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SPECTROSCOPIC APPROACHES FOR STUDYING FAINT TEXT ON A WOODEN TALLY FROM INVINCIBLE (1758)

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Abstract

In this study we describe the application of X-ray fluorescence, variable pressure scanning electron microscopy and visible (420-720 nm) hyperspectral imaging to assess the surface properties of a wood tally stick that was recovered from the 3rd rate Invincible. The Invincible was a wooden warship that sunk in 1758. The main objective of this work was to improve the legibility of very faint text that was detected on the surface of one of the three tally sticks used in this project. For imaging, an ultraviolet light source was used to achieve reasonable contrast between the text and the wood and the optimal wavelength was found to be 365nm. Single band images at 550 nm gave the best contrast, particularly if flat fielding was used to compensate for uneven lighting of the wooden surface. Finally, X-ray fluorescence (XRF) and SEM were used to assess the wood and possibly identify the material used to write on the tally stick. The scanning electron microscopy (SEM) images did not reveal the presence of any graphite particles or ink deposits, but the XRF indicated that there were higher levels of Fe where text was detected, which may indicate that an iron containing writing material was used to write on these tally sticks

Keywords: *wood; archaeology; hyperspectral imaging; SEM; XRF*

Introduction

The *Invincible* was one of the finest warships of its day, when it was captured by the Royal Navy from the French in May 1747. Equipped with 3 masts, it had a reputation of being a very swift warship. It carried a lethal armament of 74 guns (3rd rate) and set the standard for contemporary English warship design and technology. Early in the morning of February 19, 1758 the *Invincible* weighed anchor at St Helen's Roads off the Isle of Wight and set sail with a large British fleet bound for Fortress Louisbourg, in what is now known as Cape Breton, Nova Scotia (Canada). Unfortunately for the *Invincible*, it grounded in shallow water and in a matter

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of days this once magnificent warship languished on the Horse Tail Sandbank in the Solent before falling over on her beam ends on February 22, 1758 [1].

After lying partially buried in the sand and under water for more than 200 years, the *Invincible* was discovered by a Portsmouth-area fisherman who inadvertently snagged his nets on upstanding timbers. Incredibly, portions of this wooden ship that were located by divers were found to be intact and a variety of artifacts have been recovered. These objects include wooden barrels, musket balls and tally sticks [2, 3]. Tally sticks are wooden tags that are attached to objects such as barrels, crates and canvas bags used to store various items such as rope or munitions that are part of the supplies of a sailing ship. They typically have writing on them to identify contents and it was often a harbour - master who would carry out the task. The tally stick often does not contain a lot of detail, but it was the recovery of a tally stick that allowed divers to identify the *Invincible* 200 years after its sinking [4].

In this study, we have chosen a multi-technique approach for assessing the state of preservation of 3 tally sticks that were recovered from the *Invincible*. The techniques we have chosen for examining these wooden objects include hyperspectral imaging, variable pressure scanning electron microscopy and X-ray fluorescence spectroscopy. The primary goal of this work was to attempt to increase the legibility of the written text and hyperspectral imaging was chosen for this task. Hyperspectral imaging combines the spatial information of a digital camera with spectral information. A number of manuscripts have been published on the application of spectroscopic approaches for studying historical inks and manuscripts [5-7]. Multispectral and hyperspectral imaging has been described for examining potentially fraudulent [8] and historical documents [9-11]. Goltz et al. have used hyperspectral imaging for enhancing the legibility of faint inks in a copybook that was part of the Hudson's Bay Archives located in Manitoba, Canada [12]. Numerous examples of the application of hyperspectral imaging have been reported by France et al. on objects in the US Library of Congress collection [13]. Goltz et al. have used hyperspectral imaging for assessing inks in two historical treaties [14] as well as stains on the surface of a number of printed documents [15]. The development of quantitative hyperspectral imaging has also been described for classifying writing material as well as quantifying degradation of original and artificial samples subject to the effects of artificial aging [16].

