Computational Connoisseurship: Enhanced Examination Using Automated Image Analysis

Margaret Holben Ellis and C. Richard Johnson, Jr.

The feasibility of the application of image/signal processing for measuring, marking, matching, and sorting vast quantities of data derived from materials typically found in artworks is presented through four case studies. Different patterns produced by canvas weave structures, surface textures of historic photographic papers, chain line intervals in Rembrandt's printing papers, and watermark variations have been subjected to different modes of computational analysis. The art-historical implications that result from computer-generated algorithms – including dating, attribution, authenticity, and workshop practices – can be considered as "computational connoisseurship." The case studies discussed point to future areas for research. Finally, because of the need for statistically meaningful datasets of images, a practical means of recording internal paper structure is introduced.

Keywords: Image Processing; Canvas Thread Count; Photographic Paper; Decision Tree; Connoisseurship

Introduction

Opportunities for the enhanced examination of works of art in order to better understand their materials and techniques, sometimes called "technical art history," have multiplied thanks to the introduction of computational approaches – more specifically, automated digital image/signal processing software used to detect analog physical qualities.[1] The application of pattern recognition software to digital images of certain materials found in artworks, such as canvas, paper, cracked oil films, and brush strokes, has generated data that can answer persistent inquiries regarding dating, attribution, authenticity, and workshop practices. It has also allowed for the possibility of pursuing previously undreamed-of questions, but may be hampered in the future by the logistics and costs of image acquisition.

Background

Art historians and conservators have long sought to address traditional challenges of dating and attribution, not to mention authentication, by resorting to various means of visual assessment, such as canvas thread density (counting the number of warp and weft threads per specific area of canvas), dendrochronology (counting and characterizing tree growth rings as an aid in dating), radiography (imaging the internal structure of a material using X-rays or beta rays), and multispectral imaging (the visual

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recording of materials as they appear under various wavelengths of the electromagnetic spectrum), among other technologies. There is a growing arsenal of imaging options to record specific physical features of an artwork's materials and its manner of fabrication. Despite these advances, the products of these imaging technologies still need to be painstakingly measured, marked, matched, and sorted by humans.

Such attempts to address quantitative materials-based questions are impressive, but of limited scope and success, because of the necessity to manually process an enormous amount of information gleaned from a statistically meaningful number of artworks. Additionally, the logistical problems of systematically recording and accumulating data from works of art found in collections around the world can be overwhelming in terms of labor, time, and skills. Finally, a seemingly objective assessment of a pattern can vary drastically according to the operator, measuring device, sample location, image scale, and light source. A marked margin of error results when humans measure, mark, match, and sort images, which in turn easily leads to misinterpretation or inaccurate conclusions.

Over the past decade, computerized image/signal processing programs have been developed that can compare and match countless seemingly random arrangements of pixels in minutes rather than years. Algorithms can be used to identify similarities and differences in any material that produces patterns; as described below, these include thread density in the canvas supports of paintings by Vincent van Gogh (Dutch, 1853–1890) and Johannes Vermeer (Dutch, 1632–1675), chain line intervals in the etching papers of Rembrandt van Rijn (Dutch, 1606–1669), and mechanically embossed photographic papers as used by Lewis Hine (American, 1874–1940).

Based upon the promising results of our initial forays into automated computer-based pattern recognition, it seems safe to say that computational connoisseurship is a valid approach to characterizing the materiality and facture of works of art and that it can constitute a significant aspect of scholarship in the age of digital art history.

Case Studies in Computational Connoisseurship

The potential of image/signal processing software to characterize the appearance and structural properties of typical materials found in artworks can be demonstrated by four case studies in computational connoisseurship. Each one of these projects catalyzed investigations of other materials, including Chinese silks[2] and modern European printmaking papers,[3] two current research pursuits. It can be seen that these four case studies proffer tantalizing avenues for future research and may extend to the collectors' stamps found on drawings and archaeological tool marks found on ancient artifacts, to name just two potentially vast datasets.

Thread Count Automation Project (TCAP)

Begun in 2007, the Thread Count Automation Project (TCAP) used image/signal processing to count threads, create weave maps, and match the striped patterns that resulted.[4] This allowed for the virtual reconstruction of the bolts of canvas used by van Gogh.[5]

In his Dutch and late French periods, van Gogh ordered canvas in rolls and, for small to moderate-sized paintings, would cut out sections from the bolt for individual paintings. The working hypothesis is that paintings from the same canvas roll should possess common thread count (density) variations horizontally and vertically. By extension, paintings on canvas from the same roll were probably painted at about the same time. Unattributed paintings can more confidently be identified, if they are found to match a particular canvas roll.

In van Gogh's day, artists typically prepared their canvases with a painted undercoat (called the ground layer) containing lead white pigment. The purpose of the ground was to smooth out the woven fabric in preparation for painting. When applied, the liquid ground naturally settled into the interstices of the woven canvas. When these paintings are X-rayed, the lead-based ground blocks the transmission of the rays; conversely, the less dense threads of the canvas allow for the passage of the rays, as shown in Figure 1. By examining the regular screen-like pattern produced in an X-radiograph of the canvas, a thread density measurement is calculated by humans, with the use of a magnifying headset, by counting the number of threads in short vertical and horizontal strips at scattered locations in X-radiographs mounted on a lightbox. It would be impractical, if not impossible, for manual thread counts to be done across the entire canvas. The general approach was to calculate the average thread count of a limited number of spots counted.[6] When the average thread counts of two canvases differ substantially, they cannot have been manufactured in the same roll. But average thread counts alone, no matter how close, are not enough to establish that two canvases were cut from the same roll of canvas.

