same mesh. High-quality images have

been taken of each plate in the past. By aligning these images to the texture, scholars will be able to see the three-dimensional model with a higher-quality photo layered on top.
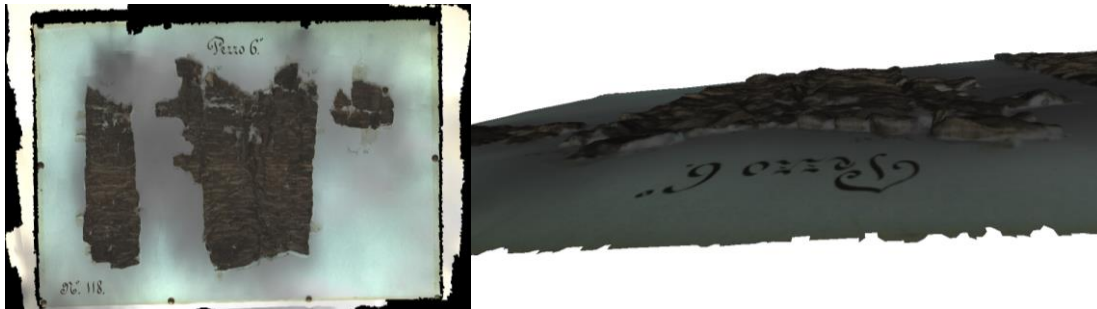

Figure 6. The texture is an image (left) that maps directly to the mesh to obtain the 3D model (right).

2.2.2 image alignment

Registration aligns one two-dimensional image to another two-dimensional image. The registration process requires one 'fixed' image, or an image to which all other images will be aligned, as well as a 'moving' image, or the image that is moved and warped in order to align it to the fixed image. In this case, the texture image is selected as the fixed image, as it maps directly to the three-dimensional mesh. The moving image is a high-resolution photo taken in 1998. The benefit of registering this image to the 3D mesh is that it will be visible in three-dimensional context. The geometry of the manuscript is very complex, and seeing a high-quality image in three-dimensional context can help scholars better identify layer changes and other notable features. However, it is important to note that the process is capable of registering any image of the manuscript to the texture image.

1998 Reference Image   Texture Image   3D model with Reference Image
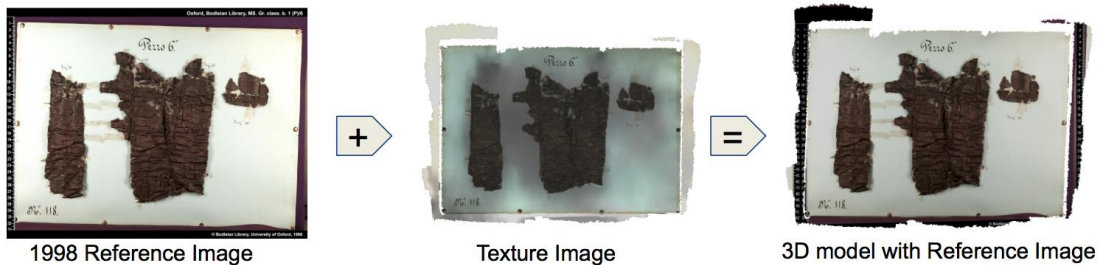
Figure 7. A timeline of image alignment using the 1998 Reference Image and the 3D created in Section 2.1

When registering two images, the angle at which each photo is taken, the size of each image, and the curvature of the camera lens must be considered for a successful result. This is due to the fact that images taken by different cameras at different times will not align exactly through manual means. It requires more work to resolve these distortions, which is where registration software becomes especially useful. An example of such distortion seen in manual alignment without the use of registration software can be seen in Figure 8.
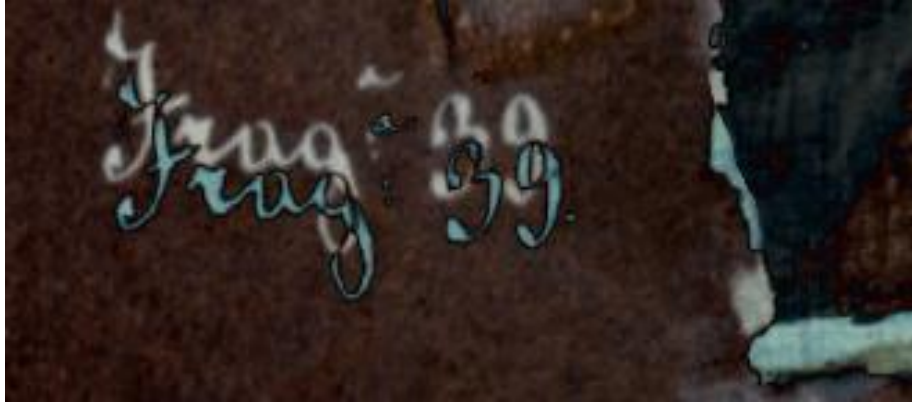
Figure 8. An attempt at manual alignment. White and blue regions are locations where the two images differ.

