Abstract:
The town of Herculaneum was destroyed by the pyroclastic flows of the erupting Mt. Vesuvius in 79CE. However, many artifacts and structures were preserved by this same process, until their rediscovery in the last few centuries. The Villa of the Papyri at Herculaneum contained many papyrus scrolls, carbonized in the eruption but otherwise still intact. Studying the text inside these papyri is made extremely difficult by their fragile state, and any attempts to read them result in irreparable damage. Scholars studying these rolls must painstakingly remove each layer of papyrus to read the text beneath and carefully preserve the resulting fragments. A non-destructive method of unwrapping the Herculaneum papyri would be of great use to scholars, while simultaneously preserving the cultural heritage of one of the greatest archaeological sites in the world. This has been the goal of the EDUCE (Enhanced Digital Unwrapping for Conservation and Exploration) project.

In the summer of 2009, our team imaged the interior of two such papyri, housed at the Académie des Inscriptions et Belles-Lettres of the Institut de France in Paris, using X-ray computed tomography. CT provides a non-destructive method to visualize the interior of these scrolls as a three-dimensional volumetric rendering. Only minimal handling of the scrolls was required, to transfer them from archival storage to custom-built sample holders derived from a laser scan of the surface of each scroll. The X-ray scans were captured with a SkyScan 1173 Micro-CT scanner, at resolutions of up to 14 microns. The resulting 3D reconstructions show a tightly compressed, highly chaotic internal structure. Accurate estimates on the length of the scrolls can be made from this data. Manual segmentation of small regions have allowed us to extract single layers. With further refinements of our algorithms, we hope to be able to unroll the entire papyri.

INTRODUCTION

The use of advanced technology in conservation presents unique opportunities to study cultural heritage artifacts that have otherwise been inaccessible due to their fragile nature. The papyrus scrolls recovered from the Villa of the Papyri in Herculaneum are one such class of artifact. These scrolls were “destroyed” in the eruption of Mt. Vesuvius in 79CE, but strangely preserved for millennia through the same process. In fact, this collection is the only known library of antiquity to have survived to the modern era. The papyri were carbonized by the pyroclastic flows of the volcanic eruption and buried beneath tens of meters of ash until their discovery in the eighteenth century. Reading the text within has been a challenge to scholars ever since.

Traditional means of physically opening these scrolls result in extensive and irreparable damage to the original materials. Over the centuries, these methods have included everything from immersion in water to pouring mercury through the rolls to suspension in various gases. The current common practice is to carefully cut away the hardened outer layers and then to attempt to separate and unroll the more flexible central layers. Even under the best of circumstances, much of the text will be lost through this process, and the final result will only be a fragmentary record of the original.
The application of non-invasive technology provides a way forward that does not require physical handling and extensive damage to the papyri. X-ray computed tomography can build a volumetric view of a scroll's interior, with only minimal handling required to place the roll inside the scanner. With the proper algorithms, the separate layers of the scroll can be segmented and virtually unrolled within a computer simulation. Any contrast between the ink and the papyrus substrate would then allow the text to be read. In this paper, we present our experience scanning two Herculaneum papyri and the subsequent processing of this data.

**MICRO COMPUTED TOMOGRAPHY**

Computed tomography (CT) is an X-ray based imaging technique that produces a three-dimensional volumetric view of the interior of opaque objects. It has been used for decades in the medical field, but only fairly recently been applied to the study of cultural heritage artifacts. A CT scan represents an object as a set of 2D slices, each corresponding to one cross section, that when stacked together and properly processed form a 3D picture. Within this volumetric view, each “voxel” corresponds to the density of the object within a small volume. Micro computed tomography (micro-CT) is a variant of CT geared toward much higher resolution views of objects. Whereas traditional CT deals with voxel sizes in the range of millimeters, micro-CT is able to resolve features in the range of tens to hundreds of microns, trading total working volume for better resolution.

Micro-CT has only become commercially available in the last decade, but it is well suited to the study of objects such as papyrus scrolls. The scans provide a non-destructive method to visualize the interior of the scrolls, without the necessity of physically opening them. CT can be immensely helpful as a tool for planning and condition assessment. It shows fracture lines within the scrolls, as well as other damage that may be hidden within the object.