The objective of this research project was to test the feasibility of using hyperspectral imaging for enhancing the written text on a wooden tally stick from the *Invincible*. Although reflectance imaging has been carried out on wooden objects [17], this is probably the first reported study where hyperspectral imaging was used to enhance text on a wooden object. A second objective of this work was to use microscopy and X-ray fluorescence spectroscopy to assess the state of preservation and possibly the identity of the materials used to write on these tally sticks.

Experimental

The three tally sticks from the *Invincible* that were used in this study are shown in Figure 1. To the unaided eye it would be difficult to detect written text on any of these objects. One tally stick that was chosen for detailed study, shown in Figure 2 is approximately 8 by 20 cm in size and approximately 5 mm thick. The surface where written text would be expected is reasonably smooth to the touch and the side which would not have written text is quite rough. In general, these objects are in very good condition, considering that they have been buried in sand and immersed in sea water for over two centuries.

Fig.1. Photograph of tally sticks #1 (top), #2 and #3 (bottom - with tag)

Fig. 2. Photograph of tally stick #1.

Hyperspectral imaging

Prior to imaging, the wooden tallies were placed flat on a platform with the imaging camera mounted directly above at a distance of approximately 0.5m. Lights were placed at 45° angles to the surface of the plate. Visible (420-720nm) imaging was performed using a Nuance™ 420 MSI multispectral imaging system (Channel Systems and Cambridge Research & Instrumentation Inc.). This instrument is equipped with a liquid crystal tunable filter, optics and digital camera with a CCD detector. The detector has an image sensor pixel count of 1.3 megapixels with a resolution of 1248 x 960 pixels. Images were acquired from 420nm to 720nm at intervals of 10nm. For this spectral range (420-720nm), an AF Micro Nikkor 105mm (f/2.8) D series lens was used. For visible reflectance imaging a pair of 35W Solux™ bulbs (3500K, 17°) were used. For fluorescence imaging two different light sources were used. One light source consisted of fluorescent bulbs (2W) at 254nm, 302nm and 365nm. These bulbs were not intense and they had a glass cover which minimized the visible light wavelengths. A second higher intensity 365nm light source was also used for fluorescence imaging. This light source consisted of a single 100W mercury bulb (Sylvania).

Data acquisition by the instrument was controlled entirely by a laptop computer using software provided with the imaging system (Nuance™). Spatial information is obtained in two dimensions (x, y) and spectral information is obtained in a third dimension (z), which allows the storage of information in a 3D-dimensional data cube. Once an image is stored in an image cube format, further processing of the data was possible using ENVI (Environment for Visualizing Images). In this study, ENVI was used to select specific 10nm band images or combine multiple bands in order to make a composite image. The exposure time for each wavelength was entirely computer controlled and varied according to the sensitivity of the system to specific wavelengths of light. Since wood does not fluoresce strongly, typical exposure times for the visible imaging camera were 5s. Visible spectra were generated by selecting specific regions of interest (pixels) for an image in ENVI and an average spectrum was calculated.

Microscopy

All of the microscopy was carried out in the Department of Biological Sciences at the University of Manitoba. A stereomicroscope was used to acquire visible images and a Hitachi TM-1000 table top electron microscope was used to acquire extremely well focused images of the wood surface. The TM-1000 uses back scattered electrons to generate images and it is a variable pressure electron microscope which enabled us to work at higher pressures. This allowed the acquisition of highly focused images from the poorly conductive wood surface without the need for coating the object with a conductive layer of graphite. The pressure used to acquire images was 50Pa and the accelerating voltage was 15kV. Due to the size restrictions of the microscope, the entire surface of the tally could not be examined and for the images acquired in this study the middle (~2cm^2) was used. Nevertheless, there was enough freedom of movement of the object to allow the inspection of surface areas that contained text as well as areas that did not.

X-ray fluorescence

A portable energy dispersive X-ray fluorescence instrument was used to identify metal on the surface of the tally sticks. The X-ray is equipped with a Rh X-ray tube and spectra were acquired using 40keV (0.02keV per channel) and 7μA output. The X-ray spectra were acquired for 480s and quantitative analysis was not attempted due to the low concentrations of metals detected. The surface area exposed to the XRF was approximately 1.0cm^2.

