Advances in Computer-Assisted Canvas Examination: Thread Counting Algorithms

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Presented May 21, 2009, PSG Program, 2009 AIC Annual Meeting, Los Angeles, CA

Revised June 18, 2009.

Thread Counts from X-rays in Art History

Scanning along the vertical and horizontal threads in a simple plain weave canvas and counting the number of crossing threads within 1 or 2 centimeters, results in descriptive data often collected by conservators or researchers in their technical study of paintings on canvas. Because the paint layers hide the original canvas on the front and, a lining canvas applied to the reverse to strengthen the painting support typically hides the back, x-rays are commonly used for thread counting.

As the initial ground layer fills the interstices in the canvas weave providing a smoother surface for the subsequent paint layers, the thickness of the ground layer can fluctuate being thicker in the valleys between threads and thinner where the threads overlap. Furthermore, this ground layer often contains a radio-absorbent material, e.g. lead white. Consequently, the thickly filled grooves between threads absorb more x-ray energy, and the regions where the threads overlap absorbs less energy. The resulting periodic variation in the x-ray image can, depending on the nature of the ground, reveal the light-to-dark-to-light transition corresponding to a count of one thread.

Over forty years ago, this thread count data obtained from x-rays was used in posing a technical art historical question[1]. The issue was whether or not there was a relationship between thread counts (i.e. weave density) and the size of paintings. The resulting examination of Dutch paintings up to 1700 in the collection of the Centraal Museum in Utrecht did not reveal a strong correlation.

A more comprehensive approach to the collection of thread count data by the Rembrandt Research Project, as reported in the 1980s[2], identified several paintings by Rembrandt and by assistants in Rembrandt's workshop from the same bolt, among other things portraits which were painted as companion pieces. The average, maximum, and

[1]M. E. Houtzager, M. Meier-Siem, H. Stark, and H. J. de Smedt, *Röntgenonderzoek van de Oude Schilderijen in het Centraal Museum te Utrecht*, 1967.

[2]E. van de Wetering, "The canvas support" in *A Corpus of Rembrandt Paintings, Vol. II*, 1986.

minimum counts across a painting form the “standard” data collected. The decision to declare two paintings as “probably from the same bolt” requires that average densities in one direction, the warp, differ by very little and the average densities in the other direction, the weft, differ by less than 1 th/cm. It also requires that the ranges from minima to maxima are similar.

In a recent study, thread counts together with the analysis of preparatory ground layers helped to place paintings by Gauguin or Van Gogh that were cut from the same bolt of coarse jute fabric[3]. From Van Gogh’s letters, we know that Gauguin purchased a 20m bolt of jute, persuading Vincent this once to paint on such coarse canvas. Identifying paintings with average thread counts of about 5.2 x 6.5 th/cm revealed 28 filling this 20m bolt of jute, some of which had been doubted as being painted by Vincent van Gogh. Thus, matching average thread counts can support investigations of authenticity.

The standard procedure for taking manual thread counts (using a light box and a magnifying eyepiece) is time-consuming, tedious, and sometimes beyond the scope of the human eye. Techniques developed in the field of computer-based image processing offer new tools to conservators. When processing a scanned image of a painting, the computer can call on a wealth of digital signal processing algorithms to assist in image analysis. From the periodic pattern of intensity values exhibited by the x-ray and related to the original canvas threads, various signal processing algorithms, such as a Fourier transform, can be applied to infer the nominal period of light to dark and back to light fluctuation exhibited in moving along the centerline of a thread from one crossing thread to the next[4].

Motivation: Investigation of major paintings facing treatment

Current investigation of two major paintings preceding decisions regarding conservation treatment raised questions regarding thread count densities. In order to try and answer these questions required the (automated) accumulation of massive amounts of thread count data.

One of these two paintings is in the collection of the Mauritshuis in The Hague. This seventeenth-century painting depicting *Saul and David* (1655-60) by Rembrandt and/or Studio (Bredius no. 526, Mauritshuis inv. no. 621) was cut-up and reassembled in the 1800s, as indicated by the hatched lines in Figure 1. The painting is now made up of ten pieces of canvas. Petria Noble has shown, however, that it originally consisted of two horizontal strips of canvas from the same bolt with a central seam[5]. At some time in the past, the two figures in the painting were cut apart and then re-joined using an

[3]K.-H. Lister, C. Peres, and I. Fielder, “Tracing an Interaction: Supporting Evidence, Experimental Grounds” in *Van Gogh and Gauguin: The Studio of the South*, ed. D. W. Druick and P. K. Zegers in collaboration with B. Salvesen, The Art Institute of Chicago/Van Gogh Museum, Amsterdam, 2001.

[4]A. G. Klein, D. H. Johnson, W. A. Sethares, H. Lee, C. R. Johnson, Jr., and E. Hendriks, “Algorithms for Old Master Painting Canvas Thread Counting from X-rays,” *Proc. 42nd Asilomar Conf. on Signals, Systems, and Computers*, October 2008 and D. H. Johnson, C. R. Johnson, Jr., A. G. Klein, W. A. Sethares, H. Lee, and E. Hendriks, “A Thread Counting Algorithm for Art Forensics,” *Proc. 13th IEEE DSP Workshop*, January 2009.