Next, points must be selected on both the fixed and moving images. This process is called landmark registration. Typically, these points are distinctive landmarks that are visible on both the lower-resolution texture as well as the high-resolution image. For example, a period (".") written on the board (Figure 9) can serve as a landmark that is external to the actual papyri. Other distinct landmarks that appear within the text, like the serif arm of a letter form, are also chosen to improve alignment.
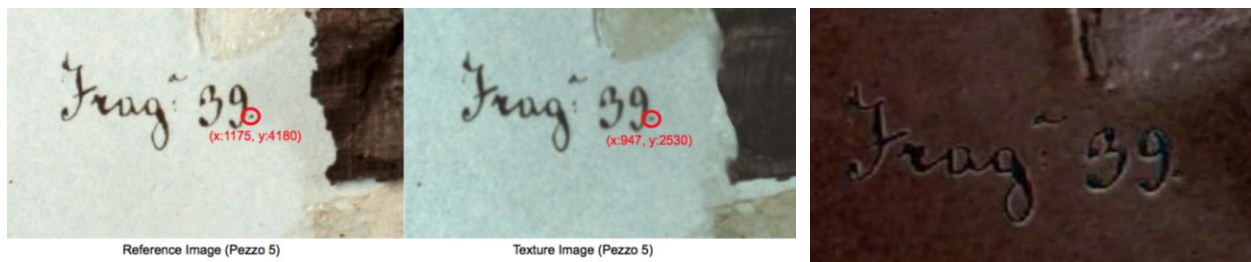

Figure 9. After running landmark registration using the period in both images, this area is now aligned.

2.2.3 results of the registration process

After running landmark and deformable registration, the moving image should be aligned closely with the fixed image. The results are also visible in three dimensions, where the moving image will fit the model closely.

Registration is an extremely powerful tool, as any two-dimensional image can be viewed in three dimensions so long as the image is able to be aligned to the texture. Scholars can now use this technique on any image set to gain better spatial awareness of the document. Providing a high-resolution 3D model of the pezzos of PHerc.118 offers many benefits over the low-resolution 3D model or high resolution 2D photos alone. Yet, even this model can be improved even further by including spectral images that reveal more surface details than ordinary photography.

2.3 Hyperspectral

2.3.1 spectral imaging

Spectral imaging offers the ability to view the world in more ways than how the human eye can perceive it simply by taking in other frequencies of light, such as infrared or ultraviolet waves. Different wavelengths reflect in unique ways and can reveal different features of an object. By exposing a document to isolated wavelengths of light in the near-visible and visible ranges and capturing an image, the different wavelengths may reveal more of the text in the document than the human eye can see alone.

There are two main types of spectral imaging: Multispectral and Hyperspectral imaging. Multispectral imaging exposes an object to a finite number of light wavelengths, usually somewhere between 10 and 50 bands. Multispectral

datasets consist of individual bands of light chosen from the spectrum with no continuity between them. Conversely, hyperspectral imaging exposes an object to pure white light that is filtered through a prism and projects it onto pixels. This form of imaging specifically captures almost the full spectrum of near-visible and visible wavelengths, with the only limitations being brightness of the light and number of pixels in the image. Instead of tens of bands being captured, hyperspectral imaging captures hundreds of bands of light. Using hyperspectral imaging, 370 bands of light were captured from near ultraviolet to infrared.

2.3.2 why hyperspectral?