Results and Discussions

For this project, we initially focused on three tally sticks to explore the feasibility of using hyperspectral imaging for identifying and possibly enhancing the legibility of written text. Visual inspection did not reveal the presence of any text on two of the tally sticks, however faint markings were visible on one which seemed to indicate the presence of some text, but it was not legible even with the aid of a magnifying glass. Hyperspectral imaging experiments were carried out using broad band light sources with visible (420-720nm) and near infrared (650-1100nm) cameras to collect reflectance spectra as well as to determine if useful images could be acquired of the surface. It was thought that these spectra would be useful for predicting which bands would be useful for imaging, particularly to enhance the contrast of the text and the wood surface. Both the near IR and visible reflectance spectra of the wood were essentially flat and lacked any useful spectral properties such as absorbance peaks. In areas where faint text was located, the visible and near IR spectra were essentially identical in appearance to that of the wood surface, except with slightly higher absorbance. As a result, the reflectance spectra confirmed the limitations of using visible and near IR light sources for enhancing the legibility of the written text on these objects.

Visible reflectance spectra were also acquired using an ultraviolet light source with three different wavelength settings: 254nm, 302nm and 365nm. The ultraviolet sources used for this experiment consisted of 3W fluorescent bulbs, which produced broadband emissions centred at these wavelengths. Figure 3a-c shows the visible spectra acquired from a portion of the wood surface without text and the wood surface where text was faintly visible.

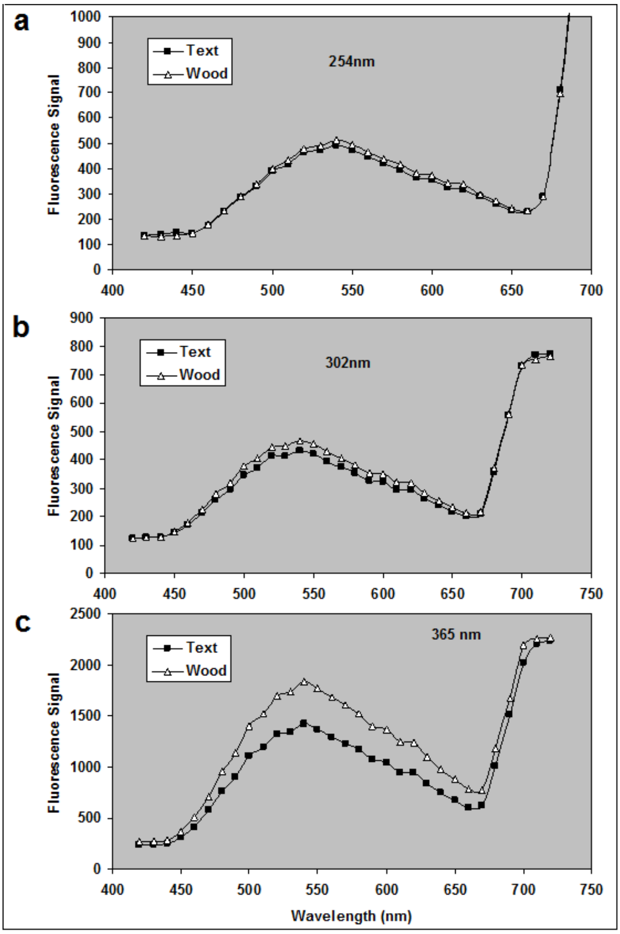

Fig. 3. Visible spectra of text and wood of tally stick #1 using:
a - 254nm; b - 302nm and c - 365nm light source.

All of the spectra shown in these figures were acquired using the visible hyperspectral imaging camera. When the 254nm (Fig. 3a) and 302nm (Fig. 3b) light sources were used, the visible spectra of areas with and without text were quite similar, which suggests that these light sources were not ideal for enhancing the contrast between the faint text and the wood. When a 365nm light source was used (Fig. 3c), the contrast between ink and wood became sufficient enough to detect letters and words. For comparison, visible images of a small (2cm x 2cm) portion of one tally stick are shown when they are exposed to different ultraviolet light sources in Figure 4a-c. When a 254nm light source is used (Fig. 4a), the contrast between text and wood is negligible and only improves marginally when a 302nm light source is used (Fig. 4b). The contrast between text and wood shown in Figure 4c is actually great enough to begin to make out the number ‘30’.

