Imaging the Third Dimension of the Archimedes Palimpsest

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Abstract

Data produced by conventional 2-dimensional imaging of manuscripts having surface relief can be augmented by use of techniques that measure the out-of-plane characteristics of the manuscript leaves. The third spatial dimension can additionally provide information regarding the arrangement of layered or successively deposited materials. Confocal microscopy allows exquisite lateral and depth resolution, and is an ideal tool for measurement of surface topography and for building a detailed 3-dimensional model of translucent materials and structures.

Our investigation of the Archimedes Palimpsest has utilized confocal microscopy to probe the distribution of faint remnants of 10th century (Archimedean) undertext, 12th century overtext, and more recent forged paintings. Image stacks are assembled from 2-dimensional confocal images acquired at different depths, and adjacent stacks are mosaiced to give a volumetric model of regions of selected regions of interest within the palimpsest's leaves.

In particular, visible spectrum (533 nm) images obtained using confocal microscopy are used to examine different strata of substrate, text, and paint in folios containing 20th century forged paintings. These data are used to improve recognition of the different classes of content.

Because confocal microscopy typically utilizes high magnification (5x or greater) and a limited field of view (typically less than 1 cm x 1 cm), confocal imaging of large areas must take into account the computational resources needed to combine and process the large data sets involved. In this paper we discuss confocal microscopy methodologies, tools, and wavelengths that address these issues and are appropriate for measurement of materials in museum and library collections.

Introduction

Object Height Variation In Imaging

Most imaging of manuscripts and documents aims at capturing the 2-dimensional properties of the object being examined. Often, such imaging utilizes both spatial and spectral descriptions of the manuscript leaves to discriminate different classes of image content. In many instances the leaves of a manuscript are not truly plan ar, and special efforts must be made to overcome the impact of out-of-plane character upon image quality (through depth-of-field limitations of the optical system) and perspective. Sources of height variation may include cockling of the manuscript leaves and height variation of the text or figures upon the leaves.

From the perspective of 2-dimensional imaging, departure of the object from true planarity is often viewed solely as a confounding problem. However, in cases where imaging goals include the determination of the sequence in which different text, inks, pigments, etc. have been written on the leaves of a manuscript, height variation of these materials can provide valuable information.

In analyzing the various texts and figures of the Archimedes Palimpsest, which were deposited at different times during its thousand year history, both spectral data and an examination of the distribution of the different writings in the third (height) dimension have proved useful. Regions where newer text (overtext) overlaps original text (undertext) or pigmented paint that is spectrally similar may be distinguished through their different heights above the surface of the leaves. Additionally, the differentiation of newer texts from older texts, which werewritten using iron gall inks, may be aided by examining the height variation of text. These inks, which are based on an acidic formulation that corrodes parchment, can penetrate parchment beneath the leaf surface. Texts applied at different times will show a stratification that can be used to distinguish overtext from undertext of a different age.

Archimedes Palimpsest

The Archimedes Palimpsest is a tenth century parchment originally containing copies of text and diagrams comprising seven treatises of Archimedes work. Two of these treatises are found no where else in the original Greek language used by Archimedes in circa 150 BC. As is described by Netz,[1] the palimpsest is of tremendous historical value to classicists and scholars of the development of Western thought and of mathematical physics.

The parchment was "recycled" (palimpsested) during the 12th century by Christian monks who removed the original writing, recut the parchment to a size convenient to their purpose, and wrote a series of prayer services upon the newly scrubbed parchment. Fortunately, the original text is still partially visible to the visible eye, which allowed the

Danish scholar Heiberg to recover much of the text through painstaking visual analysis in 1906. Thereafter, the palimpsest suffered greatly from mold damage, poorstorage, and inadequate maintenance during the bulk of the 20th century while held in private hands (and uncertain provenance). At some point during this period, several pages were defaced anew and a series of paintings were made on these leaves. After languishing unremarked through these years since Heiberg's work, the palimpsest resurfaced at auction in 1998 and has become the focus of great hopes and efforts among the classicist community.

