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THE USE OF MICRO-CT IN THE STUDY OF ARCHAEOLOGICAL ARTIFACTS

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ABSTRACT

Opaque artifacts containing obscured text continue to present significant challenges to conservators. Often, any attempt to read such fragile texts fundamentally and irreversibly alters the physical structure of the object in which they are contained. Thus, the conservator is presented with an almost impossible dilemma: risk destruction of an artifact in order to recover a text of unknown value, or maintain the artifact in its original state and possibly allow a valuable text to go undiscovered. Numerous types of fragile artifacts exist containing text which is unreadable under visible light from the object exterior. Papyrus rolls, in particular carbonized papyri such as those from Herculaneum and Tanis, present obvious difficulties along these lines.

Given the huge amount of labor and care it takes to physically unroll these scrolls, together with the risk of destruction caused by the unrolling, a technology capable of producing a readable image of a rolled-up text without the need to physically open it is an attractive concept. Virtual unrolling would offer an obvious and substantial payoff. The EDUCE project (Enhanced Digital Unwrapping for Conservation and Exploration) is developing a general restoration approach that enables access to those impenetrable objects without the need to open them. The vision is to apply this work ultimately to other types of closed documents, and to allow complete analysis while enforcing continued physical preservation.

Our paper and presentation will present our successful experiments on a variety of objects, both synthetic and authentic. We have constructed a number of proxy scrolls which use papyrus and iron-gall ink, in order to perform initial testing of the concept. Additionally, we have conducted experiments on a 15th century manuscript of Ecclesiastes which had been reused in a book binding. In this case, although the composition of the ink was unknown, we were able to non-invasively read multiple layers of previously hidden text using a custom CT setup with a resolution of 30 microns. Conservators were then able to disassemble the binding layer-by-layer and confirm our results. We will also discuss future uses of this technique, both for near-term projects and potential long-term applications to specific types of artifacts.

INTRODUCTION

Opaque artifacts containing obscured text continue to present significant challenges to conservators. Attempts to read such fragile texts may fundamentally and irreversibly alter the physical structure of the object in which it is contained. Thus, the conservator is presented with an almost impossible dilemma: risk destruction of an artifact in order to recover a text of unknown value, or maintain the artifact in its original state and possibly allow a valuable text to go undiscovered.

As a result, non-destructive, non-invasive techniques which can provide insight into such texts are a valuable topic of investigation. The EDUCE project (Enhanced Digital Unwrapping for Conservation and Exploration) is developing a general restoration approach that enables access to those impenetrable objects without the need to open them. The vision is to apply this work ultimately to enclosed text-bearing documents, and to allow complete analysis while enforcing continued physical preservation. In this paper, we describe the preliminary results of our experiments in imaging texts using micro-CT techniques, as well as discuss future applications of this technique and obstacles it faces.

THE DAMAGE OF PHYSICAL UNROLLING

Numerous types of fragile artifacts exist containing text which is unreadable under visible light from the object exterior. Papyrus rolls, in particular carbonized papyri such as those from Herculaneum and Tanis, present obvious difficulties for the conservator. Even papyrus rolls for which a conventional "unrolling" is feasible must be handled with care in preservation, as the length of a roll may cause it to be cut into sections and stored (and accessed) in this new format. There are also various examples of artifacts where a text's substrate has been reused in the creation of a new object, such as papyrus used in Egyptian mummy cartonnage (Wright 1983) or discarded parchment manuscript folios in the binding of a codex manuscript or printed book.

The history of previous efforts to read and conserve such objects provides an important context for the advantages of a repeatable method of inspection which does not require physical intervention. Papyrus scrolls which can withstand unrolling often underwent the procedure soon after acquisition, being dampened and humidified to assist the process (Leach 1995). Carbonized papyri present more obvious frustrations for those wishing to read them. First, it is not possible to physically unroll carbonized scrolls completely. Following some years of experimentation (including practices such as pouring mercury through the edges of the scrolls, immersing entire scrolls in mercury; immersing scrolls in rose water; and holding scrolls in a chamber with various types of gases), common practice developed to cut away the hard outer layers - the husks - and unroll the relatively more flexible center layers (Sider 2005). The husks, consisting of two, four, or sometimes six separate pieces, must then be dealt with. Attempts to separate the layers often resulted in damaged or even completely destroyed text. Both chemical and physical methods were used, but as with the complete scrolls there was little success.