Hyperspectral imaging was used for this data set because more spectral bands can lead to more readable text. Every different wavelength reveals nuances of a document; what shows in one wavelength may be invisible in another. The Archimedes Palimpsest is a perfect example of how hyperspectral imaging can reveal important features of a document. This manuscript, a 13th-century Christian religious text, was originally a 10th-century copy of a previously unknown work of Archimedes of Syracuse. The original writing was washed off and overwritten, but the incomplete erasure left traces of the initial text. The manuscript was imaged using ultraviolet, infrared, visible and raking light, as well as X-ray to digitally unveil the original writing underneath. Hyperspectral imaging revealed hidden attributes of this manuscript without harming the document itself, expanding knowledge without consequence.

2.3.3 image acquisition

The main goal of data acquisition was to obtain a complete dataset consisting of high resolution, hyperspectral images for each of the 12 plates. Keeping these priorities in mind shaped how data was gathered.

One week was allotted to do all 3D and hyperspectral imaging for all 12 plates of the document. Hyperspectral imaging is time consuming, even more so for the desired high-resolution images. In order to collect the hyperspectral data, a HEADWALL Hyperspec III scanner was used (Figure 10). This system shows composite light and uses a prism to filter to the desired wavelength. During data acquisition, the light and scanner were mounted above the document. The light was angled above the document, causing shadows in some areas. This resulted in occlusion similar to 3D scanning; however, unlike 3D scanning more scans would not fix the obscured areas. The light source was not moved because an initial time loss at the beginning led to making the sacrifice of sub-optimal lighting so all documents could be scanned within time constraints.
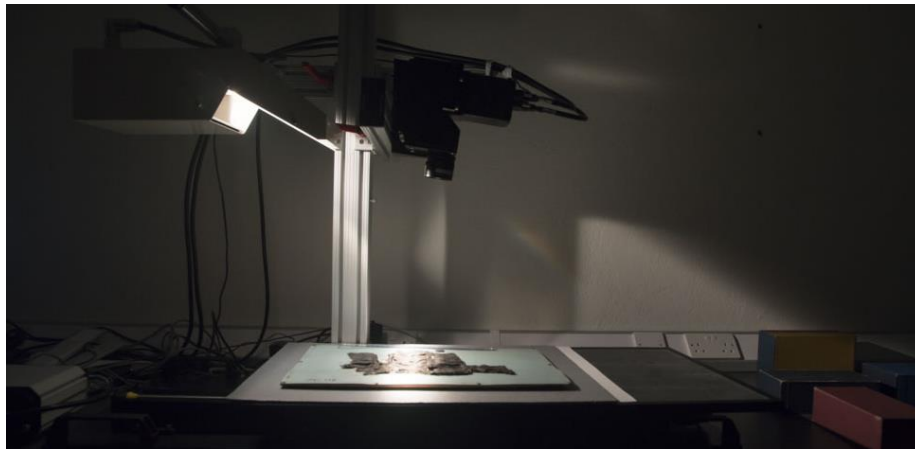

Figure 10. Scanner setup - light and scanner mounted above document; angle of light source is visible.

Spectral imaging trades spatial resolution of an image for the ability to capture more bands along the spectrum. To achieve the desired high-resolution data set, it was necessary to zoom in on the document, which meant that the whole document could not be captured in a single image. In order to image the whole document, each plate was imaged in parts, resulting in six horizontal strips which covered the entirety of the plate. Each strip overlapped vertically so that matching landmarks could be used to unify the pieces of each image.
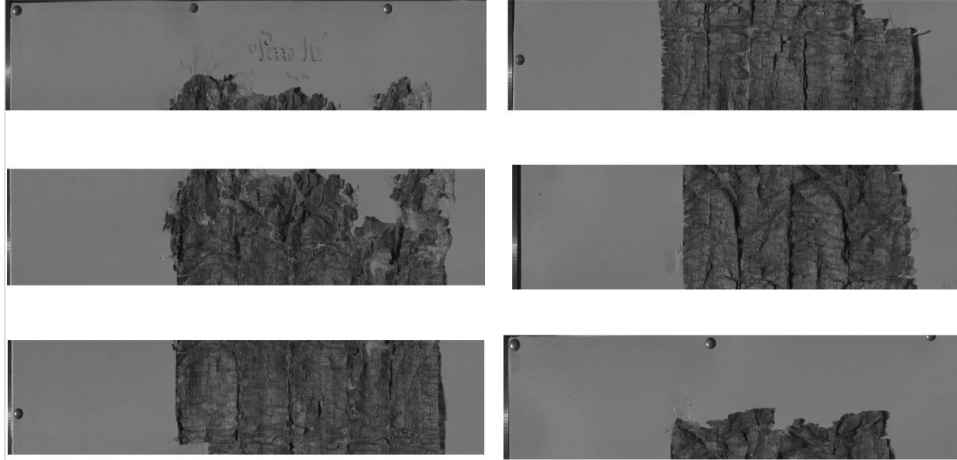
Figure 11. Six horizontal strips capture the entirety of the document in high resolution

