Document Flash Thermography

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***Abstract*—This paper presents an extension of flash thermography techniques to the analysis of documents. Motivation for this research is to develop the ability to reveal covered writings in archaeological artifacts such as the Codex Selden or Egyptian Cartonnage. An emphasis is placed on evaluating several common existing signal processing techniques for their effectiveness in enhancing subsurface writings found within a set of test documents. These processing techniques include: contrast stretching, histogram equalization, image filters, contrast images, differential absolute contrast (DAC), thermal signal reconstruction (TSR), principal component thermography (PCT), dynamic thermal tomography (DTT), pulse phase thermography (PPT), and fitting-correlation analysis (FCA). The ability of flash thermography and the combined techniques to reveal subsurface writings and document strikeouts will be evaluated. In addition, the differences in flash thermography parameters are evaluated for most effective imaging of the two document subsets.**

I. Introduction

Flash thermography, a subset of pulsed thermography or pulsed video thermography, is a technique commonly used for non-destructive testing and evaluation (NDT&E) in a variety of materials, including concrete [1][2][3], high-density polyethylene [4], CFRP/GFRP aerospace composites [5][6], wood and wood-based materials [7], and adhesive bond evaluation [8][9]. This technology has yet to be applied to documents or archaeological artifacts to reveal covered writings; for instance those found in the Codex Selden or Egyptian cartonnage [10]. This paper develops the theory and application of flash thermography to documents, and lays a foundation for the application of this technology to archaeological artifacts in general. Development of flash thermography for this application will provide the capability to non-destructively reveal covered writings — advancing the knowledge about ancient cultures without damaging irreplaceable artifacts.

Motivation for this research derives from the desire to analyze ancient archaeological documents with a non-destructive approach. Specifically of interest is the imaging of subsurface writings that may be obscured with a layer of some type of material. Example ancient documents this technology could be applied to include, but are not limited to: palimpsests from the Roman Empire, Mesoamerican codices, and Egyptian cartonnage. Also of interest is use of flash thermography to possibly detect textual changes, such as strikeouts, where older ink writings are covered with a more recent layer of ink writing.

II. Prior Research

Several imaging techniques have been developed to enhance surface writing and under-writing contained in archaeological artifacts. Infrared (IR) reflectography has been used in the analysis of paintings [11][12] and papyrus (cartonnage) [13]. The main application of IR reflectography is to see under-drawings beneath a layer of paint. With IR reflectography, a constant light source is used to excite the material. An IR imager captures an IR reflectogram detailing the different optical properties of the overlaying paint and the underwriting [14]. In addition to IR reflectography, transient thermographic techniques, including pulsed thermography, have also been used to analyze paint layers in artwork such as frescoes [15][16] and general artwork [17][18][19][20]. A comparative study was performed comparing pulse thermography, lateral heating thermography, and modulated thermography for the analysis of frescoes[16]. Pulsed thermography was shown to be successful in areas where X-radiography, infrared reflectography, and UV examination had been unsuccessful [17]. Pulsed thermography has not yet been applied to the evaluation of ancient documents or other types of archaeological artifacts.

A common technique for analyzing ancient documents is multi-spectral imaging (MSI). MSI has been shown to be effective for enhancing contrast between underwriting, overwriting, and the document substrate[21][22]. MSI is performed by imaging documents in narrow spectral bands of light, allowing the spectral signature of the different document materials to be evaluated. Processing techniques for MSI images include, but are not limited to, the use of Markov random fields[21], spectral clustering[23], principal and independent component analysis[22], and linear spectral mixture analysis[22][24].

The use of MSI has been successful in revealing obscured writing on the Archimedes palimpsest [24], carbonized scrolls [23], oxyrhynchus papyri [25], and the dead sea scrolls [26][27]. MSI is most effective enhancing writing that appears on or near the surface of the document. For example, the effectiveness of MSI to reveal the under codex within the Codex Selden was shown to be limited [28]. Another technique currently under investigation is X-Ray Fluorescence Imaging (XRF) [29].

III. Description

Active thermography is an effective tool in non-destructive evaluation. Active thermography includes modulated (lock-in), pulsed, stepped, or vibro-thermography[30]. This work limits its investigation of flash thermography, a subset of pulsed thermography, as applied to the analysis of documents.

Flash thermography works by thermally exciting a surface with a flash-lamp discharge followed by using a high-speed infrared camera to create a stream of the transient surface temperature images [31]. The surface temperatures cool as the heat is transferred through the document; however, when a material defect is reached a portion of the heat is reflected back to the surface. This creates a relatively "warm" (or "cold") spot on the surface that can be detected with the infrared imager. Deeper subsurface detection is achievable over IR reflectography or MSI and can be applied to more general documents. Signal processing techniques are used on the video stream of flash thermography images in order to enhance defect contrast and determine quantitative parameters within the document.