There is still damage to come, even after scrolls are successfully opened and unrolled. Fading ink, color changes to papyrus, weakening structure of papyrus, and the oxidization of ink that causes papyrus breakdown are all documented damage that can come from exposing the inner layers of a papyrus scroll to light and air. In addition, after unrolling and the separation of layers, scrolls and scroll fragments were at times attached to a backing material. This introduces new problems for conservators and editors: texts written on both sides of the papyrus are either mounted in a frame - with substantially less support for the center of the document - or with one side of the document permanently covered, and the backing material, if acidic, can damage the object causing discoloration and weakening of the substrate. Some fragments are mounted between two planes of glass, but this exposes the papyrus to another set of physical stresses including the possibility that the glass will simply crush the parchment to powder (Leach 1995).

There are also very specific editorial issues attached to the scrolls (Sider 2005). During the 19th century there was a program to document as many scrolls as possible. At this time practice was to read visible text and create a hand-drawn facsimile of it, then to scrape off the layer to uncover the text underneath, completely removing the top layer. For many scrolls, the only sources we have left are these hand-drawn facsimiles. Since the people who did this work were not scholars and did not know Greek, these documents must be seriously scrutinized by the editor. Another editorial issue involves the ordering of the scroll fragments- once cut into pieces and divided into layers, the original order of scroll texts was often lost. Editors are still dealing with this issue today.

CT SCANNING AND VIRTUAL UNROLLING

All of these examples serve to illustrate the underlying risks of destruction and harm to the physical artifact that traditional methods of autopsy entail and editorial problems that they introduce. The act of physical investigation frequently becomes a one-time endeavor, fundamentally altering the structure of the object and all future attempts at scholarship.

In light of these limitations, non-invasive volumetric imaging techniques seem an ideal fit for the problem of analyzing opaque artifacts. The technique we explore here is high-resolution micro-CT imaging, which has proven a versatile and powerful tool in our initial experiments. Getting a usable result from X-ray based CT depends upon the specific X-ray absorption characteristics of the object, such as the substrate and pigments involved. However, as we will discuss, X-ray imaging gives an almost ideal response for a large variety of the inks we are interested in. Its high energy radiation is able to penetrate the full depth of most objects, and its physical configuration enables construction of portable imaging equipment suitable for performing analysis on-site. Most other volumetric imaging techniques do not have these advantages. They are either unsuitable to the nature of the materials, require a large fixed facility, or simply have not matured and commoditized to the point where constructing a portable device would be feasible.

The ideal X-ray response is to have some signal from the substrate (to assist in segmentation and unwrapping, as well as to understand the overall physical configuration), and an increased response from the ink to provide contrast. The primary division among inks used for written texts is between carbon black and inks made with metallic or mineral content. Iron-gall inks, composed of galls, vitriol (iron sulfate), gum and water, are very prevalent in ancient writing. Due to the iron content of these inks, their X-ray attenuation is relatively high and ideal for our methods of investigation. In our testing of proxies which used ink with iron content, the contrast between text and papyrus is strong and consistent. One can anticipate similar X-ray response characteristics with other pigments which use metals or minerals to achieve their coloring. Aside from carbon black, this encompasses the majority of pigments used across a variety of cultures: red ochre (Fe_2O_3), azurite ($2CuCO_3*Cu(OH)_2$), verdigris ($Cu(CH_3COO)_2*Cu(OH)_2$), malachite ($CuCO_3*Cu(OH)_2$), yellow ochre ($Fe_2O_3*H_2O$), vermilion (HgS), orpiment (As_2S_3), pararealgar (As_4S_4), Egyptian Blue ($CaCuSi_4O_{10}$), Han Blue ($BaCuSi_4O_{10}$), Han Purple ($BaCuSi_2O_6$), Maya Blue ($x*indigo*(Mg,Al)_4Si_8(O,OH,H_2O)_{24}$), lead white ($2PbCO_3*Pb(OH)_2$), and so on. (Clark 2003, Clark 2007, Berke 2007, Bussotti 1997)