Since being bought at auction by a private owner, the conservation department at the Walters Art Museum has worked to conserve the palimpsest and has launched a digital imaging project aimed at recovering and enhancing the original Archimedean text of the palimpsest. Because the palimpsest is severely damaged, discolored, and misshapen, this project has explored the use of techniques that might augment the digital imaging techniques used to distinguish and enhance the various classes of text and diagrams upon it. Because the palimpsest contains a stratographic record of the various writings laid down at different times, we used confocal microscopy to assess the variation of depth of the text and figures upon the surface of the parchment. This technique can augment the use of spectral techniques to distinguish different content having similar reflectance spectra and that may be otherwise indistinguishable.

Confocal Microscopy

Confocal laser scanning microscopy (CLSM) is a 3-dimensional imaging technique utilizing laser illumination that involves scanning a solid object point by point to build up an image of a thin plane within the depth-of-focus of the imaging system. A three dimensional image can be reconstructed by computer from data obtained layer by layer via successive scanning of image planes (slices) at different depths. Pawley[2] gives detailed descripttions of many powerful techniques in CLSM.

The critical advance of confocal microscopy over conventional microscopic techniques lies in its ability to reject light from all but a thin section of interest at a particular depth. The ability to penetrate into a semitransparent object and optically isolate narrow sections allows the reconstruction of volume images from a set of image slices at different depths. When an epiillumination configuration is used (i.e. one in which both illumination and detected light utilize the same optical components and path), there is the added benefit that incident light (illumination) is concentrated in this same zone, thereby greatly reducing diffuse background signal that would otherwise degrade the image.

Methods

Confocal microscopy was performed at Microcosm, Inc. in Columbia, MD using a Zeiss 210 CLSM at a wavelength of 533 nm and using Microcosm's Z-NT upgrade. The Z-NT upgrade to the Zeiss 210 includes improved capabilities in dynamic range (12-bits), image format standardization (TIFF 6.0), and a variety of operational features (e.g. network access, signal processing, and computational speed). The CLSM system is controlled by an integral Pentium III microcomputer system. Images were stored in TIFF format on the system hard drive and later written to CD-ROM.

Scanning utilized 2.5x and 5x microscope objectives to acquire slices of 768 x 512 pixels (resolution of 7.8 microns x 7.8 microns and 3.9 microns x 3.9 microns, respectively), resulting in images of 6.0 mm x 4.0 mm and 3.0 mm x 2.0 mm, respectively. Different slices were acquired using a depth separation (or z-step) of 50 microns.

Because of extensive out-of-plane cockling of the parchment, and to reduce the possibility that vertical creep could occur due to changes in temperature and humidity during imaging, the leaf to be images was levelled and positioned within the wells of a mat board frame and constrained using monofilament line along its edges.

Results

Images of a 2.2 mm x 2.2 mm region of a palimpsest leaf on which a 20th century figure is painted were acquired using conventional and confocal microscopy. An image acquired using conventional microscopy is shown in Figure 1. The painting had been applied over the 12th century Euchologion prayer text, which in turn had been written over previously removed Archimedean text from the 10th century. The figure contains highly reflective bronze paint as well as a variety of pigmented oil-based paints. This image is necessarily monochromatic, due to single wavelength laser illumination at 533 nm. Figure 2 illustrates a single confocal image of this region acquired using CLSM. Because of substantial height variation (> 500 microns peak-to-peak within the field of view), only a few subregions (or contours) of the field of view fall within the depth-of-field of the microscope at this height; the remainder of the image is out of focus. In Figure 3, the leaf has been moved 150 microns closer to the objective lens, so that the acceptance zone is 150 microns deeper than in Figure 2. Different portions of the area fall within this acceptance zone and allow reflected light to reach the detection photomultiplier.

The lower right portion of Figure 2 shows an area containing bronze paint (bright region), part of which has been overpainted with black pigmented paint (dark region). The reflective gold paint in this area falls within the depth of focus and allows light reflected from this surface to meet the confocal condition of the microscope. In Figure 3, in which the imaging zone is placed 150 microns deeper, this same area appears uniformly dark. This occurs since because the reflective surface is above the zone meeting the confocal condition. The change in apparent intensity and increased spatial frequency content in the acceptance zone forms the basis for identifying the depth of regions in a sucession of image slices.