The plates could only fit so far on the platform beneath the scanner, and the scanner field of view could not capture the entire plate with its field of view. In order to counteract this, the plates were rotated 180 degrees beneath the scanner halfway through acquisition. This resulted in three strips being scanned in each direction, and the shadows from the angled light switched sides with the new orientation (Figure 11).

2.3.4 registration of the six strips

The ultimate goal of spectral imaging was to create a unified dataset. In order to achieve this, the separate strips needed to be aligned into one cohesive image. The overlap between the strips served as a way to align the images, but distortion along the edges of the strips due to lens distortion made it difficult to manually rectify these images.

We used the existing registration pipeline to more quickly and accurately align the separate strips. A historical 1998 image was used as a fixed image for alignment, and each strip was aligned accordingly. Once strips were aligned, they were blended together to get rid of harsh lines and make a more cohesive image. Since all images in a hyperspectral cube have the same alignment, once the first transform is done, the same geometry can be used to align any band image to the reference image, creating a full image for any desired wavelength quickly and easily.

Figure 12. Result of registration with inputs shows in Figure 11

The result of this registration was a set of hyperspectral images for all twelve pezzos (Figure 12). Once the hyperspectral data was collected and registered to the 3D model, this research analyzed the unified image set.

3. Results:

The result of this research is a 3D model for each of the twelve pezzos of PHerc.118, each of which contains a set of three images registered to it. These three images are the results of each of the imaging processes in the methodology and are as follows: the 1998 Full Color Image, the 2017 Full Color image comprised of the hyperspectral bands 480, 530, and 709 combined into one image, and the 2017 Infrared Image found by extracting hyperspectral band 950.

Ultimately, this research created a tool that will serve as a foundation for future imaging projects and scholarship. Registering the available imaging projects of PHerc.118 to an interactive 3D model allows scholars to look at all of the visual data at once, preserving and consolidating the results of many individual studies to benefit the entire scholarly community. This is invaluable, as it allows scholars to gain a variety of visual perspectives on a document all in one convenient and centralized location. By registering photos to the 3D mesh, scholars are able to look at the text as it would lie on the form of the scroll or manuscript, ultimately making it easier to determine which characters lie on the same line and on the same layer. It also creates a tangible object that can be used as a tool to teach people about these ancient documents without threatening their frail conditions.

It is important to note, however, that our model is only as good as the photos registered to it. In the case of the hyperspectral imaging project, time and technology constraints limited the size of the images that could be captured. The resulting process of piecing together bands of images taken from different lighting angles generated a distinct line across the center of some pezzos (Figure 13). As such, there is room for improvement in the hyperspectral imaging of PHerc.118, and any future images collected will now have a designated 3D model to which they can be mapped. Despite these challenges, the resulting images will be useful in understanding the text that PHerc.118 contains.

Figure 13. The reconstructed full color image of Pezzo 3. A visible line appears across the middle where the shadows flipped due to the rotation of the board during scanning.