Carbon black inks are not so clear-cut in their properties concerning X-ray attenuation. Iron gall ink did not supersede carbon black in use until sometime around 300AD, so there is still a large corpus of materials for which the majority of writing will be in carbon black (Bearman 1996). Here there are some distinctions that must be made, as the term "carbon black" suitably describes a variety of pigments with varying production techniques and time periods (Winter 1983). The typical mode of production in ancient times was to use soot (or, less commonly, natural graphite) as the particulate coloring material, combined with water to liquefy it and gum arabic (*Acacia senegal*) as a binding agent to increase viscosity and adhesion. The soot used was usually produced by means of burning oil, resins, or animal fat and collecting the deposited carbons (Winter 1983). The inks from this production process are often referred to as lampblack, sometimes in order to provide a distinction with soot produced by burning wood or plants. At a superficial level, one may not expect much contrast between this organic material, and the organic, often carbonized, papyrus substrates we are interested in. However, there are a number of subtle properties which it may be possible to exploit in order to use X-ray based techniques to image these texts. Where iron gall inks behave similarly to the inks we are familiar with today in the penetration and dyeing of the substrate, carbon black inks essentially rest in a suspension atop the writing surface (Bearman 1996). Although surface profilometry of carbon ink on papyrus may prove difficult due to overall surface roughness, high-resolution volumetric imaging which can determine the total thickness of a layer may be able to use the expected geometric increase in thickness in order to determine textual content. There are also numerous cases where impurities were introduced into the pigment during production or use (possibly intentionally), occasionally leading to small amounts of iron or other metallic content in the ink (Lucas 1922). One avenue which may offer a more consistent promise is the possibility of an elemental contribution from the binding agent, such as the Ca often present in *Acacia senegal* (Parija 2001). In addition, inks which may be cursorily classified as solely carbon black may in fact be ivory or bone black. These pigments share similar production methods and periods with ancient carbon black, but incorporated pyrolyzed bone or ivory and as a result contain hydroxyapatite ($Ca_5(OH)(PO_4)_3$) (Winter 1983). In either case, Ca or other elements may be present in the ink but absent in the substrate, and it may be possible to obtain some contrast from the differing X-ray absorption characteristics of the materials.

Though recovered text alone lends itself to paleographical analysis, allowing scholars to determine provenance and dating, the potential for information provided by micro-CT imaging is not limited solely to textual content. Because the scans are acquired with known physical voxel dimensions, measurements such as the unrolled length and area of a scroll can be conducted. At sufficient resolution, it may also be possible to see the size and nature of the joins between papyrus sheets. The interior of the object can be assessed to see if damages such as fragmentation, existing deterioration, or attack by insects has occurred, allowing valuable analysis of these effects isolated from the changes introduced by physical manipulation. Even or especially in cases where a traditional autopsy is still deemed necessary, this information could also greatly assist conservators in planning the process.

Synthetic Objects

Prior to testing with real-world objects, we tested several proxy (synthetic) objects including a canvas replica scroll, papyrus replica scroll, and papyrus and ink fragments embedded in polyurethane plastic (one a scroll, the other a Möbius strip). The canvas scroll was scanned using a CT scanner at the University of Kentucky Chandler Medical Center, while the other proxy objects were scanned using our custom-built micro-CT scanner which has a much higher resolution than the typical medical CT scanner. The data for all objects was then segmented and virtual unrolling applied. All experiments were successful, although it should be noted that the ink used on all the proxy papyrus was iron gall ink, which would be expected to give reasonable contrast in the CT scan. See Lin 2007 for complete description of the proxy experiments.

Figure 1: Unrolled strip inset over digital photo of unrolled original.