TCAP sought to produce reliable, accurate techniques that would allow thread density to be measured with minimal human intervention using a digitized composite X-radiograph of the entire painting. With the advent of computer methods, it is now

Figure 1. Thread count or density is determined by counting the number of warp and weft threads in a predetermined square area using an X-radiograph. It can be measured by humans or by computerized image/signal processing.

possible to "count" the threads at every location in a canvas. The computational technique used to automate thread counting of the digitized X-radiograph relies on the approximate regularity of the canvas weave across small (0.5 cm to 2 cm square) evaluation "tiles." Counting the number of threads in one centimeter (threads/centimeter) provides a measure that is the inverse of the frequency (centimeters/thread) of the periodic shift from light to dark and back in a horizontal or vertical strip from the grayscale image of the X-radiograph. Fortunately, as numerous engineering problems involve the determination of the frequency of a periodically fluctuating signal, a variety of computational algorithms exist for extracting the frequency from approximately periodic signals. A fundamental approach to frequency estimation relies on Fourier analysis, which is a tool taught to undergraduate electrical engineers. In the thread counting application, the "signal" is the grayscale intensity fluctuations corresponding to the threads visible in the X-radiograph.

The next step was to merge all the individual thread count tiles taken across the painting to form one composite image of the entire canvas. The choice made was to color each tile of thread counts according to density – that is, a more closely woven section would be one color and a looser one would be another color. This procedure produced "weave maps," as seen in Figure 2.

The striking feature of weave maps is the appearance of multicolored striped patterns, which are attributable to the mechanics of the weaving process. These variations often extend over the width and length of the canvas roll. A weave match occurs when the weave maps from two different canvases have the same pattern of stripes. This has proven to be compelling forensic evidence in establishing rollmate status between two separate canvases.[7] When two canvases have similar patterns of stripes, such as the two by Vermeer shown in Figure 2, they are regarded as rollmates and can be presumed to have a common origin, thus placing the canvases (and potentially the paintings) in the same place at the same time.

When combined with information about a painter's studio practice, as well as material data (e.g. the range of ground layer materials used by the artist) and documentation (e.g. letters, financial transactions, and memoirs), canvas weave matches can assist in authentication, dating, and inference of artist's intent, as recognized six years ago in several paintings by Vermeer.[8] That same year, document-rich studies incorporating weave matches appeared concerning paintings by van Gogh[9] and Diego Velázquez (Spanish, 1559–1660).[10] In the case of Vermeer, for whom documentation is lacking, the eight weave match pairs discovered so far[11] raise unanswered questions as well, in particular regarding dating. When a weave match is found between canvases typically dated via stylistic analysis as several years apart, this challenges the prevailing assumption that an artist would be unlikely to hoard canvas for such a long period. Assembling a weave match study across the entire *oeuvre* of a painter can provide valuable data regarding chronology. Expanding to a comparison of weave maps for paintings by different artists from the same period and place could help in establishing patterns of interaction among artists.

In the decade since the creation of the first fully automated thread counting procedures, the utility of weave maps of thread density and angle has been shown for European paintings from the fifteenth to the early twentieth century. Striped weave maps

