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Speeding up the Raster Scanning Methods used in the X-Ray Fluorescence Imaging of the Ancient Greek Text of Archimedes

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ABSTRACT

Speeding up the Raster Scanning Methods used in the X-Ray Fluorescence Imaging of the Ancient Greek Text of Archimedes. MANISHA TURNER (Norfolk Sate University, Norfolk, VA 23504) DR. UWE BERGMANN (Stanford Linear Accelerator Center, Menlow Park, California 94025).

Progress has been made at the Stanford Linear Accelerator Center (SLAC) toward deciphering the remaining 10-20% of ancient Greek text contained in the Archimedes palimpsest. The text is known to contain valuable works by the mathematician, including the *Method of Mechanical Theorems*, the *Equilibrium of Planes*, *On Floating Bodies*, and several diagrams as well. The only surviving copy of the text was recycled into a prayer book in the Middle Ages. The ink used to write on the goat skin parchment is partly composed of iron, which is visible by x-ray radiation.

To image the palimpsest pages, the parchment is framed and placed in a stage that moves according to the raster method. When an x-ray beam strikes the parchment, the iron in the ink is detected by a germanium detector. The resulting signal is converted to a gray-scale image on the imaging program, Rasplot. It is extremely important that each line of data is perfectly aligned with the line that came before it because the image is scanned in two directions.

The objectives of this experiment were to determine the best parameters for producing well-aligned images and to reduce the scanning time. Imaging half a page of parchment during previous beam time for this project was achieved in thirty hours. Equations were produced to evaluate count time, shutter time, and the number of pixels in

this experiment. On Beamline 6-2 at the Stanford Synchrotron Radiation Laboratory (SSRL), actual scanning time was reduced by one fourth. The remaining pages were successfully imaged and sent to ancient Greek experts for translation.

INTRODUCTION

Throughout history, science and religion have been at odds over the right to explain how and why things happen. While both sides have innovated since medieval times, it would seem that yet another battle inadvertently began during exactly that dark period…

Centuries ago, ancient Greek mathematical mastermind Archimedes documented his ideas, many of which were far advanced for his time. In 4 A.D., as there were no printing presses to copy an author's work, scribes painstakingly copied Archimedes' works by hand onto parchment made of goatskin. During a series of wars in the Middle Ages when paper was a scarce commodity, a Christian monk in need of a prayer book recycled a copy of Archimedes' work. This was accomplished by erasing the genius's writing with a weak acid (like lemon juice) and scraping it with pumice stone [1]. The parchment was then folded parallel and bound such that Archimedes' text lay perpendicular to the monk's prayers [2]. This now makes the work a *palimpsest*, a writing material (as a parchment or tablet) used one or more times after earlier writing has been erased.

These invaluable copies of Archimedes' work contain the details of many of his ideas, such as floating bodies and the equilibrium of planes, and the treatise *Method of Mechanical Theorems* [1]. First discovered in 1906 and resurfacing again in the 1990's, the palimpsest has gone through experiments to safely and effectively read what lies beneath the soot from centuries of extreme damage from mold, forgery, candle wax, and ink. A great deal of the text has been read by visible or ultraviolet light during six years of careful analysis and restoration through a method called multi-spectral imaging [3]. In this process, light of various wavelengths is used to differentiate between the two manuscripts [2]. Unfortunately, multi-spectral imaging proved ineffective in reading of text (about 10-20%) because of obstructions like forgery paintings, dirt, mold, glue or other parchment.

At the Stanford Synchrotron Radiation Laboratory (SSRL), a kind of radiation known as synchrotron light is produced when electrons, racing at nearly the speed of light, move around a curved storage ring, emitting radiation ranging from x-ray to infrared wavelengths in the process [4]. It was realized that, because the parchments were written on with ink containing iron, x-ray fluorescence could be used to see Archimedes' work beneath the damage. X-ray fluorescence occurs when a photon strikes an atom (such as iron) and is either absorbed or scattered. If the ray is absorbed, the photoelectric effect takes place [2], in which photons of significant energy knock electrons from the inner shells out, leaving electron holes. These holes launch the atom into a highly energized state. Electrons from outer shells swiftly fill the available spaces to return the atom to its ground (lowest energy) state. This rapid movement of electrons gives off photons characteristic of the atom. Because each element has a unique set of energy levels that produce energy-specific x-rays, it is possible to obtain the elemental composition of a sample.