Based on current literature, flash thermography has not been applied to the analysis of documents. This paper applies flash thermography to documents and analyzes the effectiveness of current processing techniques when applied to documents.

IV. Experiment Methodology

A. Test Document Construction

The test documents were constructed to simulate ancient documents and were constructed out of a combination of materials. Substrate layers of card-stock and papyrus were used. Three ink types were evaluated, carbon based, iron gall, and ball point pen. Finally, the ink layers were covered with either a substrate layer, a paint layer, or a mineral gesso mixture. For evaluating strikeouts, the base layer of ink was then covered with an additional layer of ink of the same type.

B. Equipment Used

The high-speed, mid-IR camera used was a Lockheed-martin/Santa Barbara Focal plane model SBF 180 with a custom data collection computer and software. The flash units were SunPak Pro-System 622 Super. The camera was set horizontally and aimed at an angled mirror. This mirror was used to image the test document lying flat on the surface of a table. The flash units were then elevated above the sides of the document on the table with the flash heads pointed toward the test document. Two camera lens notch filters were used, a $3.42 - 4.05\mu m$ and a $2.65 - 3.24\mu m$ filter were evaluated. A sampling frequency of 87 Hz was used for the acquisition of all images.

V. Processing Techniques

A. Background Theory

The majority of algorithms process the data on a pixel by pixel basis evaluating the time series of each pixel separately without taking into account the lateral diffusion process. These time series represent the post-flash surface temperature decay of the material through time. It is often assumed that the diffusion into the material is significantly greater than the lateral diffusion and therefore the lateral diffusion can be neglected. This allows the diffusion into the document to be described using the equation for one-dimensional thermal diffusion as given by

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{1}$$

where T is the temperature and α is the thermal diffusivity of the material. For an ideal impulsive heat flux, the response for a semi-infinite surface is [32]

$$T(x,t) = \frac{Q}{e\sqrt{\pi t}} e^{-\frac{x^2}{4\alpha t}} \tag{2}$$

where $e = \sqrt{k\rho c}$ is the thermal effusivity of the material and is determined through the thermal conductivity, k, mass density ρ, and specific heat c. Q is the quantity of energy absorbed by the surface. The time is represented by t and the depth into the material is given by x. Since the infrared imager can only evaluate surface temperatures, Equation 2 can be evaluated at $x = 0$, resulting in the surface temperature decay given by

$$T_{surf}(t) = T(0,t) = \frac{Q}{e\sqrt{\pi t}} \tag{3}$$

However, the thermal imager only gives relative temperatures, therefore substituting $\Delta T_{surf}(t) = T_{surf}(t) - T_{ambient}$ for $T_{surf}(t)$, where $T_{ambient}$ is the pre-flash initial temperature of the sample. The response is thus more accurately described relative to the thermal imager.

$$\Delta T_{surf}(t) = \frac{Q}{e\sqrt{\pi t}} \tag{4}$$

Equation 4 provides a basis for many of the algorithms discussed in this section. This equation can be further simplified to[31]

$$\Delta T_{surf}(t) = T_{init}\sqrt{\frac{T_s}{t}} \tag{5}$$

where T_{init} is the value of the surface temperature at one time step, T_s, and is given by

$$T_{init} = \frac{Q}{e\sqrt{\pi T_s}} \tag{6}$$

B. Contrast Stretching

Contrast stretching is a point processing technique used to expand the dynamic range of an image to increase visibility of image features. This technique is used to enhance visibility of the raw thermal images or as a post-processing step for the other techniques described in this section. The simplest form of contrast stretching is image normalization which is given by

$$I_N = (I - c)\left(\frac{b-a}{d-c}\right) + a \tag{7}$$

where I is the input image with initial range $[c, d]$ and I_N is the normalized output image in the desired range $[a, b]$. Note the normalization process is used on individual frames within the time sequence. Image normalization is greatly affected by dead pixels and other outliers in pixel values. To compensate, a useful technique is to saturate the top 1% and bottom 1% of pixels. This can be implemented with the Matlab function `imadjust`.