[5]P. Noble, *Saul and David* Discussion Meeting, Mauritshuis, 20 May 2008.

unusual crenellated seam. The original horizontal seam was properly aligned in this assemblage and several other canvas segments were added to the edges and the upper right. A narrow strip below the figure segment of David playing the harp is labelled “B” in Figure 1. Manual thread counts carried out by Michiel Franken of approximately 14 th/cm by 14 th/cm for the average thread counts of segment B and that of the figure segments above and below the seam support the suggestion that strip B was once part of the original painting. If strip B was part of the original, what was its orientation and location in the original composition? Vertically between the two figure segments? Horizontally above the current David segment? Vertically above the David segment?

The second painting raising questions on thread count to be considered in this paper is *Vincent's Bedroom in Arles* by Vincent van Gogh (F482[6], Van Gogh Museum, Amsterdam (Vincent van Gogh Foundation) inv. no. S47 V/1962) illustrated in Figure 2. A question of art historical interest involves a second painted version of the subject in the Art Institute of Chicago (F484)[7]. From Vincent's letters we know that the first study was painted in October 1888 and subsequently water-damaged in his studio. In September 1889 the (possibly repaired) original was copied by the artist. Some experts have questioned which version is which? One way to answer this question is to locate other pictures with secure dating originating from the same bolt of linen as F482.

These questions regarding issues of adjacent placement on the same canvas bolt of two now-separated pieces of canvas motivate the search for a technique that facilitates, not just comparison of average thread densities, but assessment of weave density pattern match. The direct approach of assembling full-coverage weave density maps for paintings that can be compared for continuity/similarity in their individual weave patterns is not feasible if the data is to be assembled with manual spot counts. A first attempt at automating a spot count is described by an example at the start of the next section. Subsequently, this automated counting procedure will be extended to counting in closely-packed spots across the entire painting, thereby generating the desired weave density maps.

Spot Thread Count

Consider *Falling Leaves* by Vincent van Gogh (F651, Van Gogh Museum, Amsterdam (Vincent van Gogh Foundation), 73.5 x 60.5 cm, November 1889) illustrated in Figure 3. The x-ray of the upper left corner of F651 is shown in Figure 4. The tree trunk contours are visible in the negative as inhibiting the passage of the x-rays more than adjacent parts of the painting.

A magnified swatch of a 600 dpi scan[8] of the x-ray of the upper left corner of F651 is shown in Figure 5. The same swatch but with the greyscale reversed (so white becomes black, black becomes white) in Figure 6 provides a quite readable image with regard to thread count. This swatch is approximately 430 horizontal pixels by 330 vertical pixels. Counting 21 vertical threads across the top edge of this swatch results in approximately

[6] All F numbers in this paper refer to the catalog numbers in J.-B. de la Faille, *The Works of Vincent van Gogh: His paintings and drawings*, 1970.

[7] `http://www.artic.edu/aic/collections/artwork/28560`

[8] All x-ray greyscale scans used in this paper were collected at 600dpi by Frans Stive, Technical Documentalist, Conservation Department, Van Gogh Museum.

Figure 1: Construction of the canvas support of *Saul and David* by Rembrandt and/or Studio, 1655-1660, 130.5 x 164.5 cm (Mauritshuis, The Hague, inv. no. 621)

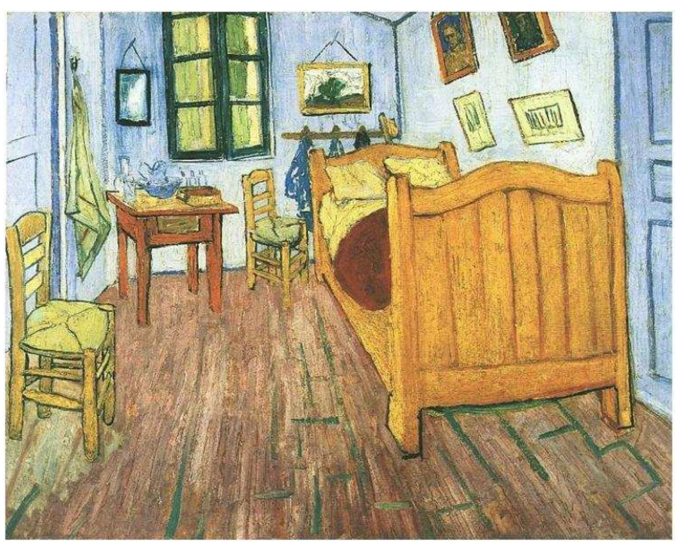

Figure 2: *Vincent's Bedroom in Arles* (F482) by Vincent van Gogh, Van Gogh Museum, Amsterdam (Vincent van Gogh Foundation)

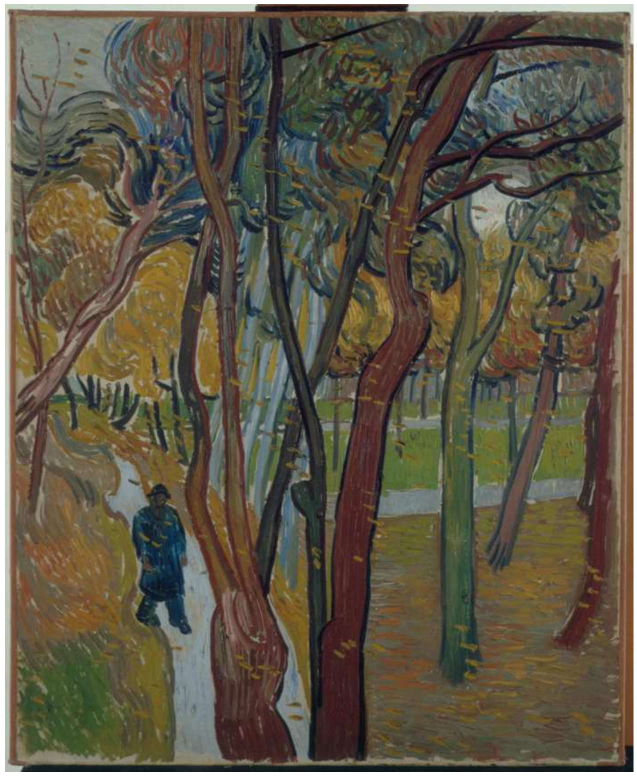

Figure 3: *Falling Leaves* (F651) by Vincent van Gogh, Van Gogh Museum, Amsterdam (Vincent van Gogh Foundation)