The integral component of this experiment is fine-tuning the scanning methods used in the project. The speed with which the work is deciphered is increased by synchronizing the scanning speed and read-out time. Originally, the time it took for a 40μm beam to decipher half a page (approx. 8,312,500 pixels) was thirty hours with a resolution of 600dpi. The pages were scanned using the raster format, which is continuous in both the positive and negative x-directions, then stepwise down in the y-direction (See Fig. 1). However, it would be advantageous to scan the page faster.

The purpose of this project is to test and commission a new readout system that was built in order to minimize the dead time and speed up the readout time, allowing for faster scans without loss of resolution.

The main constraints being adjusted are motor speed, count time and shutter time, which directly affect how well subsequent scanning lines are adjusted and how well the edges of the images are lined up. Accomplishing this will allow the researchers to use the improved faster scanning method.

MATERIALS AND METHODS

In order to speed up the raster scanning method, a new readout system developed at SSRL was commissioned. The high-intensity x-ray beam from the original experiment was replaced with a Class II He Ne laser, and a photodiode detector was substituted for the original germanium detector. A template made from a thick paper material (used in manila folders) was scanned for image testing. This material was more practical than cardboard or traditional writing paper because its thickness is closer to the goat skin used in the original text.

The template was attached to a frame that slid directly into a stage positioned between the laser and detector. The photodiode detector was placed across from the laser beam to measure the beam's transmission through the template. Scanning with this material produced clear images; however, the edges of the cutout lines were not completely straight. Scanning perfect vertical lines is very important because, since the line scanning is in both directions (see Diagram 1), if the interval between read-out time and scanning speed isn't perfect, the lines of the image do not line up. Therefore, knife edges were scanned to produce perfectly aligned images. Later, printed text on transparency was used to produce nice images of complete text. The stage was driven by two motors, allowing x-range data to be recorded when scanning in both directions.

All data were recorded "on the fly," or while the scanning was underway. As soon as the beam reached a cutout, the photodiode detector collected the transmission. For each beam, the detector would send a current to an amplifier where was converted to a voltage. The voltage signal was changed to a frequency via a voltage/ frequency converter, resulting in a number of counts. The grey-scaling program, Rasplot, then produced an image based on the numerical values. The count time, the time it took the template to move between readouts, was tested for several different scanning distances. To calculate the count time for each distance, it was necessary to first calculate how many pixels were contained in that distance. This was done by dividing the scanning distance by the pixel size (40microns [~600dpi]),

$$*40\mu m = 0.04mm \rightarrow [\text{Distance (mm)}] / [0.04mm] = \text{no. pixels.} \qquad (1)$$

Next, a fixed motor speed of 2160steps/sec and rate of 157.48steps/millimeter were used to calculate how many pixels were scanned per second,

$$[2160 steps/sec]*[1mm/157.48 steps]*[no. pixels/distance (mm)]= pixels/sec \quad (2)$$