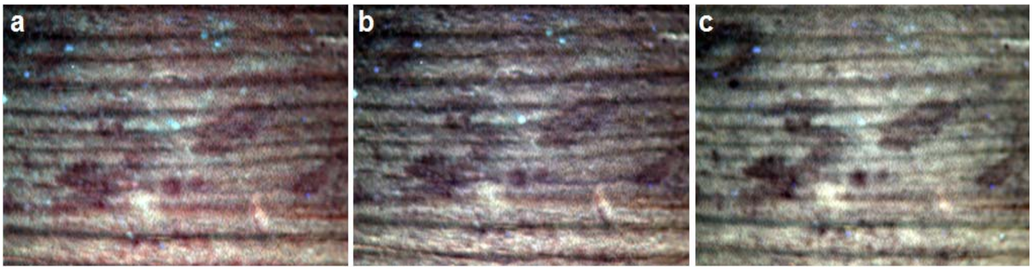

Fig. 4. Visible (450-700nm) images of a portion of text on tally stick #1 using: a - 254nm; b - 302nm and c - 365nm light source.

As these experiments demonstrated that the 365nm light source provided the highest contrast, experiments were also carried out to compare the quality of single band images for enhancing the faint text on this object. In Figure 5a-c, a larger portion of tally stick #1 was illuminated using the 365nm light source. In these figures, it is evident that the optimal wavelength for maximizing contrast between text and wood was at 550nm (Fig. 5b), which is consistent with the visible spectra acquired at this wavelength. The optimal wavelength for minimizing the contrast between text and wood could be either 440nm (Fig. 5a) or 700nm (Fig. 5c). In general, the light-absorbing properties of the text decreased significantly at longer visible wavelengths and diminished completely in the near infrared (>780nm).

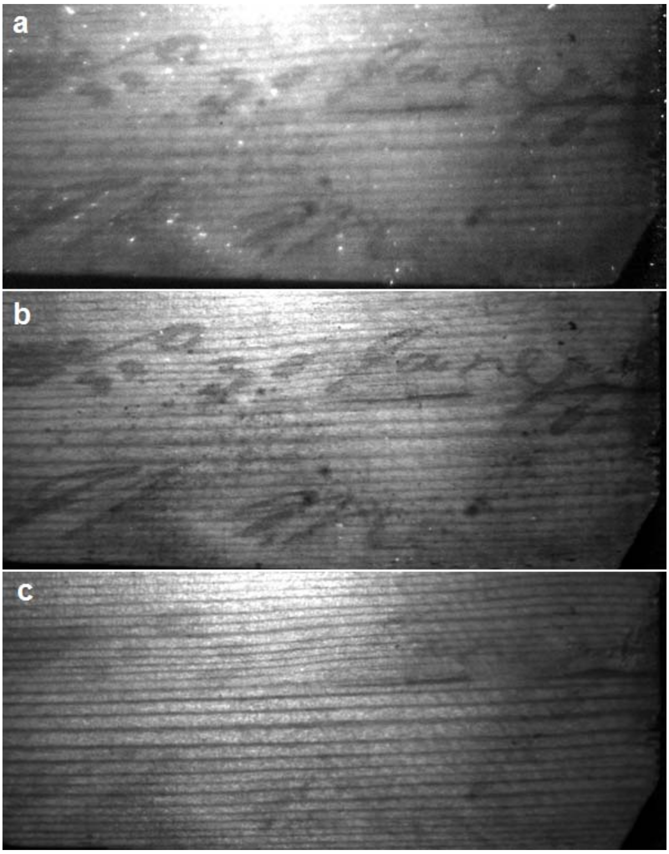

Fig. 5. Single 10 nm band images of a portion of text on tally stick #1: a - 450nm, b - 560nm and c - 700nm using a 365nm light source