Though this research did not focus on the textual interpretation of PHerc.118, it is possible to make comparisons to previous image sets. As such, the newly captured infrared dataset is an improvement upon the quality of text visibility on the papyrus. Compare the area depicted on the left in Figure 14, the 1998 Full Color image, which shows less text to the naked eye compared, to the 2017 Infrared image depicted on the right. While text is visible in both images, the

newly captured hyperspectral images are not only of higher resolution, but they are also less visually crowded, allowing scholars to see letterforms with greater ease and greater understanding of the geometry of the page on which they are written.
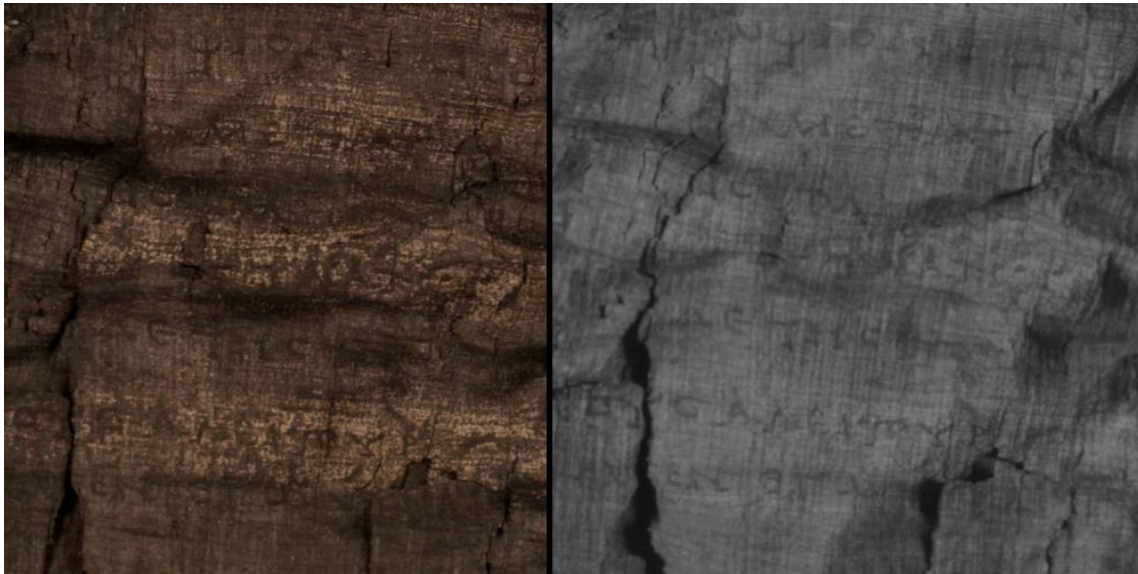

Figure 14. Comparison of the 1998 full color image with the 2017 hyperspectral image - not only is more text visible, but the visible text is clearer as well.

In total, this research has begun the process of creating a unified dataset while also adding to the data available. By generating a 3D model, this research gained new understandings regarding the geometry of the document, as well as a better understanding of how the text lies upon it. The images added to the data set also provided new wavelengths and higher resolutions of the document. The results of this research are novel and hopefully will lead to a new generation of interpretation of this fragile document.

4. Conclusion

PHerc.118 is an incredibly fragile piece of history that, due to its condition, is not widely available to scholars or the public. However, the mystery behind the stories it contains has long awaited solving. While imaging projects of the document have occurred a few times, the limits of technology and the document's physical condition have made a unified dataset of PHerc.118 incredibly difficult. However, this research aimed to fix such frustrations and provide a complete facsimile of PHerc.118 material that is not only useful to scholars today, but can also adapt to the needs of future scholars. Through the use of 3D modeling and hyperspectral imaging, this research was able to create a three-dimensional tool where a variety of imaging projects commissioned for PHerc.118 can be zoomed, rotated, and explored in a hands-on way. This completely non-invasive tool allows anyone who is interested in the document to have access to its secrets without causing damage. Though 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. In the past, reading PHerc.118 was considered a lost cause. But now this research has inspired scholars to take a second look, and their initial reports on interpreting new text and determining the document's origin appears to be more promising than ever.

5. Acknowledgements

6. References

1. Brent Seales, "Visualizing PHerc.118," Thinking3D, https://www.thinking3d.ac.uk/Seales/

2. Bodleian Libraries staff, "Philosophical(?) treatise, fragments: PHerc.118," Digital Bodleian, Bodleian Libraries, University of Oxford, https://digital.bodleian.ox.ac.uk/inquire/Discover/Search/#/?p=c+0,t+,rsrs+0,rsps+10,fa+,so+ox%3Asort%5Easc,scids+,pid+c4248f2e-d319-4c22-9fb8-c79d263cfbd0,vi+1571a43a-9540-439b-bdba-1266dace0ad8