Finally, because count time is reported in seconds/ pixel, it was easily found as the inverse of equation two,

$$1/[pixels/second]= count time (sec/ pixel) \quad (3)$$

The shutter box is a device used to safe-guard the parchment against radiation damage from the x-ray beam while the endpoints are exposed. The shutter opened at the start of each line scan and closed at the end of each line scan, where the stage would move to the next line. The amount of time the shutter took to open greatly affected the image's alignment and was adjusted, for each distance, according to the following formula,

$$[Pixels] \times [count time (sec/ pixel)]= shutter time (sec) \quad (4)$$

The most important part of this experiment was determining the best count time and shutter time for each scanning distance. These values are ideal when the pixels of the resulting image at the end of each scan line up perfectly. Tests were run to determine the best values for count time and shutter time for 60, 70, 80, 160, 170, and 200mm scanning distances (See Table 1). By commanding the Rasplot program to plot each image on a single pixel scale, any offset in time could be seen almost immediately, after about three line scans. Count time proved most difficult to adjust, as an offset of even a microsecond would cause the pixels to be misaligned and distort the image immensely. Correctly determining shutter time was vital because it ensured that a) the edges of the image were straight and more importantly b) that the parchment would not be exposed to x-rays when the motor movement stopped at the end of each line. If the count time was significantly off, aspects of the image such as sharp edges and curves were harder to determine and would appear blurry or stretched (see Images 1 and 2). These times, remarkably, were perfected to microsecond precision.

A series of long scans were commissioned to determine how well the program could perform, producing well-aligned images at the desired count time for each distance. An 80mm scan of the template was run overnight, at a count time of 0.003001 seconds per pixel and a shutter time of 5.8 seconds. The resulting image was satisfactory because the characters were easy to make out, which means the count time was excellent; however, it was difficult to tell whether the shutter time was best because the cutouts were made by hand with a razor and did not image straight vertical lines (see Image 2). In order to test for shutter time, knife edges were scanned overnight to produce an image of a full 80mm scan. The image did not align completely and needed to be corrected. The shutter time was adjusted slightly to 5.785 seconds, producing the best image (see Image 3). After the best scanning conditions were optimized, the stencil was scanned again and produced a perfectly aligned image (see Image 4). A long scan of text on transparency was imaged to produce a full-text image (see Image 5).

The motors also needed to be considered, as they had to be monitored to prevent over heating. A thermocouple was attached to the stepper motor and a fan was placed close by to make sure the motor temperature did not exceed 70 degrees celsius.

RESULTS AND DISCUSSION

It was determined that the very best images resulted from very carefully adjusted count times and the corresponding shutter times. The count time proved most important in producing perfectly aligned images, as an offset of merely a microsecond would introduce visible distortions in the image from misalignment of subsequent lines. The shutter time, however could be manipulated according to the desired count time without having to be as meticulously perfect.

The new parameters found in this experiment have sped up the Raster scanning method by ~5 times the speed accomplished in previous experiments (a remarkable 12hours/ page). The helpfulness of this experiment in accomplishing better images in less time is evident in the scanning of the ancient texts of Archimedes conducted at Beamline 6-2 at SSRL this summer. The team from SSRL, the Walters Art Museum in Baltimore and the other collaborating institutes set up the experiment according to the newly found parameters. The final scans were completed on Monday, August 7, 2006. One of the significant new findings was the complete image of a previously only partly seen diagram in Archimedes' most important work 'The Method of Mechanical Theorems'. It was published in Science on August 11, 2006 [5].

CONCLUSIONS

The palimpsest was successfully imaged using the new readout system achieved from this experiment. The resulting images were sent to ancient Greek experts for translation and made available online at www.archimedespalimpsest.org. The total time taken to image one page of parchment was reduced to 12 hours, an improvement by a factor of 5 from the original time of approximately 30 hours. *Future experimentation with the palimpsest may involve alternative imaging methods such as confocal imaging and scanning for other atoms (like calcium) to make the text more legible for the ancient Greek experts.*

ACKNOWLEDGEMENTS

I would like to thank my mentor, Dr. Uwe Bergmann, for giving me the opportunity to work on such an amazing project and helping me to gain better understanding of all that goes into conducting quality research. I greatly admire you for the work you have done and I am so grateful I had the chance to work with you. I would also like to thank Martin George for supporting me and helping to make sure things were running properly. Thank you so much to the staff at SSRL who offered technical support on many occasions. Finally, thank you to the Department of Energy for providing me a chance to participate in the SULI program, which was an experience I will never forget.