**DATA ACQUISITION**

Two intact Herculaneum papyri (P.Herc.Paris 3 and P.Herc.Paris 4) are housed in the collections of the library of the Institut de France in Paris. These scrolls were badly carbonized in the eruption of Mt. Vesuvius and are extremely fragile. Using custom-built sample holders molded to precisely fit the contours of each roll, our team mounted the scrolls inside a SkyScan 1173 Micro-CT scanner to perform extensive X-ray scans of the scroll interiors (Figure 1). Both scrolls were imaged from top to bottom at resolutions ranging from 14 to 27 microns.

Our sample holders were prepared by building a 3D surface model of each scroll using a laser scanner. A proxy was built from this model, and a polyurethane mold cast to perfectly conform to the hardened contours of the papyrus husk. These molds could then support the scrolls with only minimal stress while inside the micro-CT scanner.

The SkyScan 1173 scanner required the samples to be mounted vertically to fit within the field of view of the X-ray beam. We performed two complete scans of each scroll, at a higher (14 micron) and a lower (23-27 micron) resolution. The higher resolution scans had significantly higher noise levels due to technical constraints in the reconstruction algorithms, which offset the gain in image detail. For the bulk of our analysis, we have focused on the cleaner lower resolution scans.
Fig. 1: External laser-based surface scan supports a 3D proxy used to make a mold. This mold is used to create a polyurethane container to hold the scroll in a vertical orientation inside the micro-CT scanner.

ANALYSIS AND VIRTUAL UNROLLING

Given a high enough resolution scan, and the ability to segment layers within a scroll, a computer simulation can virtually unroll a scroll, revealing its original form. Assuming contrast between ink and papyrus, the ink features can then reveal the original text, without necessitating an invasive and damaging physical unrolling. We have developed such software and algorithms, which have been tested on a number of proxy objects. However, the Herculaneum papyri present unique challenges to our system.

Fig. 2: Micro-CT slice showing the scroll structure surrounded by the cast polyurethane container. These images are “end-on” views at about the midpoint. At higher resolution (right) the interior portions show surprising, unpredictable structure.

Upon first glance at a cross section of one of these papyri, the compactness of the roll is immediately apparent (Figure 2). As our segmentation algorithms require at least a single voxel of empty space
between layers, this makes automated segmentation nearly impossible. The three-dimensional shape adds another wrinkle, as this minimal separation between layers must be present along all three axes. Furthermore, the tortured shape of the scrolls shows that some layers bend inward and outward as they move through the roll. On the whole, even with CT scans in the range of tens of microns, our resolution is not high enough for our current automated segmentation algorithms to be successful. With the continual march of technological progress, image sensor size can be expected to grow at a near exponential rate, so it may only be a matter of time until micro-CT resolution reaches the range we need for successful automatic segmentation of these papyri.

Our team has performed multiple manual segmentations of small regions of the scrolls, on the order of a few square centimeters at a time. This process is extremely labor intensive, as it requires a technician to propagate the contours of a selected layer in a single 2D slice through hundreds of neighboring slices to form a 3D model of that single layer of papyrus. These segmentations clearly show the papyrus structure, with the visible fibers running horizontally and vertically through the sheets (Figure 3). In these minimal samples, we have yet to uncover visible text. This is likely due to the use of predominantly carbon black inks, which have a much lower contrast to the papyrus substrate than pigments with metallic bases.

![Figure 3: 3D structure from micro CT scan. Scale shot with writing (photograph) fixes the scale expectation for the small “unwrapped” portions (15mm square), which show papyrus structure as vertical and horizontal stripes. Changes in intensity are from a multi-power, registered scan.](image)

**CONCLUSION**

We have collected the first scan of Herculaneum papyri using micro-CT, allowing visualization of the interior of these scrolls without the risk of major damage to them. These scans show the internal structure of the rolls, including fissures, fractures, and air gaps. This knowledge could inform any physical intervention or conservation plan for these papyri. Initial data analysis has been slowed by the complex nature of this internal structure. Automated segmentation for separating layers within the
scrolls has been virtually impossible. Manual segmentations have yielded success in viewing small regions of the scrolls, though no ink has yet been visible. Fortunately, little to no damage was done to the scrolls by this non-destructive scanning process, thus preserving the scrolls for future study. Based on CT scans of similar objects, we know that our “virtual unrolling” method has merit, and if a procedure can be developed to increase ink contrast, another scan has the potential to reveal much hidden text.

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