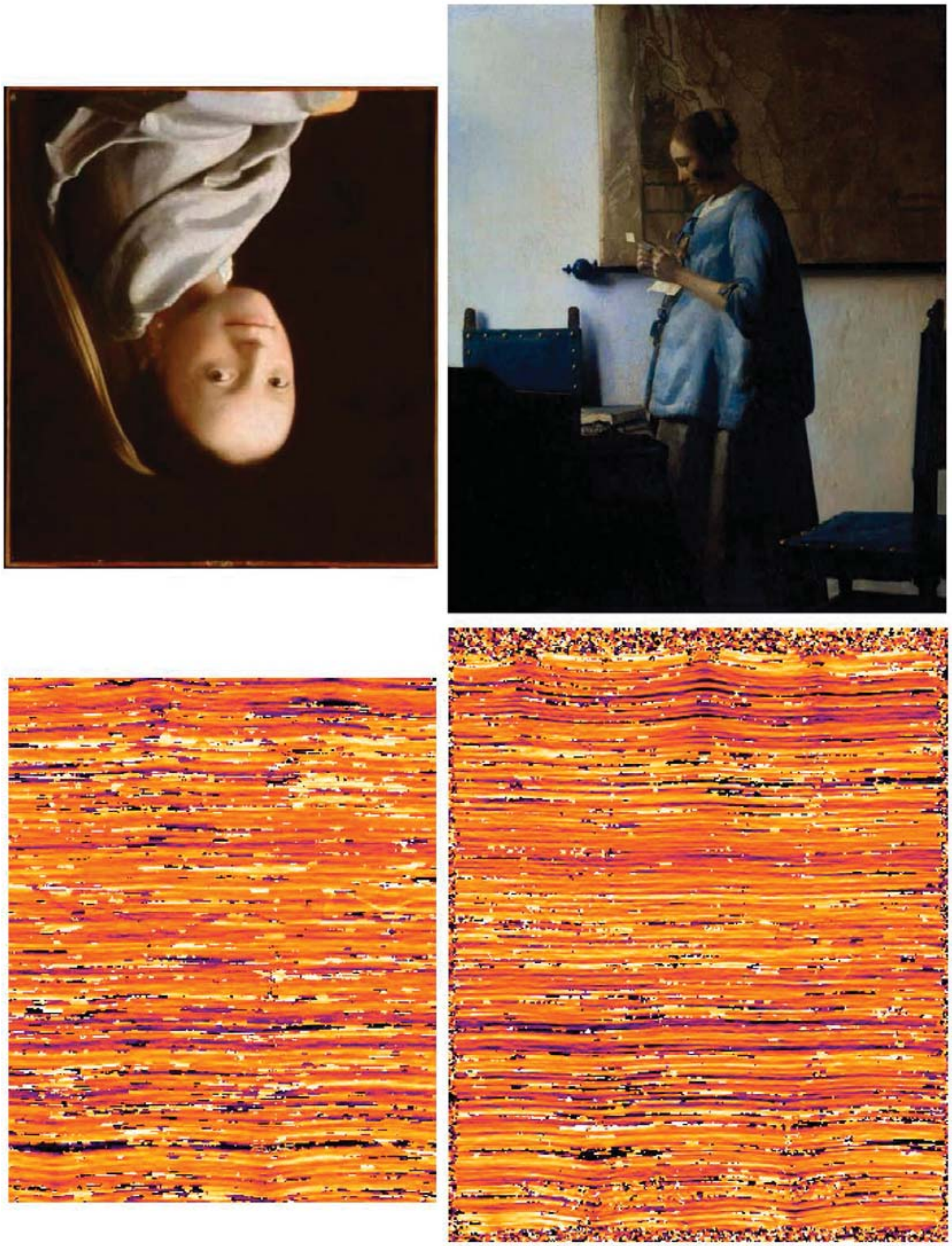

Figure 2. Left: Johannes Vermeer, *Study of a Young Woman*, (L23) (1665–1667). Right: Johannes Vermeer, *Woman in Blue Reading a Letter*, (L17) (1662–1665). Paintings are placed above their corresponding weave maps of horizontal thread densities. The weave maps were computed using software written by W.A. Sethares, which appears in C.R. Johnson, Jr. and W.A. Sethares, eds., "Counting Vermeer: Using Weave Maps to Study Vermeer's Canvases," *RKD Studies* (2017), countingvermeer.rkdmonographs.nl/.

have also been produced for twelfth- and thirteenth-century Chinese Southern Song Dynasty silk paintings.[12] The extension to other fabrics with periodic weave patterns, such as clothing, flags, and other woven cultural heritage objects, is both alluring and possible, providing the fabric can be reproduced at a resolution sufficient for a human to count the threads.

Historic Photographic Paper Classification (HPPC) Project

Building on the successful imaging of previously undetectable or unreadable patterns, this project demonstrated the feasibility of automatic computer-based classification of historic embossed silver gelatin photographic papers using “texture maps” – digital images that record the topography of the surface of the work undergoing examination.[13]

Surface texture is a design variable in the manufacture of photographic papers and is a major factor in their marketing and use. Starting in the early twentieth century, manufacturers manipulated texture to differentiate their products and satisfy the aesthetic desires and work practices of photographers. The identification of a proprietary texture associated with, for example, the Eastman Kodak Company, provides scholars with valuable information regarding a photographer’s intention and practice. It also serves as an aid in attribution and dating. Currently, the determination of texture of a specific commercial product is accomplished by comparison of a sample with a known reference using raking light, a strong source of illumination cast parallel to the surface of the work undergoing examination. Raking light can reveal the surface texture of these papers by producing a high-contrast rendering of highlights and shadows, as seen in Figure 3. Despite successful documentation of surface features of historic photographic papers, the sheer number and diversity of their textures prohibited any attempt to sort, compare, and match them by hand. Begun in 2010 as part of research surrounding the Thomas Walther Collection of photographs belonging to the Museum of Modern Art, New York, the goal of the HPPC project was to advance scholarship about dating and characterization techniques for twentieth-century photographic materials and establish a new model for collaborative research, interpretation, and interdisciplinary dialogue.[14] To aid in their comparison, the raking light photographs were converted to 16-bit grayscale, cropped to 1024 × 1024 pixels, flat field corrected, sharpened slightly using an unsharp mask, and contrast enhanced by histogram equalization to produce images as in Figure 4. A set of 120 standardized raking light images

Figure 3. Raking light photographs capture the subtle and unique surface texture of vintage photographic papers. (Photo: P. Messier)