Authentic Objects

Following the success of the proxy experiments, we made an attempt on an authentic manuscript object. With the assistance of curators from the Special Collections Library at the University of Michigan, we were given access to a parchment manuscript from the 15th century that had been dismantled and used in the binding of a printed book soon after its creation. The manuscript is located in the spine of the binding, and consists of seven or so layers that were stuck together, as shown in Figure 2. The handwritten text on the top layer is recognizable from the book of *Ecclesiastes*. The two columns of text correspond to Eccl 2:4/2:5 (2:4 word 5 through 2:5 word 6) and Eccl 2:10 (word 10.5 through word 16). However, prior to CT scanning it was not clear what writing appeared on the inner layers, or whether they contained any writing at all.

Figure 2: Spine from a binding made of a fifteenth-century manuscript.

We were able to distinguish several layers of text, including the text on the back of the top layer. Figure 3 shows the result generated by our method to reveal the back side of the top layer which is glued inside and inaccessible. The left and right columns were identified as Eccl. 1:16 and 1:11 respectively.

To verify our findings, conservation specialists at the University of Michigan uncovered the back side of the top layer by removing the first layer from the rest of the strip of manuscript. The process required precision, skill and patience. First, the strip was soaked in water to dissolve the glue and enhance the flexibility of the material, which was fragile due to its age. The water temperature and duration of exposure were controlled to protect against the risk of the ink dissolving. Then, using tweezers, the first layer was carefully pulled apart from the rest of the binding. The process was very slow to avoid tearing the material. Any remaining residue was scraped off gently.

The back side of the top layer is shown in figure 4. Most of the Hebrew characters in the images are legible and align well with those in the digital images of the manuscript. The middle rows show better results than the rows on the edges. This is because the edge areas were damaged, torn, and abraded, degrading the quality of the restoration.

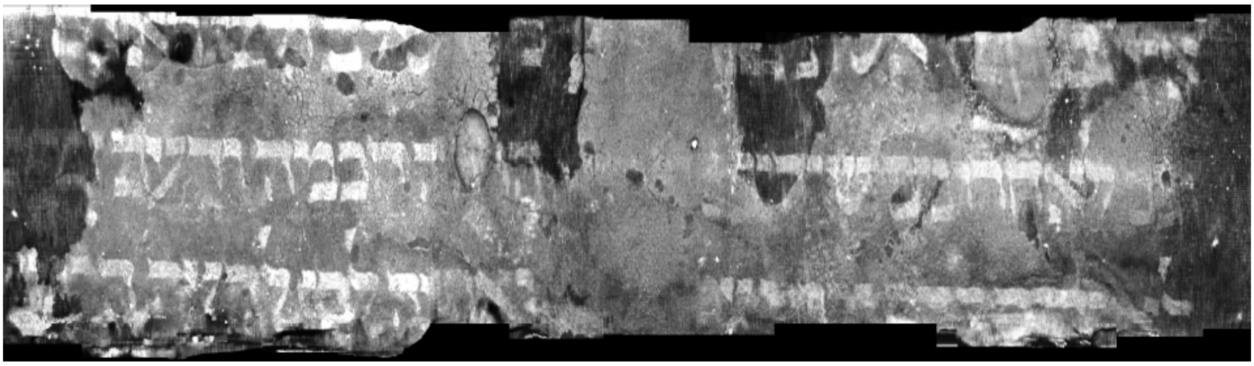

Figure 3: Generated result showing the back side of the top layer, identified as Eccl. 1:16 and 1:11.

Figure 4: Photo of the back side of the top layer, once removed from the binding.

Without applying our digital restoration framework, the choices would be either to preserve the manuscript with the hidden text unknown or to risk its destruction in an attempt to read it. In this case, we first read the text with non-invasive methods then disassembled the artifact in order to confirm our findings.

NEXT STEPS

In June of 2008, we will be applying these technologies to a scroll in the British Museum which has never been unrolled. The scroll, BM 10748, is presumed to be a text belonging to the work collectively referred to as the Egyptian Book of the Dead. Scanning a full scroll such as this poses significant challenges, in terms of resolution and sampling. The scroll is 71.5mm across at its widest, and extremely compact (Figure 5). The system we have developed should have a voxel size of approximately 25 microns and an axial resolution of 4096x4096. Approximately 12000 slices will be required to image the entire scroll. The amount of data alone is many orders of magnitude beyond what most CT systems are capable of. The system must also be portable so that it can be used on-site, including reconstruction and visualization hardware.