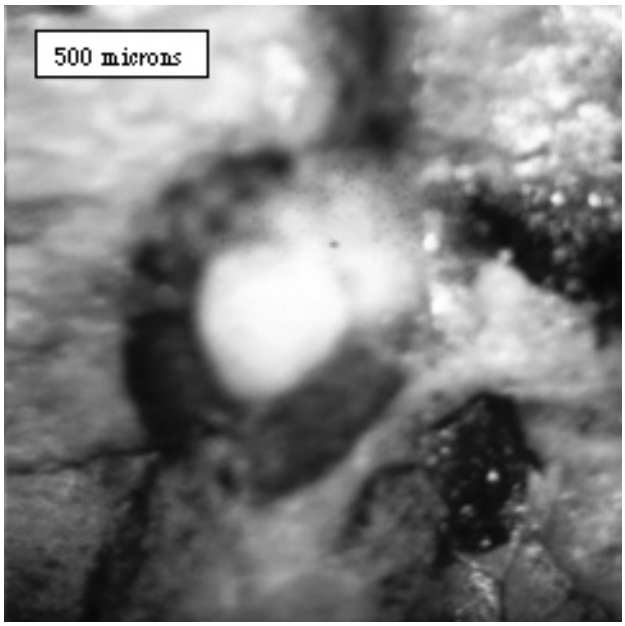

Figure 1. Conventional microscopic image using 533 nm illumination at 5x magnification. Image width and height are both 2.24 mm.

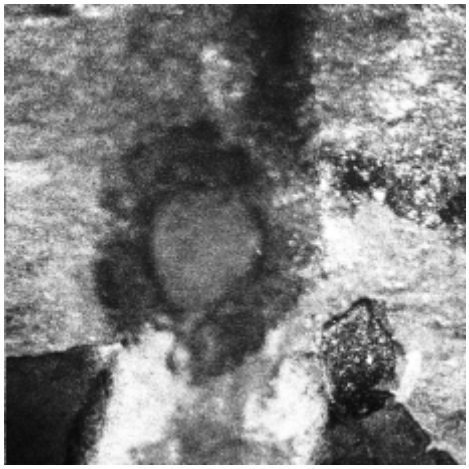

Figure 2. CLSM image of same region using the same conditions as in Fig. 1. Regions within the focal zone appear with sharp detail; shallower and deeper regions appear out of focus.

Cross-sectional views along selected lines within this region were constructed from a sequence of 14 images at depth intervals $\Delta z = 50$ micrometers. In Figures 4a and 4b, a cross-sectional view is given of the region shown by the dotted line AB in Figure 3. The curving, bright-to-dark boundary running across the cross-sections in Figs. 4a and 4b correspond to the parchment surface at the location.

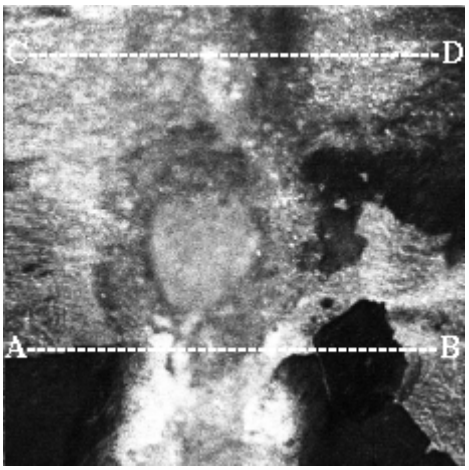

Figure 3. CLSM image of same region using the same conditions as in Figs. 1 and 2, but with a selected focal zone 150 microns deeper than in Fig. 2. Different features fall within the focal zone.

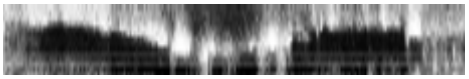

Figure 4a. Cross sectional view (height not to scale) through 14 successive slices at depth intervals of *50 microns. This cross section corresponds to a cut along the line joining the points labelled A and B in Fig. 3.*

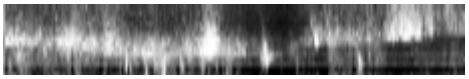

Figure 4b. Cross sectional view along the line joining the points labelled C and D in Fig. 3.