C. Histogram Equalization

A histogram in digital images is a discrete function that counts the number of pixels within a given intensity level. The histogram is a discrete estimation of the probability density function (PDF) of the image. In histogram equalization, the goal is to transform the histogram of the input image into an image with a uniformly distributed histogram. This enhances the image contrast resulting in the increased ability to see details within an image. The transformation takes place on each pixel and can be represented by [33]

$$s = T(r) \tag{8}$$

where s is the equalized pixel value, r is the input pixel value, and $T(r)$ represents the transformation performed on r to obtain s. The mapping of the PDF of r to s is obtained by

$$p_s(s) = p_r(r)\left|\frac{dr}{ds}\right| \tag{9}$$

which states that the PDF of the output image is dependent on the input intensities and the transformation function used. The transformation is given by

$$s = T(r) = (L-1)\int_0^r p_r(w)dw \tag{10}$$

where L represents the number of intensity levels and w is the dummy variable of integration. Equation 10 represents the cumulative distribution function (CDF) of the image. It will now be shown the transformation given in Equation 10 results in the transformed image having a uniform distribution. First, the value of $\frac{dr}{ds}$ needs to be found and put into Equation 9.

$$\begin{aligned} \frac{ds}{dr} &= \frac{dT(r)}{dr} && (11) \\ &= (L-1)\frac{d}{dr}\left[\int_0^r p_r(w)dw\right] && (12) \\ &= (L-1)p_r(r) && (13) \end{aligned}$$

using this result in Equation 9 to find

$$\begin{aligned} p_s(s) &= p_r(r)\left|\frac{1}{(L-1)p_r(r)}\right| && (14) \\ &= \frac{1}{L-1} \qquad 0 \le s \le L-1 && (15) \end{aligned}$$

Equation 15 shows $p_s(s)$ to be a uniform distribution for the continuous case. For discrete digital images, transformation function becomes

$$s_k = T(r_k) = \frac{L-1}{MN}\sum_{j=0}^{k} n_j \qquad k = 0, 1, 2, ..., L-1 \tag{16}$$

where MN is the total number of pixels in the image, and n_k is the number of pixels that have intensity r_k. A plot of $p_r(r_k)$ versus r_k results in the histogram of the image. Since the histogram is a discrete approximation of the PDF and no new intensity levels can be created, perfectly flat histograms are rare in practical images[33]. Histogram equalization can be implemented in Matlab using the `histeq` function.

The histogram equalization process is used to post-process the images after running the other algorithms described in this section or to better evaluate the raw, unprocessed images.

D. Image Filters

Two image filters have been found useful in noise reduction in flash thermography data, a median filter [33] and a Gaussian low-pass filter [30]. Median filters are useful for removing salt and pepper noise. The median filter is a nonlinear filter which ranks the pixels within a neighborhood, replacing the center pixel with the median of the intensity values. The median filter has advantages over a mean filter because it is not affected by outliers (such as those caused by dead pixels) and better preserves edges within the image. The median filter is common in imaging software and can be implemented in Matlab using the `medfilt2` function.

The Gaussian filter is a frequency domain filter that assumes the image has a limited bandwidth and any spatial frequencies above the given bandwidth are the result of noise. Since image noise tends to be characterized by high spatial frequencies, a low-pass filter can be used to reduce the noise content in the image. A derivation of the Gaussian filter for thermal images can be found elsewhere [30]. The Gaussian filter can be implemented in Matlab using the `fspecial` command to create the filter and the `imfilter` command to apply the filter to the image.

E. Contrast Images

There are several definitions of contrast commonly used: absolute, running, normalized, and standard contrast. Each of the techniques are outlined below and are summarized from [30]. The absolute contrast is defined as the excess temperature over a defect free region at a given time t and is defined as

$$C_{abs}(t) = T_{defect}(t) - T_{sound}(t) \tag{17}$$

where T is the temperature over a defect region and a sound region, respectively. This increases the contrast and improves the visibility of the defective region over the sound region.

The running contrast reduces the effects of differences in surface emissivities and is defined as

$$C_{run}(t) = \frac{C_{abs}(t)}{T_{sound}(t)} \tag{18}$$

Note if the contrast images are post-processed with the contrast stretching techniques given previously, then the absolute contrast and running contrast are the same.

The normalized contrast can be computed with respect to the end of the thermal process, at time t_{end}, or the time of temperature max, t_{max} (for pulsed thermography, this is the first frame). The normalized contrast is defined as

$$C_{norm}(t) = \frac{T_{def}(t)}{T_{def}(t_{max})} - \frac{T_{sound}(t)}{T_{sound}(t_{max})} \tag{19}$$

where t_{max} can be replaced with t_{end}.

Finally, the standard contrast was developed to eliminate contributions from the surrounding environment by subtracting out pre-flash information given at time t_0.

$$C_{std}(t) = \frac{T_{defect}(t) - T_{defect}(t_0)}{T_{sound}(t) - T_{sound}(t_0)} \tag{20}$$

Each of these contrast images require an operator to choose the sound area.