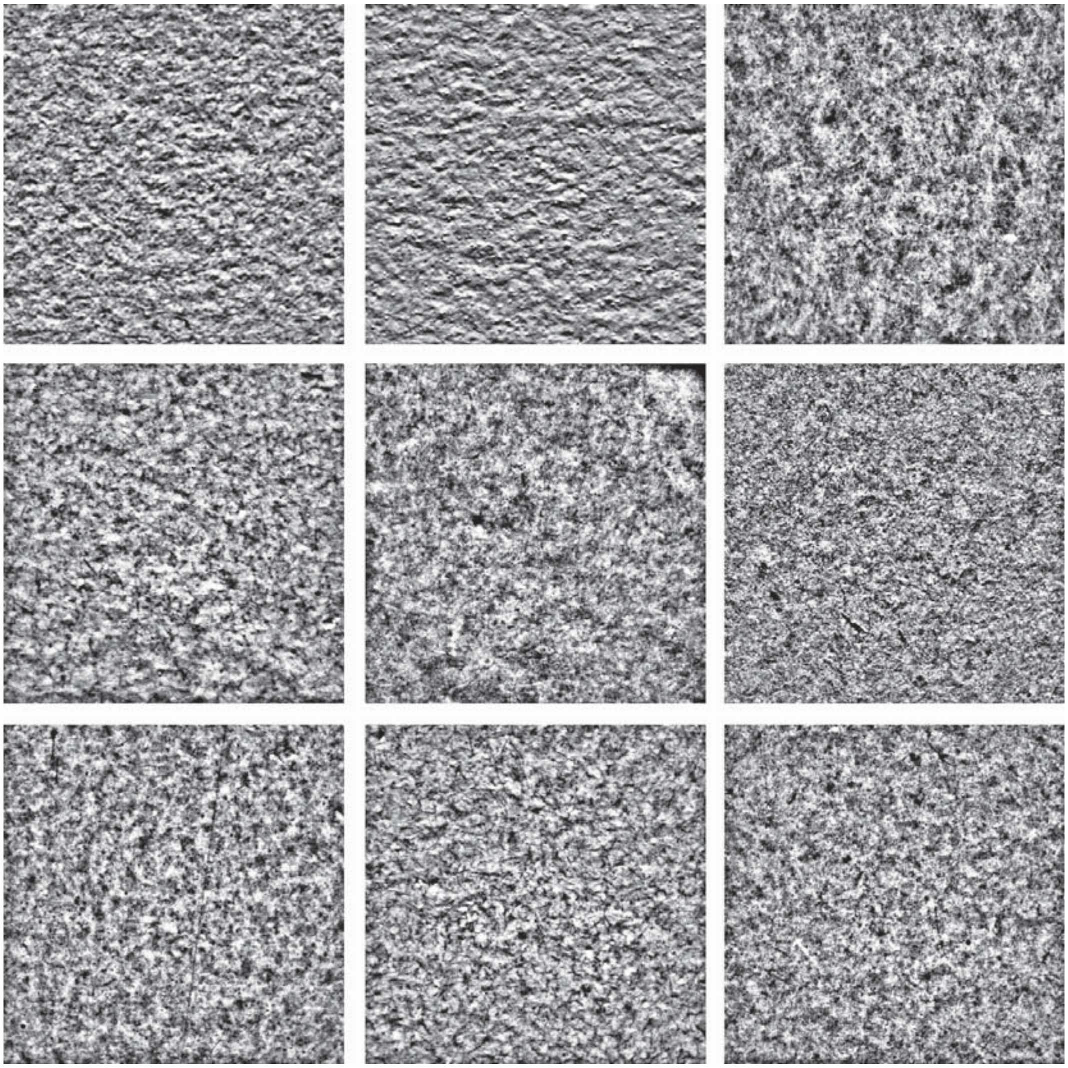

Figure 4. Raking light images of historic textured photographic papers are standardized to grayscale images prior to automatic feature extraction and degree of similarity quantification via image/signal processing. TP04 and TP08 are a match. (Photo: P. Messier)

made from a reference set of historic silver gelatin papers was submitted to four university teams who applied different signal processing strategies for automatic feature extraction and degree of similarity quantification. Their results demonstrated an encouraging degree of success in sorting the papers and successfully detected strong affinities, as well as outliers built into the dataset. The teams had no prior knowledge of the distributions of samples and the inclusion of exceptional examples when they created and deployed their algorithms. To cite just one finding, surprising paper pairings were discovered between photographs by Alfred Stieglitz (American, 1864–1946) and Edward Weston (American, 1886–1958), which suggests that their meeting in 1922 may have had not only inspirational, but practical ramifications. Such intriguing results suggest that computerized classification of historic silver gelatin photographic papers based upon raking light texture maps is feasible and should be pursued.

Given the success of the HPPC project, attention turned to applying image/signal processing to the smoother, but still distinctive surfaces of so-called "wove" papers, those lacking the internal grid pattern of antique "laid" papers. Samples were selected from *Specimens*, a 1953 publication of the Stevens-Nelson Paper Corporation which contains 107 predominantly mold-made papers from some of the oldest paper mills in Europe.[15] Many of these papers were popular with twentieth-century artists including Pablo Picasso (Spanish, 1881–1973), Henri Matisse (French, 1869–1954), and Fernand Léger (French, 1881–1955), whose work has been widely copied and sold as authentic. Initial results of this study demonstrated that, as a concept, the computational and automated matching of the wove paper surface textures is achievable.[16]

Chain Line Pattern (CLiP) Marking and Matching Project

The Chain Line Pattern (CLiP) Marking and Matching Project, begun in 2012, demonstrated the potential of image/signal processing to mark and measure unique chain line intervals in antique laid papers.[17] This allows for the matching of papers made from the same papermaking mold, even those lacking watermarks.

The study of prints by Rembrandt has occupied scholars for more than two centuries. With several thousand in existence today, the papers the artist used to print upon have received much attention. Rembrandt's prints were predominantly executed on laid paper, which is formed on molds, or porous screens, fabricated from finely spaced horizontal rows of laid wires held into position by thicker, widely spaced vertical chain wires. The grid-like configuration of the laid and chain patterned screen was replicated in the sheet of paper produced, as seen in Figure 5. Each mold was made by hand and, while at first glance two molds may appear to be identical, small variations exist between the exact intervals of chains from one mold to the next. Two papers having identical laid and chain line patterns can occur only if they have been formed on the same mold – hence, they are called moldmates. When there exists a large body of one artist's work on paper, as is the case with Rembrandt, the identification of moldmates can help in establishing chronology, suggest paper preferences, and indicate periods of intense activity.

To date, moldmates have been identified primarily by the ability to superimpose their watermarks exactly. Stitching a thin wire bent to form a shape onto the surface of the mold forms watermarks. As with the chain and laid lines, the wire influences pulp density and results in a pattern detectable in the paper using transmitted light. The watermark in Figure 5 is located in the upper left corner, but it is difficult to decipher due to interference from the black printing ink. A significant drawback in identifying moldmates is the prevalence of non-watermarked papers. Indeed, among Rembrandt prints, approximately two-thirds lack a watermark or even a fragment of one.[18] Because images of watermarks are typically captured using beta radiography, which penetrates dense printing ink, as seen in Figure 6, and hundreds of beta radiographs of Rembrandt prints already exist, theoretically one could visually match papers using chain line intervals through superimposition.[19] Once again, however, the sheer number of images, not to mention the four possible orientations of a series of simple parallel lines in each image, made the task impossible to carry out by hand.