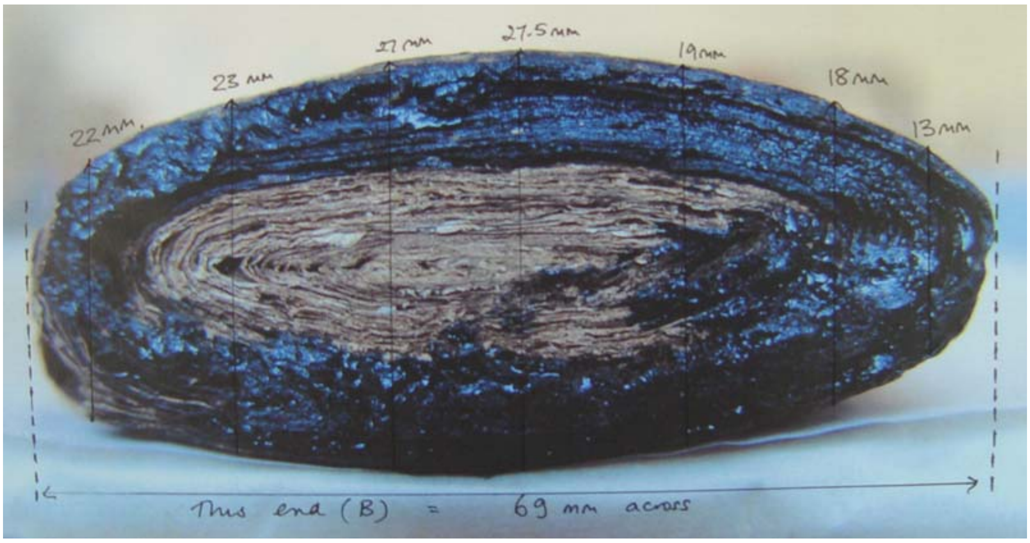

Figure 5: End of roll (B) of BM10748

Obviously, as the scroll has never been unrolled, all current knowledge of it is solely based on its exterior dimensions and appearance. Since the details surrounding the acquisition of many Egyptian antiquities were not recorded, provenance can be difficult to establish (Leach 1995). Thus, it is impossible to know with certainty *a priori* what the interior structure will be like and what pigments it will contain. However, Book of the Dead papyri from the approximate period of the scroll have certain elements which are often present. For text, one important element is the chapter heading, usually written in a red ink and consequently referred to as a rubric (Allen 1936, Lucas 1962). As the vast majority of Egyptian red pigments contain iron (Edwards 2004, Calza 2007), this should provide significant X-ray contrast. Another consistent feature is the vignettes, which are illustrations placed regularly throughout the text, often corresponding to a certain event or telling a story of their own. As these used many bright, non-black colors, it is likely that there will be some mineral or metallic content which will provide contrast against the papyrus. However, contrast between different inks within a single vignette will depend upon the exact pigments and elements involved. Both the vignettes and rubrics are consistently associated with specific chapters of the Book of the Dead. Thus, it may be possible to determine which chapters the scroll contains from these alone, or to determine if it may have some previously unknown content. It is unknown if the main text, usually written in carbon black, is likely to be visible with our current X-ray imaging configuration. This experiment, along with experiments we are conducting on Herculaneum fragments on loan from the Sorbonne, will likely give us our first indications as to the feasibility of the current imaging technique on ancient carbon black inks.

CONCLUSION

High resolution micro-CT imaging is a valuable tool for analysis of fragile text-bearing artifacts that have posed a serious and ongoing problem for conservators and scholars. The various difficulties traditionally associated with physically manipulating these objects, as well as the typical characteristics of pigment composition, make a portable CT imaging system almost ideal for conducting non-destructive analysis. In order to explore and appropriately visualize the data captured on such a system, a general restoration framework has been implemented and demonstrated on a variety of artificial objects in addition to a genuine manuscript. Going forward, we hope both to apply these techniques to other authentic artifacts, as well as to determine the characteristics and practicality of the system for a variety of pigments and substrates.

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