REFERENCES

[1] "X-Ray fluorescence: Reading tool for ancient manuscripts." 25 Aug. 2005. http://www.iisc.ernet.in/currsci/aug252005/598.pdf

[2] "Placed under X-ray gaze, Archimedes manuscript yields secrets lost to time." 19 May 2005. http://news-service.stanford.edu/news/2005/may25/archimedes-052505.html

[3] "X-Ray Fluorescence Spectroscopy." 2 Aug. 2005. http://www.amptek.com/technology/radiation_detection.html

[4] "Stanford lab reveals hidden writing on ancient parchment; Scientists analyze Archimedes text at accelerator center." 23 May 2005. http://www.sfgate.com/cgi-bin/article.cgi?f=/c/a/2005/05/23/MNGQ2CSVND1.DTL&type=science

[5] "Brilliant X-rays Reveal Fruits of a Brilliant Mind", Science, Vol. 313 , page 744 2006

Tables

Scan Distance (mm)	x-Num Pts. (pixels)	Count Time (secs/pixel)	Shutter Time (secs)
60	1500	0.003027	4.33
70	1750	0.003012	5.065
80	2000	0.003001	5.785
160	4000	0.0029605	11.64
170	4250	0.0029585	12.37
200	5000	0.002953	14.55

Table 1: Count time, shutter time and number of pixels determined for various scanning distances.

Diagrams

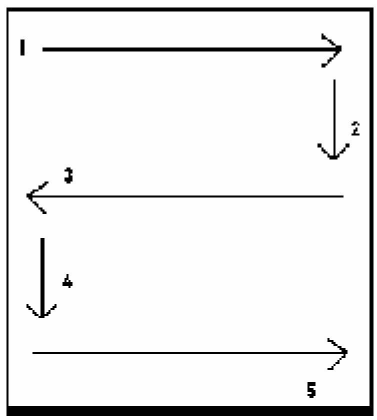

Diagram 1: The Raster scanning format.

Figures

Figure 1: The class II He Ne laser was positioned in front of the stage (below).

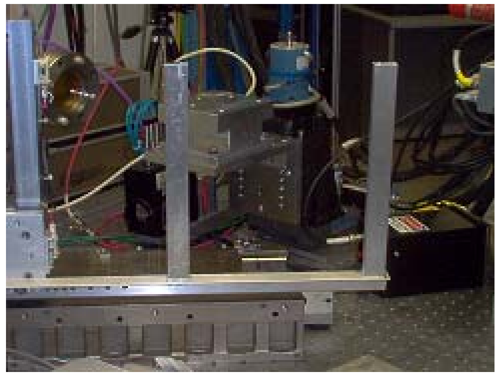

Figure 2: The stage, positioned between the laser and detector, held the parchment in its frame for scanning.

Figure 3: The photodiode detector, positioned behind the shutter box.

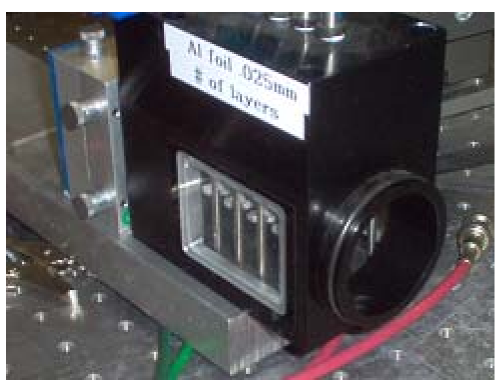

Figure 4: The shutter box, positioned behind the stage, used air pressure (green tubing) to open and close shutters.