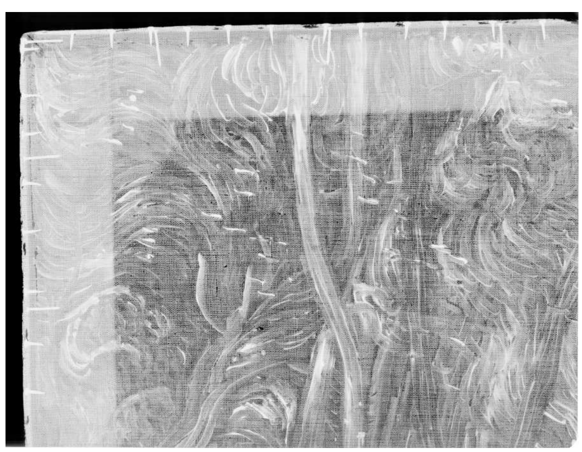

Figure 4: X-ray of upper left corner of F651

Figure	row index	col index	H (th/cm)	V (th/cm)
6	50	180	11.8	17.4
9	240	140	11.1	16.8
10	290	400	11.4	16.4
average	-	-	**11.4**	**16.9**

Table 1: Automated spot counts for F651

21/430= 0.0488 threads/pixel. As a 600 dpi scan corresponds to approximately 236 pixels/cm, the vertical thread count for the swatch in Figure 6 is approximately 11.5 threads/cm. Similarly, for the 24 horizontal threads crossing the right edge of the swatch in Figure 6 the thread count is approximately 24(236)/330=17.2 threads/cm.

Figure 7 plots the intensity levels of the approximately 430 pixels in row 50 of Figure 6. Starting at the first peak on the left near index 0, counting “one” with the next peak at approximately index 25, and continuing to count produces an integer count of 21 gaps (or thread widths) between peaks. Attempting to repeat this peak-counting procedure for the column 180 data in Figure 8 proves problematic. Due to the much darker/lower “peaks” of every other thread, a convincing count is difficult, though 24 seems close.

As the intensity pattern is roughly periodic its Fourier series composition can be expected to have a strong term that corresponds to the average period of this particular signal. For a set of sampled data, the Discrete Fourier Transform (DFT)[9] can be used to numerically determine the strengths of sinusoidal components of the data across a range of frequencies. In June 2007, this realization spawned a simple semi-automated procedure involving the following steps:

- Draw horizontal/vertical line across scanned x-ray image.
- Compute discrete Fourier transform (DFT) of horizontal/vertical intensity curve.
- Ascertain frequency location – within suitable range – of DFT magnitude maximum.
- Convert to threads/cm.

Using this crude automated procedure on the three swatches from F651 in Figures 6, 9, and 10 produces Table 1. The average of the three measurements from different areas of the x-ray of F651 compares quite favorably with the museum hand count record of 11.5 $\times$ 17 th/cm. To accelerate the development of more sophisticated algorithms accommodating weave tilt relative to the x-ray image and varying weave clarity across an x-ray, a competition was organized for a more sophisticated spectrum-based algorithm.

To provide an accurate dataset of thread counts to be used to determine the relative performance of candidate algorithms, a graphical user interface (gui) was built that prompts the user to draw a line along a thread and records end coordinates of the test line and then queries the user for a manual count of crossing threads. Using this gui, a team of Cornell University students counted over 900 spots (with verification) in over

[9] J. H. McClellan, R. W. Schafer, and M. A. Yoder, *Signal Processing First*, chpt. 13, Pearson Prentice Hall, 2003.