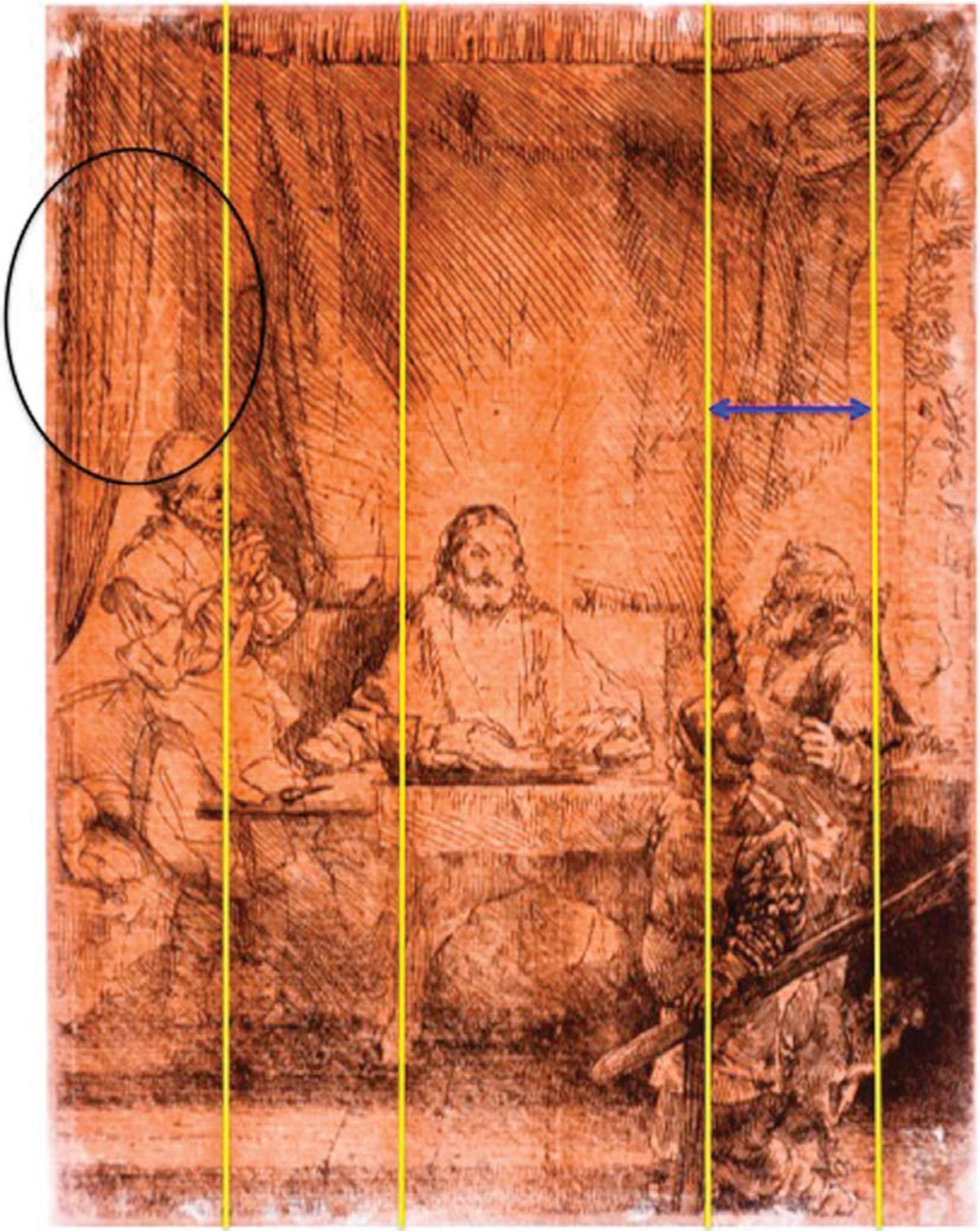

Figure 5. Rembrandt's etching *Christ at Emmaus*, 1654, (B87) is seen over transmitted light. The vertical chain lines, with the exception of the center chain line, are highlighted in yellow. Their intervals, as indicated by the blue arrow, vary slightly across the sheet. The watermark is partially visible in the black oval; however, it is obscured by the dense black printing ink. (Photo: L. Aikenhead)

Therefore, the possibility of using algorithms to automatically identify moldmates by marking, measuring, and matching only chain line intervals was explored.

Using sheets found in a blank ledger produced by the Austrian Kremsmunster mill dating from the 1570s or 1580s,[20] this project showed that closely related molds, even those used by a single maker in alternating sequence, could be recognized

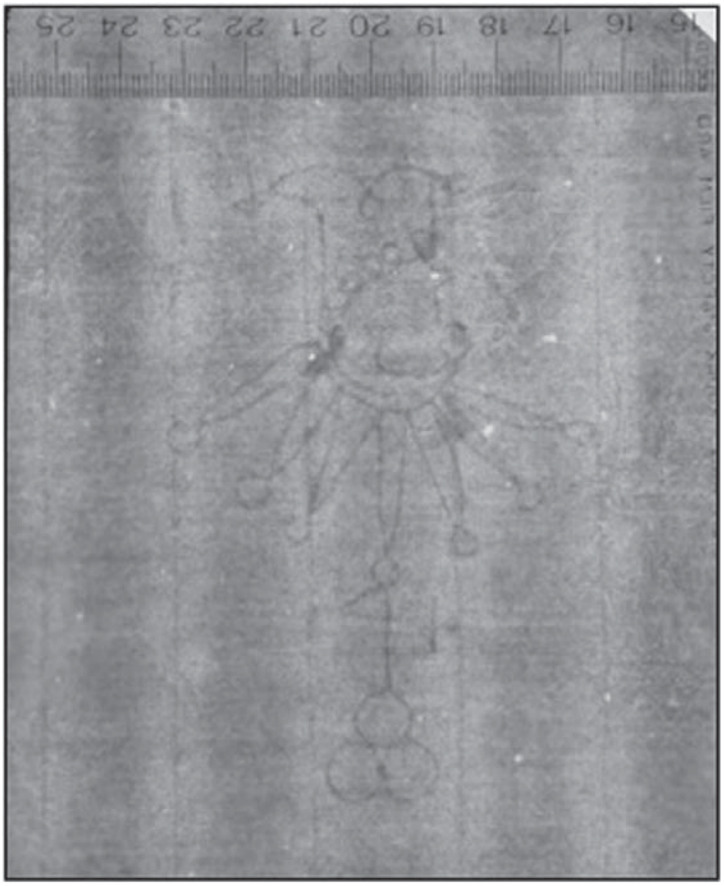

Figure 6. A beta radiograph of Rembrandt's etching, *Man in a Coat and Fur Cap Leaning Against a Bank*, c. 1630, (B151) captures precise variations in paper density without interference from dense printing ink. The watermark depicts a "foolscap." (Photo: L. Aikenhead)

as unique. Applied to the hundreds of images taken of Rembrandt prints from several collections, CLiP matching identified two newly discovered moldmates, affecting dating and attribution as well as providing fresh insight into Rembrandt's printmaking practices.