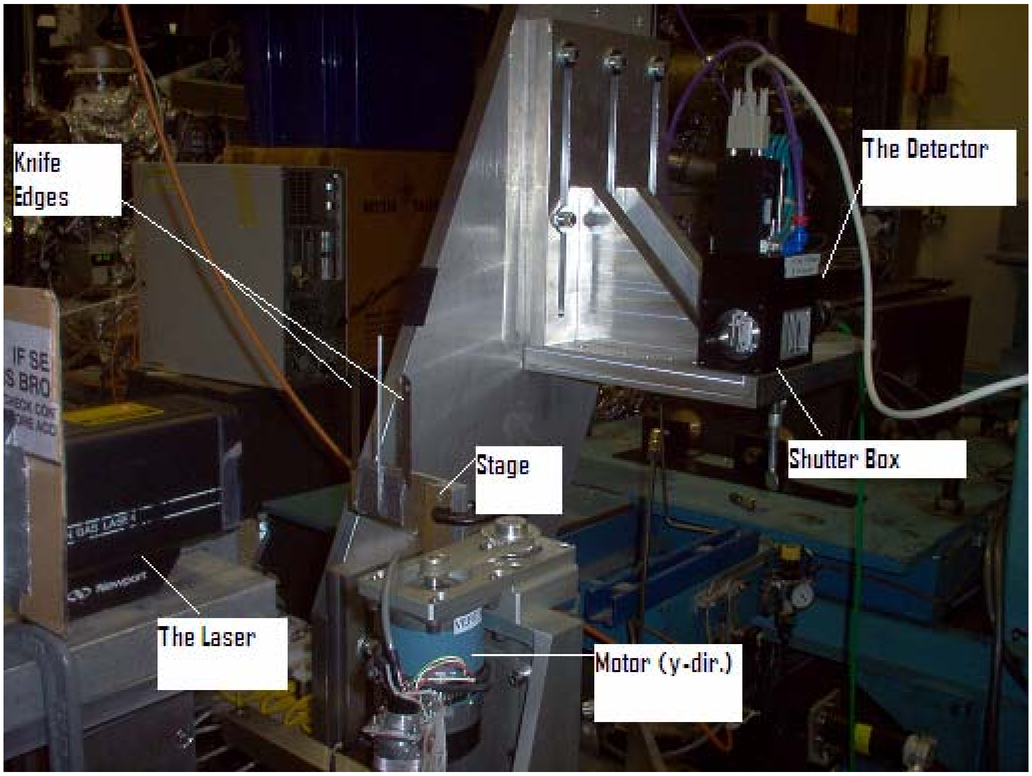

Figure 5: The experimental setup, showing knife edges mounted on stage for scanning (x-motor not shown).

Images

Image 1: Part of 80mm scan of transparency. Image is stretched because of offset in count time.

Image 2: 80mm scan of template is blurry and stretched because of offsets in count time and shutter time.

Image 3: Part of 80mm scan of knife edges. This image has near-perfect count time and a shutter time offset of only one pixel (see Table 1).

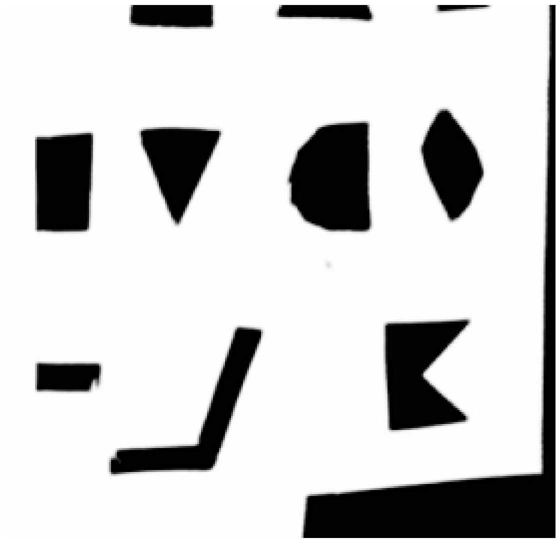

Image 4: 80mm scan of stencil, repeated using new parameters from knife edge scan (see Table 1).

Figure 5: perfectly aligned 80mm full-text scan of transparency, scanned with new parameters (see Table 1).