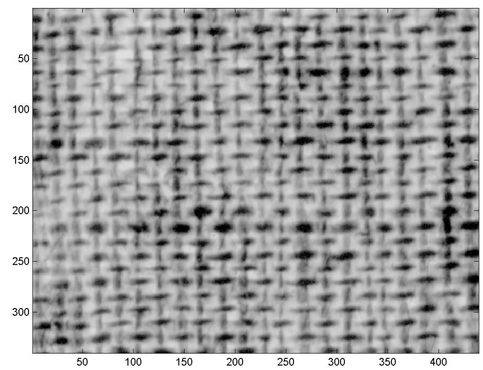

Figure 5: Magnified swatch from x-ray of F651

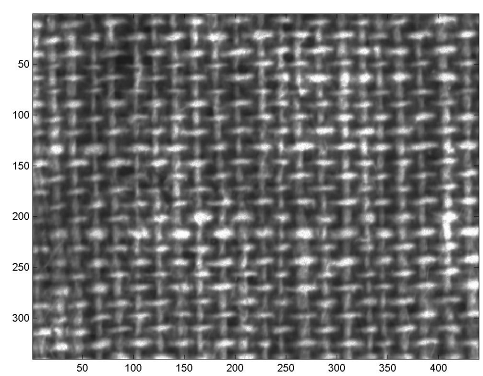

Figure 6: Reversed greyscale image of swatch in Figure 5

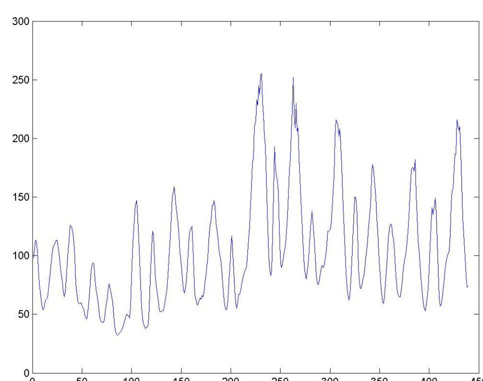

Figure 7: Row 50 intensities from Figure 6

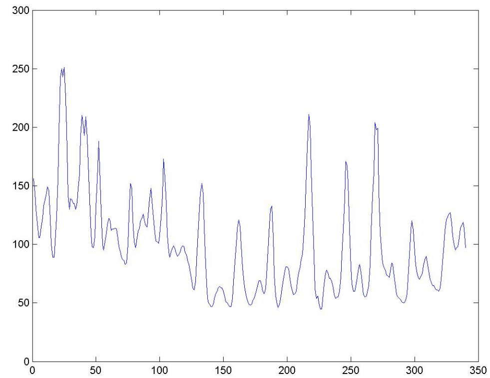

Figure 8: Column 180 intensities from Figure 6

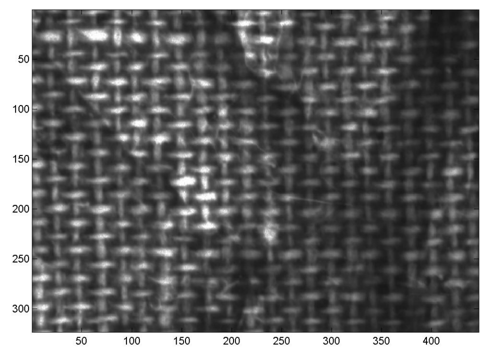

Figure 9: Reversed greyscale image of a second swatch from F651

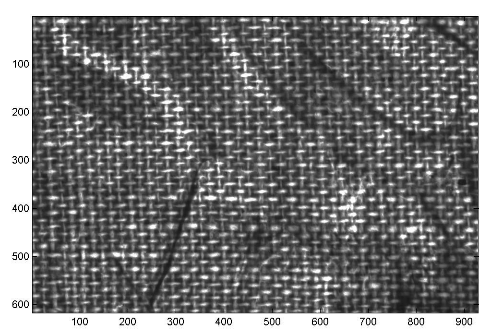

Figure 10: Reversed greyscale image of a third swatch from F651

20 paintings by Vincent van Gogh as a test base for candidate algorithms. Each spot was counted independently by two students, and was considered "verified" when their answers agreed.

Candidate algorithms were created by researchers in electrical and computer engineering departments at Rice University, University of Wisconsin, and Worcester Polytechnic Institute and were tested on this database in May 2008[10]. The best algorithms achieve 95% of counts within ±1 th/cm of verified spot count. From the museum records of average manual thread counts compiled by Ella Hendriks for the paintings in the test set, 83% of the average counts for paintings were within ±1 th/cm of average of the verified spot counts for that painting. This suggests that the automated techniques are of comparable quality to the traditional manual methods.

Weave Density and Thread Angle Maps

With this evidence of satisfactory accuracy, we set up our best-performing algorithm to provide the average count inside any 1/2 inch square swatch. Then we wrote a program that would repeat this calculation for every 1/2 inch square on 1/4 inch centers across an entire x-ray film. These values can then be color-coded to indicate the deviation in the local thread count from the average measured across the painting. The resulting color values could be assembled into a map of the weave density deviation variation, and superimposed, if desired, over the corresponding portion of the x-ray.

Let us consider *Portrait of an Old Man* by Vincent van Gogh (F205, Van Gogh Museum (Vincent van Gogh Foundation), 44.5 x 33.5 cm, painted in Antwerp on 7 or 8 December 1885) as shown in Figure 11. The scanned (600 dpi) x-ray of this painting is shown in Figure 12. The superimposed colors indicating the deviation in horizontal threads/cm from the painting average of 13.3 threads/cm appear in Figure 13. This figure also includes a color bar for interpreting the horizontal thread density values. A similar plot for the vertical threads is shown in Figure 14.

The first thing to notice in these two weave density maps are the stripes. Figure 13, which illustrates the density of horizontally oriented threads exhibits horizontal stripes of the same color. Figure 14 exhibits similarly stripy behavior, but with vertical stripes. This is to be expected. The weaving process is such that the closeness of small groups of threads to each other continues across the entire piece of fabric. The expectation is that the variation in the density pattern of the horizontal (vertical) threads down (across) a piece of canvas would be matched by a horizontal (vertical) neighbor.

A byproduct of our calculations of average thread densities in each small square is a calculation of the average angle of these threads relative to the horizontal (or vertical) orientation of the x-ray. Using a similar color coding to that in the weave density maps produces thread angle maps, as shown in Figure 15. The two images in Figure 15 illustrate the deviation from horizontal and vertical of the (nearly) horizontal and (nearly) vertical threads, respectively. The associated color bar indicates a range of +8 to −8 degrees from the associated horizontal or vertical. The most obvious feature is the variation in the horizontal thread angle across the top of F205. The horizontal threads are oriented down (blue), then flat (yellow), then up (red), then down (blue), then flat

[10] J. S. Ng, "A Common Platform for Thread Count Automation," MEng Report, Cornell University, August 2008.