Figure 6a shows a contrast-enhanced visible image (420-720nm) of the tally stick when a 365nm light source was used. The size of the object and the uneven distribution of the ultraviolet light source meant that a composite image would be more useful in reading the text on the tally stick rather than a single image. Further complicating the imaging were the wood grains and the uneven surface features which scattered much of the light. The hyperspectral imaging cameras were equipped with polarizers which helped minimize the effects of scattered light. Figure 6b shows a similar composite image of the same tally stick except that single 550nm band images were used. It should also be noted that this image is also contrast-enhanced to maximize the contrast between the text and the wood surface. Although we explored a number of approaches for enhancing the text, such as principal components, supervised classifications and band subtraction, none of them provided significant improvements in legibility of the text when compared to the single band images at 550nm. Again part of the reason for this was the inability to flat field the visible images properly and the uneven distribution of light on the wood surface.

Fig. 6. Tally stick #1 (365nm light source): a - Colour enhanced composite visible image and b - Single band (550nm) composite image

Apart from enhancing the legibility of the written text, experiments were also carried out using a variety of microscopic techniques in order to evaluate the surface properties of these objects. Each of these wooden tally sticks were originally cut in a radial direction. Stereomicroscopy enhanced the visibility of a number of surface features such as the wood grain as well as the presence of small areas where oxidized iron particles can be seen. These tiny particles are not readily visible to the unaided eye and may be a result of iron corrosion from other objects (i.e. nails, bolts and other fixtures) that were in the vicinity of this shipwreck. Similarly scanning electron microscopy (SEM) was also applied to examine areas of the wood surface that contained text as well as areas that did not appear to have text. For this work, a variable pressure SEM was used as it would allow us to see surface details in very high magnification without the need of conductive coatings such as graphite. Figure 7 shows an area of the wood surface that contained text. Images acquired from the SEM were quite useful as they provided a visual indicator of the surface damage that this object has undergone.

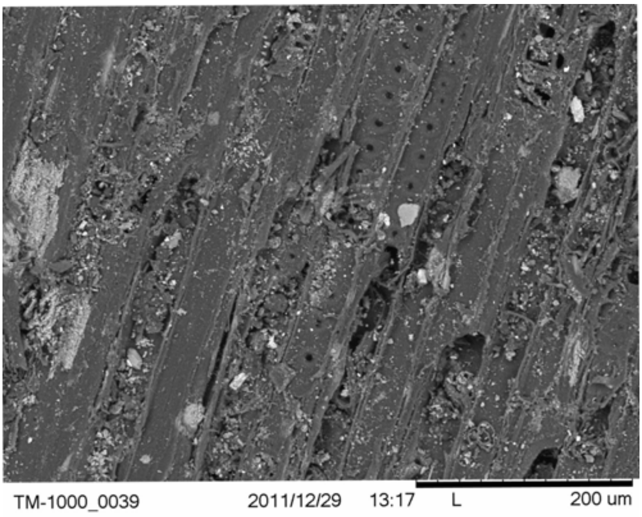

Fig. 7. SEM image of a portion of the tally stick (#1) surface.

A lot of debris, including dust, can be seen on the surface. The SEM images also revealed an absence of large vessel elements which indicates that the tally sticks were manufactured using wood from softwood (coniferous) as opposed to hardwood (deciduous) trees. The objects used in this study were 'split' tally sticks that were manufactured by taking a larger piece of wood and splitting it into smaller pieces. Hazel and occasionally oak have been used to manufacture tally sticks, however the tally sticks in this study are thought to have been manufactured from pine.

It was hypothesized that areas containing text on the wood surface could be somewhat more damaged than areas that did not contain text, possibly if iron gall ink were used as a writing material. Unfortunately, it was not possible to conclude this as the images of the wood surface that contained text were surprisingly similar to images that did not, regardless of the magnification. While the SEM was extremely useful for examining surface properties, we were unable to discriminate areas containing text from areas without text. The absence of particles that could not be attributed to dust or debris from the wood itself meant that we were unable to identify the type of material (graphite, pencil, iron gall ink) that was used to write on the surface. It is very interesting to note that small barrels containing iron gall ink were found among the objects collected from the *Invincible* and therefore, it would not be unreasonable for iron gall ink to be used.