Watermark Identification in Rembrandt's Etchings (WIRE) Project

Begun in 2015, the Watermark Identification in Rembrandt's Etchings (WIRE) Project is an ongoing multidisciplinary collaboration among museums, university faculty, and students. Based at Cornell University, its aim is to promote Rembrandt scholarship through digital access to his printmaking papers. The chief innovation of WIRE was the development of an automated decision tree for the differentiation of watermarks, which incorporated an interactive and expandable online identification aid illustrated with images of all known Rembrandt watermarks.[21]

Users of WIRE are prompted to answer questions about the visible features of a particular watermark. The questions posed about these features, the answers to which guide the user through the decision tree, need to be answerable with high confidence in order to keep the user from taking the wrong branch due to an incorrect assessment. The string of questions and the associated answers leading to a specific watermark label provide a finite set of visible features that uniquely define that watermark and distinguish it from all others.

In this way, users are quickly moved through a decision tree to reach the appropriate sub-variant level designation taken from E. Hinterding's taxonomy of watermarks found in Rembrandt's etchings.[22] An example of one decision tree "branch" for a foolscap watermark with a five-pointed collar is seen in Figure 7.[23] Given the enormous number of variants of foolscap watermarks found in Rembrandt's prints, the advantages of automation are obvious.[24]

Not surprisingly, as of this writing, WIRE has brought to light 15 new watermarks in Rembrandt's papers.[25] Additional data, especially full-sheet-sized images of prints and drawings from Rembrandt and his circle from as yet untapped collections, will hopefully be provided by the Watermark Imaging Box (WImBo) Project (described below), which will significantly enhance the decision tree through many more images of greater clarity and completeness. Accumulating more images may also assist efforts to date papers lacking watermarks through chain line pattern (CLiP) matching.

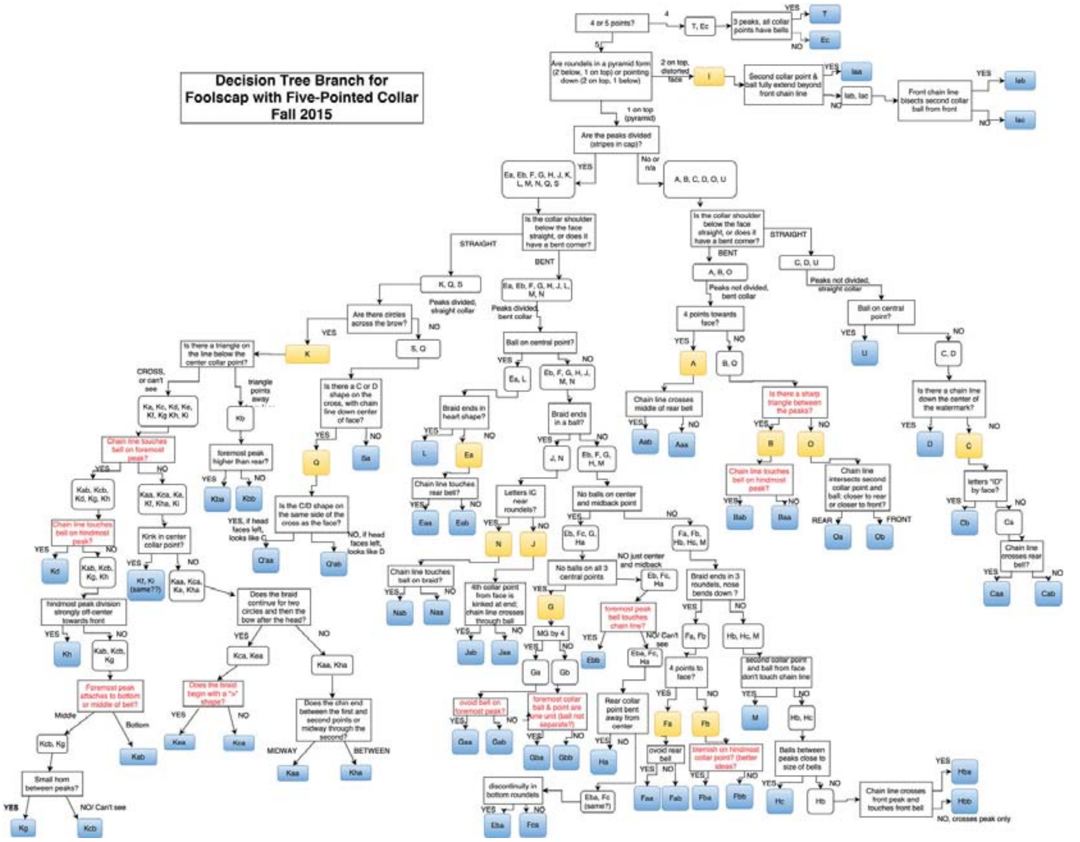

Figure 7. The decision tree branch diagram for Foolscap with Five-Pointed Collar watermark developed by Louisa Smieska and Alison McCann (*Lines of Inquiry: Learning from Rembrandt Etchings* [Ithaca, NY: Herbert F. Johnson Museum, Cornell University, 2017], 32).