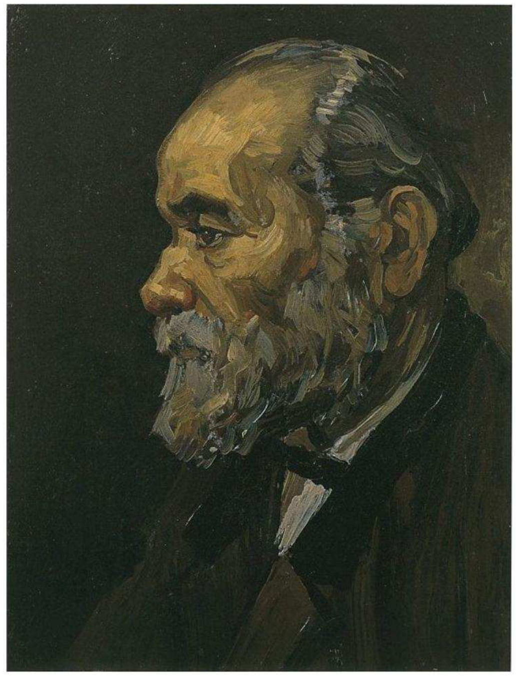

Figure 11: *Portrait of an Old Man* (F205) by Vincent van Gogh, Van Gogh Museum (Vincent van Gogh Foundation)

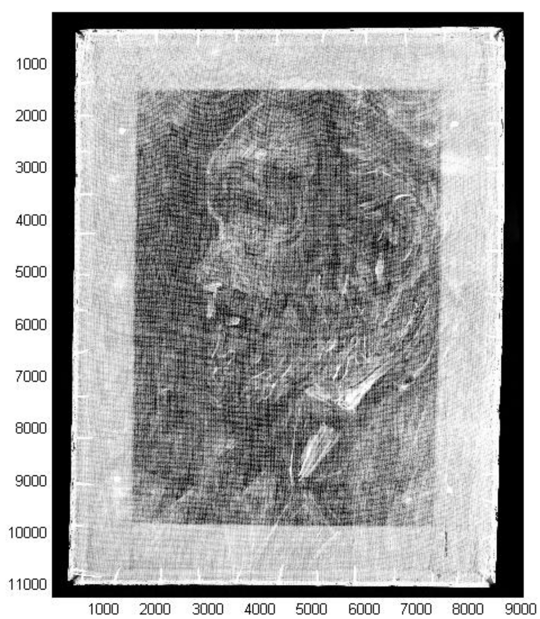

Figure 12: Scanned x-ray of F205

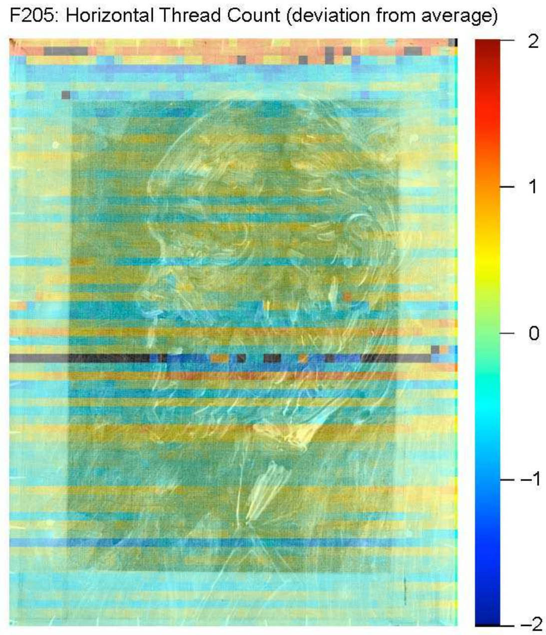

Figure 13: Horizontal weave density deviation map for F205

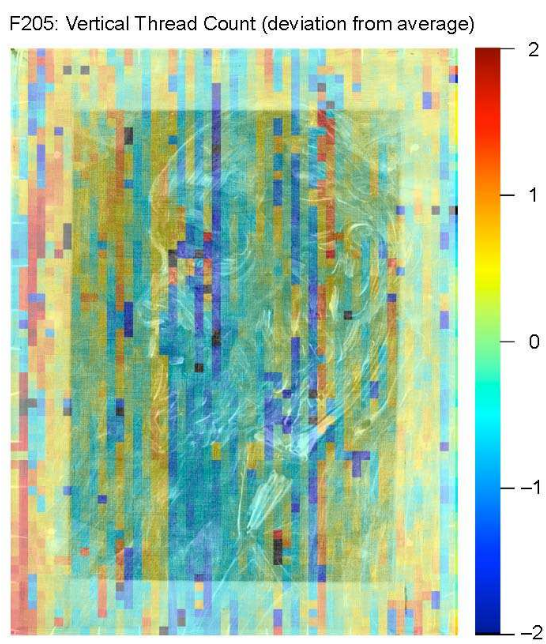

Figure 14: Vertical weave density deviation map for F205

horizontal	max	min	avg	std
F205	14.6	12.1	**13.3**	0.4
F260	14.6	11.6	**13.2**	0.5
vertical	max	min	avg	std
F205	18.0	14.1	**16.0**	0.6
F260	17.4	14.0	**15.7**	0.5

Table 2: Weave density map count data for F205 and F260

(yellow), then up (red), etc. This repeated variation from blue through yellow to red and back through yellow to blue is an indication of a particular sort of scalloped deformation known as primary cusping caused by the pull of the canvas edges where these are nailed or otherwise fixed to the priming frame. The vertical thread map for F205 in Figure 15 illustrates less pronounced cusping down its right side. The other noteworthy feature of the horizontal weave density map for F205 is that the right edge is predominantly red, which indicates an upward tilt to all of the horizontal threads at the right edge.