In Figure 4, the bright-dark boundary is apparent across the field of view, and can be seen in spite of the overlying paint and ink. The existence of the boundary is only possible for semitransparent paint and ink: in the central portion of Figure 4a the boundary lies beneath the dark region (due to the 12th century iron gall ink), while toward the left and right of the figure the boundary is above the opaque 20th century paint.

In the central region containing 12th century ink, it is notable that with increasing depth the intensity of the reflected light initially diminishes, then reaches a maximum value, and then diminishes further at greater depths. This behavior is only observable using a confocal configuration that eliminates all light but that arising from a zone having a selected vertical range.

Discussion

Findings

The confocal technique was able to identify the parchment surface in areas covered by 20th century painting

and 12th century text and to distinguish each of these layers in the cross-sectional reconstructions.

The thickness of the bronze and black paints seen in the lower half of Figure 3 can be estimated from the height of the sharp downward step in the surface that is seen along the A-B line in Figure 4a (approximately 1 cm from the right edge of the figure):using the known vertical scale (Figures 4a and 4b span 650 microns vertically) the thickness is approximately 130 microns. The thickness of the 12th century iron gall ink (forming the donut shape in the middle of Figures 1 to 3) appears to be substantially thinner than the paint layer, but the depth step (50 microns) used in this experiment was too large to allow the precise thickness to be ascertained.

Considerations For Use In Imaging Museum Objects

The composition and structure of a manuscript leaf, painting, or other museum object must be carefully considered in determining the potential utility of confocal microscopy. Relevant factors include:

(i) Sources and scale of height variation. In order to survey a region throughout the range of its vertical excursions (peak-to-peak height variation), slice interval and slice number must be considered in tandem. A smaller depth interval between slices will yield improved depth resolution, yet will require a greater number of slices on order to capture all information from the highest to the lowest points in the field of view. A highly corrugated surface with very fine (shallow) features will require a large number of closely spaced image slices, while a relatively flat substrate with coarse features will require a lesser number. The surface should be levelled prior to imaging in order to minimize the peak-to-peak excursion within the field of view.

(ii) Optical properties of paints, inks, and substrates. Confocal microscopy is uniquely able to probe beneath the surface of materials that are partially transparent. Materials such as varnishes, paints, and inks that do not form a continuous, highly absorbing or reflective layer may be penetrated to a depths up to several hundred microns. The illumination wavelength selected for a particular study should be based on the spectral properties of the materials under examination. If determination of surface topography is the goal in a particular study, a wavelength at which the materials are highly reflective should be used. If surface penetration is of interest, a wavelength at which the overlying materials transmit light well can improve the signal from structures beneath the surface.

(iii) Optical exposure. Exposure calculations should consider total dose as well as average and peak irradiance. Dose can be calculated from average power values and duration of exposure. While total light dose required for a single confocal image slice is often less than for conventional microscopic imaging, the need to collect multiple image slices and the use of a scanning process require attention in considering optical exposure standards. The potential for thermal or optical damage is calculated from peak average and peak irradiance values. Average and peak irradiance are determined by the duration of exposure, laser power, total area imaged, and the spot size of the laser at the object. While the laser source operates at a constant power level (typically several milliwatts), scanning consists of a focussed flying spot from the laser that is raster scanned over the region being imaged. In consequence, the average irradiance is determined from the power of the source laser divided by the area that is scanned, while peak irradiance is determined as the laser power divided by the laser spot size at the object. Spot size decreases with increasing magnification, with the result that higher magnification leads to higher peak power and irradiance.

References

1. Reviel Netz, The Origin of Mathematical Physics: New Light on an Old Question, Physics Today, pg. 32-37 (June 2000)
2. James B. Pawley, *Handbook of Biological Confocal Microscopy*, Plenum Press, NY (1995)

Biography

William A. Christens-Barry is a physicist at Johns Hopkins University. Since receiving his PhD in 1987, he has developed optical and imaging techniques in basic life sciences research and a variety of cross-disciplinary applications. His research activities include: optical measurement of tissue, cell, and nuclear organization in prostate and breast cancer; 3-d optical metrology; DNA array techniques for genome analysis; optical correlation and pattern recognition; polarized light techniques in materials analysis and remote sensing.