Portable X-ray fluorescence was used to acquire elemental analysis of the areas that contained text in order to compare with areas that did not contain text. Figure 8 shows typical X-ray spectra of an area of the tally stick that contained text. Spectra of the tally sticks in areas that contain text and areas without text show the presence of calcium ($Ca_{K\alpha}$ = 3.6keV, $Ca_{K\beta}$ = 4.0keV), chloride ($Cl_{K\alpha}$ = 2.6keV, $Cl_{K\beta}$ = 2.8keV), bromide ($Br_{K\alpha}$ = 11.9keV, $Br_{K\beta}$ = 13.4keV) as well as iron ($Fe_{K\alpha}$ = 6.4 keV, $Fe_{K\beta}$ = 7.0keV) and copper ($Cu_{K\alpha}$ = 8.0keV, $Cu_{K\beta}$ = 8.9keV).

Signals for these elements are not unexpected given the nature of this sample as well as the fact that the wooden tally was in a salt water environment. It should be noted that areas of the wood surface that contained text also had higher signals for Fe (10,800 counts) than areas that did not contain text (8,300 counts). It is interesting to note that the XRF signals for Cu, Cl and Br in all areas of the wood were essentially the same in intensity as areas that contained text. This strongly suggests that the difference in Fe signals between areas containing text and areas that did not contain text is likely not random. Furthermore, the higher levels of Fe would also be consistent with the application of iron gall ink for writing on the tally sticks.

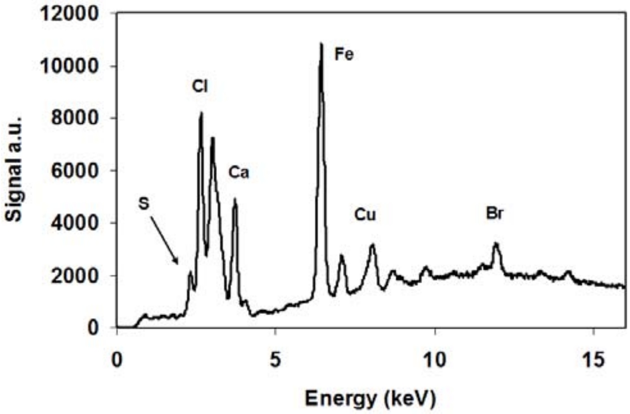

Fig. 8. XRF spectra of the tally stick surface in an area containing written text.

Conclusions

The legibility of the faint text on the tally stick could be significantly enhanced with an ultraviolet light source, particularly when the wavelength of the light source had a maximum output at 365nm. The hyperspectral camera was particularly useful for acquiring spatial and spectral information of the object. A single band image at 550nm appeared to provide the most enhanced image. Surprisingly further improvements in text legibility were not made using statistical approaches such as principal components analysis. For text legibility, it is also interesting to note that increasing the magnification did not improve the legibility significantly. Highly magnified views of the surface simply resulted in a more visually distracting image which obscured the legibility of the written text even more.

As it was one of stated goals in this project, it is worth noting that the written text on the wooden tally appears to contain the following words: (top row): “Coyles” (Cringles?), “8 doz” and “1-10”; (middle row) “unknown text” (possibly a short-hand for “Portsmouth”) and “30 Janey” and (bottom row) “J l” and “M r”. For anyone who is not familiar with writing styles or the English terminology of this period, it would be a challenge to read this text. For some of the text it is impossible to state the identity of a word with absolute certainty. Alternatively, the word “30 Janey” is almost certainly referring to a date (“30 January”).

It is also interesting to hypothesize why it was possible to enhance the legibility of the text under ultraviolet light. Wood will fluoresce very weakly when a 365nm light source is used, most likely as a result of the presence of lignin [18]. It would appear that areas of wood that contained text simply did not fluoresce as strongly as areas that did not contain text. In the absence of any detectable particles from the writing material used to write the text, it seems likely that areas of the wood surface that contain text probably experienced bond breakage to the π-bonded functional groups (C=O or C=C) in the lignin and possibly cellulose. Bond breakage of these functional groups would destroy the conjugation required for fluorescence when exposed to ultraviolet light.

Acknowledgments

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