The painting *Backyards in Antwerp* by Vincent van Gogh (F260, 44.0 x 33.5 cm, painted in Antwerp between December 9 and late February 1885, Van Gogh Museum (Vincent van Gogh Foundation)) illustrated in Figure 16 is suspected as being cut from the same piece of ready-primed canvas as that used for F205. There is documentary, but also, physical, evidence to support this idea, including similar average manual thread counts and the comparable build-up and composition of ground layers[11]. Its horizontal weave density map appears in Figure 17 and its vertical weave density map in Figure 18. The thread angle maps for F260 are provided in Figure 19. While there is no primary cusping in the horizontal threads across the top of F260, there is mild cusping in the vertical threads along its right side. The horizontal threads show an upward tilt at the right edge, though less so than with F205.

The current method of determining whether pieces of canvas originate from the same bolt is to decide if the basic descriptors (maximum, minimum, average, and standard deviation) of the average thread counts in the 1/2 inch squares covering each painting are sufficiently similar. This data is provided in Table 2. The average thread counts for horizontal threads are within 0.1 th/cm of each other. For vertical threads the average values are separated by only 0.3 th/cm and the respective minimum and maximum values are no more than 0.6 th/cm apart. The corresponding standard deviations are within 0.1 th/cm of each other. The close similarity of these thread count descriptors provides support for the contention that F205 and F260 are from the same canvas bolt.

Given the weave density maps, we can attempt to line up their characteristic patterns to provide even stronger evidence that these two paintings come from the same bolt of canvas. While the side-by-side alignment of F205 and F260 does not produce a convincing match, their vertical alignment one above the other, as shown in Figure 20, does.

Furthermore, the thread angle maps provide evidence that F205 and F260 are neigh-

[11] E. Hendriks and L. van Tilborgh, *New Views on Van Gogh's Development in Antwerp and Paris: An Integrated Art Historical and Technical Study of his Paintings in the Van Gogh Museum*, PhD Thesis, University of Amsterdam, 2006, vol. 1, p. 102 and vol. 2, p. 29.

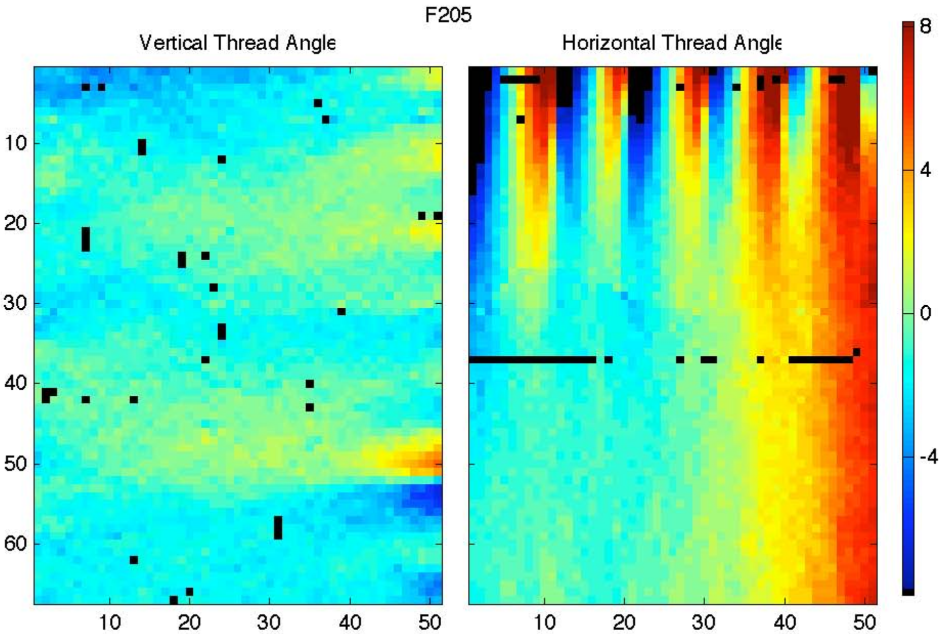

Figure 15: Thread angle maps for F205

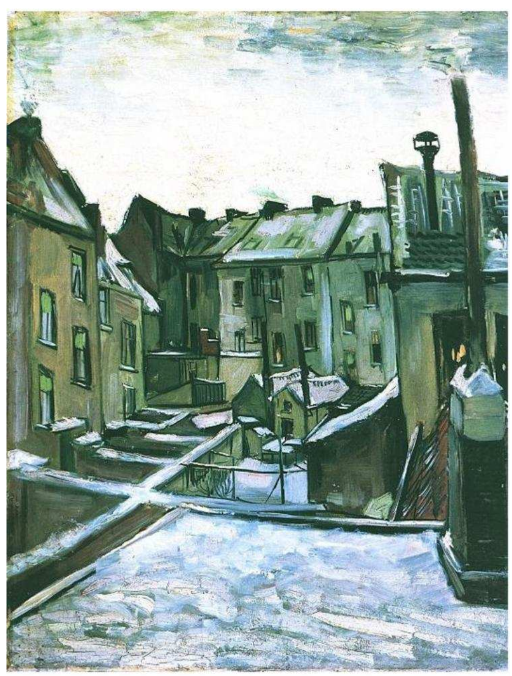

Figure 16: *Backyards in Antwerp* (F260) by Vincent van Gogh, Van Gogh Museum (Vincent van Gogh Foundation)