Future Directions

Potential areas for further material studies are limitless, but all will require large datasets of images, such as radiographs, photographs, or other yet to be tried images, such as rubbings, taken under identical conditions, which can then be transformed into analogous digital images. To date, these datasets have either existed already or were readily compiled. Today, many known collections of computer-readable images of selected paintings (X-radiographs), etchings (beta radiographs), and photographic papers (raking light) have been accessed and analyzed. The difficulty of achieving the two critical requirements of a dataset – quantity and consistency of images – threatens to stall current investigations and prohibit others from starting.

Facilitating Data Collection across Collections

One final initiative, described below, is intended to simplify and standardize procedures for gathering images for computational analysis. We hope that this simplified procedure will decrease the chances that ongoing image/signal processing projects will stagnate due to the time, expense, and skill required to produce satisfactory images for analysis.

The Watermark Imaging Box (WImBo) Project

The Watermark Imaging Box (WImBo) Project is an inter-institutional collaboration to develop a low-cost portable system for imaging watermarks and chain lines in papers, with a special focus on the prints of Rembrandt and his pupils.[26] It is an extension of the two foundational projects described above, Chain Line Pattern (CLiP) Marking and Matching and Watermark Identification in Rembrandt's Etchings (WIRE).

Watermarks and their adjacent chain lines can provide scholars with important information about the origins of prints and their interrelationships. A significant effort has been devoted to the characterization of these attributes, yielding valuable insights for scholars, archivists, and conservators. However, existing imaging procedures have serious limitations – specifically the labor, time, and skills that are necessary to assemble a sufficient quantity of usable images. WImBo addresses these challenges through the development of a low-cost, easily used, portable system for imaging watermarks and chain lines in paper. The watermark imaging box (WImBo) would be delivered to collections of any size and enable untrained staff to rapidly produce satisfactory images from their print collections. These data, shared and networked, not only will provide a more comprehensible catalog of existing watermarks, but will also produce a dataset for the development of an automatic classification scheme. A step-by-step procedure for recording digital images of watermarks is being developed using papers taken from a seventeenth-century printed atlas by Joan Blaue (Dutch, 1599–1673) as a template. Figure 8 shows a beta radiograph of a page from the Blaue *Atlas Major* of 1662. We hope that the easier and faster production of digital images will result in richer datasets of images for future computational analysis. One intriguing direction might be to expand the reference set to include works by artists known to be

Figure 8. A beta radiograph of a page from the Joan Blaue's *Atlas Major* of 1662, selected for the test paper to be sent to imaging teams, depicts the internal paper structure to be documented for future image/signal processing. (Photo: L. Aikenhead)

working in the same studio, or to include related materials, for example papers used for Rembrandt's drawings as well as those used in his prints.

Conclusion

Through a look back at four case studies, this article addresses the lessons learned and the insights gained from more than a decade of collaboration between image/signal processing engineers, conservators, curators, art historians, university faculty, and students. We have found these cross-disciplinary collaborations somewhat unusual and not without difficulty. Visual arts-oriented participants need to acquire an appreciation of the range and limitations of the signal processor's tools in order for useful, viable, and novel tasks to be identified. Signal processing experts must learn to describe their skills without resorting to the language of mathematics, and to appreciate the intellectual depth of materials-based expertise. Computer-based tools, in particular the application of image/signal processing algorithms to digitized images, promise to extend the reach of traditional connoisseurship studies into heretofore unimagined areas of investigation and beyond. Hence, connoisseurship is strengthened rather than subverted by the use of computer technology.

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C. RICHARD JOHNSON, JR. is the Jacobs Fellow in Computational Arts and Humanities in the Jacobs Technion-Cornell Institute at Cornell Tech in New York City and the Geoffrey S.M. Hedrick Senior Professor of Engineering at Cornell University in Ithaca, NY. He founded the Thread Count Automation Project (TCAP) in 2007, the Historic Photographic Paper Classification (HPPC) Challenge in 2010, the Chain Line Pattern (CLiP) Marking and Matching Project in 2012, and the Project on Watermark Identification in Rembrandt's Etchings (WIRE) in 2015. Professor Johnson's research in the past decade on automated matching of manufactured patterns in art supports via canvas weave mapping, photographic paper texture classification, and laid paper moldmate identification has appeared in the *Burlington Magazine*, *Metropolitan Museum Journal*, *Studies in Conservation*, *Journal of the American Institute for Conservation*, *Art Matters*, *Journal of Historians of Netherlandish Art*, *International Journal for Digital Art History*, *Journal of Interactive Technology and Pedagogy*, and *IEEE Signal Processing Magazine*.

Notes

1 C. Richard Johnson, Jr. et al., "Image Processing for Artist Identification," *IEEE Signal Processing Magazine*, July 2008, 37–48.

2 As of this writing, this research is ongoing and unpublished.

3 Patrice Abry et al., “Wove Paper Analysis through Texture Similarities,” *Proceedings 50th Asilomar Conference on Signals, Systems, and Computers*, ed. Michael B. Matthews (Piscataway, NJ: Institute of Electrical and Electronic Engineering, 2016).

4 The first paper in art history and conservation literature proposing spectral methods such as Fourier analysis to thread counting of canvas painting supports appears in C. Richard Johnson, Jr. et al., “Advances in Computer-Assisted Canvas Examination: Thread Counting Algorithms” (paper presented at the 37th Annual Meeting of the American Institute for Conservation of Historic and Artistic Works, Los Angeles, CA, May 2009). The first paper in technical and engineering literature on the topic was Andrew G. Klein et al., “Algorithms for Old Master Painting Canvas Thread Counting from X-rays,” *Proceedings 42nd Asilomar Conference on Signals, Systems, and Computers*, ed. Michael B. Matthews (Piscataway, NJ: Institute of Electrical and Electronic Engineering, 2008), 1229–1233.

5 Don H. Johnson et al., “Do Weave Matches Imply Canvas Roll Matches?” (paper presented at the 38th Annual Meeting of the American Institute for Conservation of Historic and Artistic Works, Milwaukee, WI, May 2010).