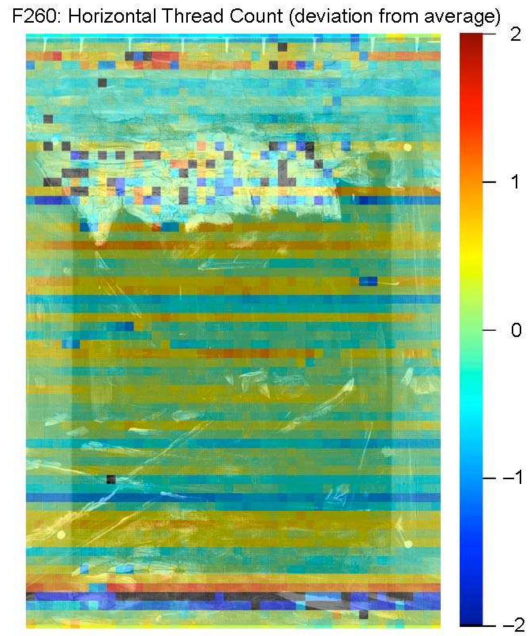

Figure 17: Horizontal weave density deviation map for F260

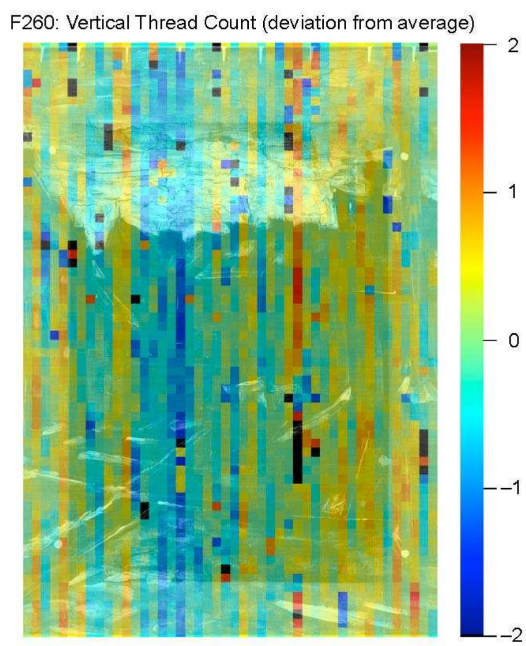

Figure 18: Vertical weave density deviation map for F260

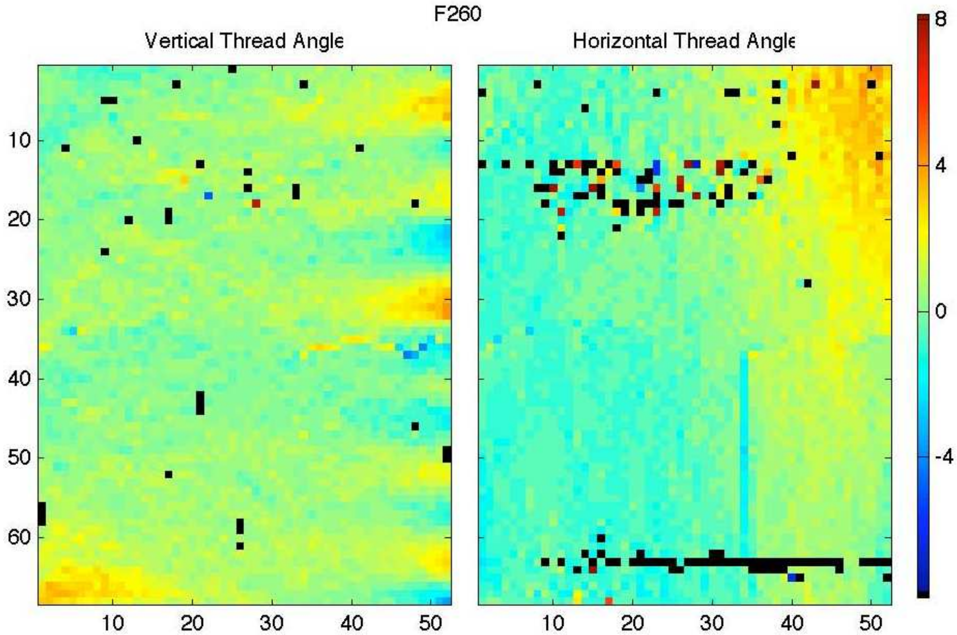

Figure 19: Thread angle maps for F260

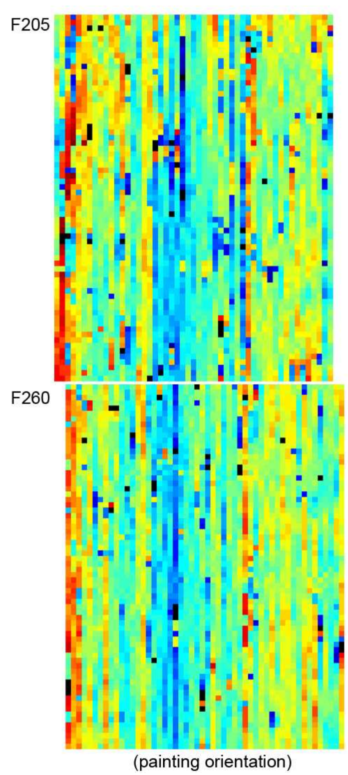

Figure 20: Vertical alignment of the vertical weave density deviation maps for F205 and F260 reveals a match

bors on the stub end of the canvas bolt, as illustrated in Figure 21. Both F205 and F260 show an upward tilt of the horizontal threads towards their right edge. This is more marked for F205, which is located closer to the edge of the canvas as primary cusping is evident along its top edge. It appears that this warp edge[12] of the canvas bolt was tensioned and fixed to the priming frame before the weft edge was, causing the uneven pull visible in the corner of the horizontal thread angle map.