6 Ernst van de Wetering, “The Canvas Support,” in *Rembrandt: The Painter at Work* (Amsterdam: University of Amsterdam Press, 1997), 90–131. Counting at 15 scattered locations in each direction is recommended, but fewer are more typical in practice.

7 A recent description of using freely available software to test the resulting weave maps for matching striped patterns appears in C. Richard Johnson, Jr. and William A. Sethares, “Hunting for Weave Matches: Computation in Art Scholarship,” in “Re-viewing Digital Technologies and Art History,” special issue, *Journal of Interactive Technology and Pedagogy* 12 (February 2018), https://jitp.commons.gc.cuny.edu/hunting-for-weave-matches-computation-in-art-scholarship/.

8 Walter Liedtke, C. Richard Johnson, Jr., and Don H. Johnson, “Canvas Matches in Vermeer: A Case Study in the Computer Analysis of Fabric Supports,” *Metropolitan Museum Journal* 47 (2012): 99–106. More recently the fourth weave match pair among Vermeer’s paintings was presented in C. Richard Johnson, Jr. and William A. Sethares, “Canvas Weave Match Supports Designation of Vermeer’s Geographer and Astronomer as a Pendant Pair,” *Journal of Historians of Netherlandish Art* 9, no. 1 (Winter 2017). doi:10.5092/jhna.2017.9.1.17.

9 Louis van Tilborgh et al., “Weave Matching and Dating of Van Gogh’s Paintings: An Interdisciplinary Approach,” *The Burlington Magazine* CLIV (February 2012): 112–22.

10 Pablo Perez D’Ors, C. Richard Johnson, Jr., and Don H. Johnson, “Velázquez in Fraga: A New Hypothesis about the Portraits of El Primo and Philip IV,” *The Burlington Magazine* CLIV (September 2012): 620–25.

11 C. Richard Johnson, Jr. and William A. Sethares, eds., “Counting Vermeer: Using Weave Maps to Study Vermeer’s Canvases,” *RKD Studies* (2017), countingvermeer.rkdmonographs.nl/.

12 This research is ongoing and unpublished.

13 C. Richard Johnson, Jr. et al., “Pursuing Automated Classification of Historic Photographic Papers from Raking Light Images,” *Journal of the AIC* 53, no. 3 (2014): 159–70; Patrice Abry et al., “Multiscale Anisotropic Texture Analysis and Classification of Photographic Prints,” in “Signal Processing for Art Investigation,” special issue, *IEEE Signal Processing Magazine* 32 (July 2015): 18–27.

14 Lee Ann Daffner, “The Proof Is in the Print: Characterization and Collaboration in the Thomas Walther Collection Project at the Museum of Modern Art,” *Topics in Photographic Preservation* 15 (2013): 25.

15 *Specimens: A Stevens-Nelson Paper Catalogue* (New York: Stevens-Nelson Paper Corporation, 1953).

16 Abry et al., "Wove Paper Analysis through Texture Similarities."

17 C. Richard Johnson, Jr. et al., "Hunting for Paper Moldmates among Rembrandt's Prints," in "Signal Processing for Art Investigation," special issue, *IEEE Signal Processing Magazine* 32 (July 2015): 28–37; C. Richard Johnson, Jr. et al., "Chain Line Pattern Matching and Rembrandt's Prints," in *Rembrandt and His Circle: Insights and Discoveries*, ed. Stephanie S. Dickey (Amsterdam: Amsterdam University Press, 2017), 319–34.

18 Erik Hinterding, *Rembrandt as an Etcher: The Practice of Production and Distribution*. 3 vols. (Ouderkerk aan den Ijissel: Sound & Vision, 2006), III: 27.

19 A far faster and more convenient technology is digital radiography, which does not require wet chemical processing in a darkroom and captures a larger image field. Digital radiography also eliminates interference from dense printing inks as occurs when using transmitted light. Concerns have been raised, however, about achieving the degree of resolution required for thread counting.

20 Peter Bower, personal communication.

21 Andrew C. Weislogel, C. Richard Johnson, Jr., and students, "Decision Trees and Fruitful Collaborations: The Watermark Identification in Rembrandt's Etchings (WIRE) Project at Cornell," in *Lines of Inquiry: Learning from Rembrandt's Etchings* (Ithaca, NY: Herbert F. Johnson Museum, Cornell University, 2017), 33–58; Andrew C. Weislogel et al., "The WIRE Project at Cornell: A Decision Tree-Based Approach for Accurate Comparison and Identification of Watermarks in Rembrandt's Etchings," *Proceedings 2018 Conference on Information Systems and Sciences* (Piscataway, NJ: Institute of Electrical and Electronic Engineering, March 2018).

22 Hinterding, *Rembrandt as an Etcher*.

23 Weislogel, Johnson, and students, "Decision Trees and Fruitful Collaborations," 32.

24 Thanks are extended to Daniel Biddle for his assistance; Hinterding, *Rembrandt as an Etcher*, II: 116–50 and III: 195–283.

25 Weislogel, Johnson, and students, "Decision Trees and Fruitful Collaborations," 45.

26 C. Richard Johnson, Jr., "WImBo – Watermark Imaging Box Project: A Digital Art History Data Acquisition Tool"; Paul Messier and Emily Frank, "Establishing Parameters: Building a Watermark Imaging Box Prototype"; Emily Frank et al., "The Computational Analysis of Watermarks: Setting the Stage for the Development of a Watermark Imaging Box (WImBo)"; Weislogel et al., "The WIRE Project at Cornell"; Pablo Ruiz et al., "Surface Suppression: A Visible-Light Transmission Approach to Watermark Imaging"; John Delaney and Murray Loew, "Use of Infrared Hyperspectral Imaging (960–1680 nm) and Low Energy X-Radiography to Visualize Watermarks," all in *Proceedings 2018 Conference on Information Systems and Sciences*, Princeton, NJ, March 2018.