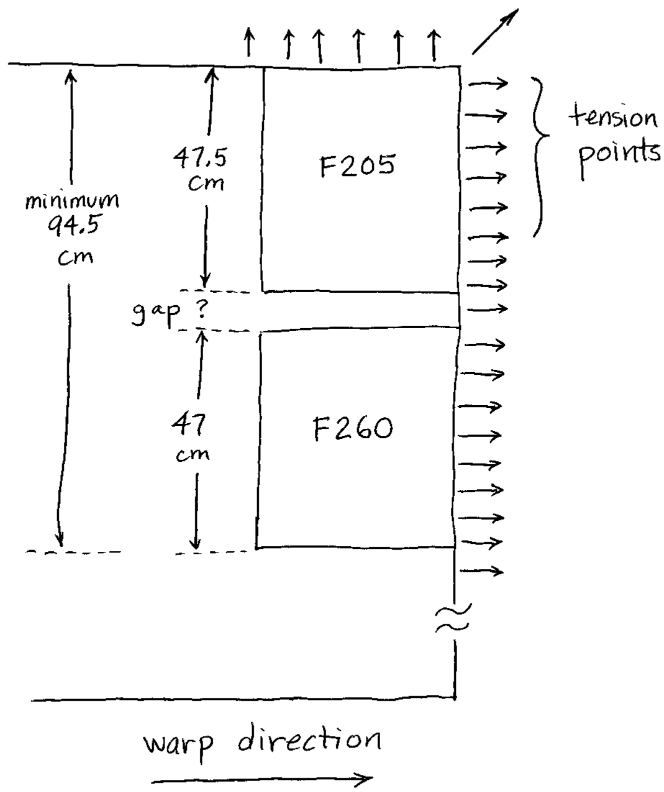

Figure 21: Canvas bolt stub end hypothetical layout of F205 and F260

Concluding Remarks

Automatically generated weave density maps and thread angle maps offer powerful new forensic tools. These maps and the associated statistics of the accumulated data can offer assistance in determining warp and weft directions of the canvas threads, visualizing cusping, and evaluating boltmate status. Motivation for our development of thread counting tools used to produce weave density and thread angle maps was provided by

[12]The warp direction is aligned with the longer dimension of the original canvas bolt and the weft with the shorter one. Typically, due to the method of manufacture, warp threads have less variation in their local weave density values than weft threads. In our case, comparison of the vertical and horizontal standard deviations in Table 2 indicates that the difference in weave density regularity is noticeable for F205, with the horizontal threads showing less variability with a lower standard deviation, but not apparent for F260. The presence of primary cusping across the top of F205 is a more convincing marker of warp designation of the horizontal threads.

our study of Rembrandt's *Saul and David* and van Gogh's *Vincent's Bedroom in Arles*. However, more work is needed before the problems associated with these works can be resolved.

Thorough manual and computer-assisted thread counts for the figure portions and strip B in the *Saul and David* confirm that strip B with an average count H:14.03 x V:13.98 th/cm closely matches the average weave densities in the original canvas portions of V:13.98 x H:14.06 th/cm. However, the narrowness of strip B together with its weave irregularities (i.e. aperiodicities) and potentially large gap between strip B and the remaining original canvas portions complicate matching the weave density patterns of strip B and the figure portions, leaving it inconclusive (so far).

For the Amsterdam version of *Vincent's Bedroom in Arles* (F482) a unique identifier, i.e. a denser than average (by 2 th/cm) horizontal stripe, was discovered with the composition of the weave density maps[13]. However, no convincing weave match has yet been found with the few paintings now in museums that date from exactly the right fall 1888 or fall 1889 time frame. The search continues.

In this paper, we have presented a case study (of two paintings by Vincent van Gogh) using automated thread counting software that can provide extensive information useful in canvas research. This case study demonstrates that this new computer-based tool will allow conservators to gain deeper insight from canvas examination than traditional manual thread counting procedures allow.

Computer-assisted spot-counting software is available for free distribution to interested museums. Software to be used by conservators for automatically generating full weave density and thread angle maps and performing weave match tests is currently under development.

The authors would like to thank our technical (ECE) collaborators Don Johnson (Rice University), Bill Sethares (University of Wisconsin), and Andy Klein (Worcester Polytechnic Institute) and our x-ray scanner Frans Stive (Van Gogh Museum).

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[13]E. Hendriks, L. Jansen, I. Fielder, M. Geldof, M. van Bommel, L. Megens, C. R. Johnson, Jr., D. H. Johnson, M. Menu, E. Ravaud, and J. Salvant, "A Comparative Study of Vincent van Gogh's Bedroom Series," *Proc. The National Gallery Technical Bulletin 30th Anniversary Conf.: Studying Old Master Paintings - Technology and Practice*, September 2009.