F. Differential Absolute Contrast (DAC)

The contrast methods described previously are greatly affected by non-uniform heating of the surface and requires an operator to choose a sound area. Differential Absolute Contrast (DAC) [34] removes the operator from choosing a sound area and is therefore more robust when non-uniform surface heating occurs. Let t' be the time at which the defect begins to appear in the sequence and $\Delta T(t)$ represent the frame at time t. Define the sound area as

$$\Delta T_{snd}(t') = \Delta T(t') \tag{21}$$

From Equation 2, the value of $\frac{Q}{e}$ can be solved for

$$\frac{Q}{e} = \sqrt{\pi t'}\Delta T(t') \tag{22}$$

using this result in Equation 2, the ideal sound area can be found as

$$\Delta T_{snd}(t) = \sqrt{\frac{t'}{t}}\Delta T(t') \tag{23}$$

using this definition of the sound area, combined with the definition of absolute contrast given in Equation 17, the DAC image is given by

$$DAC(t) = \Delta T(t) - \sqrt{\frac{t'}{t}}\Delta T(t') \tag{24}$$

Since the input pulse is not an ideal impulse, small differences in pulse length can also be accounted for within different parts of the image. Defining t_e to be the amount of error in pulse length, a fit can be done in the logarithmic domain to find t_e and compensate for the error. The error compensated DAC image is then found as

$$DAC(t-t_e) = \Delta T(t-t_e) - \sqrt{\frac{t'-t_e}{t-t_e}}\Delta T(t'-t_e) \tag{25}$$

where the values of t_e can vary over every pixel. The definition of the sound area can also be used with the other definitions of contrast given previously. A technique called Interpolated Differential Absolute Contrast (IDAC) has been developed to remove the need of the operator to choose a time t' [35]. In addition, thermal quadrapole theory has been used to extend the validity of DAC to later times [36][37].

G. Thermal Signal Reconstruction (TSR)

The TSR algorithm [38][39] processes each individual pixel's time sequence, rather than each frame as a whole. The time response data can be linearized by transforming it to a logarithmic domain. The logarithmic transform of Equation 4 is

$$\ln(\Delta T_{surf}(t)) = \ln(\frac{Q}{e}) - \frac{1}{2}\ln(\pi t) \tag{26}$$

This implies that, regardless of the thermal properties of the material, the logarithmic decay response will be a straight line with a slope of $-\frac{1}{2}$ for an ideal, defect-free region. Thus, the defect can theoretically be detected without the use of a reference region by evaluating deviations from this ideal slope. The linearized sequence can be least squares fit to a Nth order polynomial

$$\ln[\Delta T_{surf}(t)] = \sum_{n=0}^{N} a_n[\ln(t)]^n \tag{27}$$

It was found a fifth or sixth order polynomial effectively acts as a low-pass filter, smoothing the data without reconstructing the noise [39]. Advantages of using the reconstructed data include a significant improvement in sensitivity, a reduction of blurring, increased depth range, decreased memory requirements, and improvements in signal-to-noise performance. To increase defect contrast and limit the effects of blurring caused by lateral diffusion, the derivatives of the analytical model for the data are taken. The derivatives allow for detection of an earlier time of maximum contrast, thus reducing lateral diffusion blurring. However, the diameter of the subsurface defect must be greater than its depth beneath the surface for the lateral diffusion to be effectively ignored [40].

The pixel time histories are differentiated using the expressions [39]

$$\frac{d\ln(\Delta T_{surf}(t))}{d\ln(t)} = \sum_{n=0}^{N} n a_n \ln(t)^{n-1} \tag{28}$$

$$\frac{d^2\ln(\Delta T_{surf}(t))}{d\ln(t)^2} = \sum_{n=0}^{N} n(n-1) a_n \ln(t)^{n-2} \tag{29}$$

The reconstructed signal and its time derivatives are transformed into the linear time domain by exponentiating the function as shown

$$\Delta T_{surf} = \exp\left(\sum_{n=0}^{N} a_n[\ln(t)]^n\right) \tag{30}$$

$$\frac{d\Delta T_{surf}(t)}{dt} = \exp\left(\sum_{n=0}^{N} n a_n \ln(t)^{n-1}\right) \tag{31}$$

$$\frac{d^2\Delta T_{surf}(t)}{dt^2} = \exp\left(\sum_{n=0}^{N} n(n-1) a_n \ln(t)^{n-2}\right) \tag{32}$$

The resulting derivative time sequences can be output and analyzed. Quantitative defect depth analysis can be estimated as described in [41][42][31].

H. Principal Component Thermography (PCT)

Principal Component Thermography (PCT) [43][44] uses singular value decomposition (SVD) to reduce data to a compact statistical representation of the spatial and temporal variations relating the contrasts associated with underlying material defects [43]. In flash thermography data, a time series of 2D image frames are stored, essentially creating a 3D data set. In order to perform PCT, a raster-like operation must be performed to create a 2D representation of the 3D data. Given the original data is loaded into an image cube with dimensions N_x, N_y, and N_t; where the N_x and N_y describe the pixel dimensions of each frame and N_t describes the number of frames. This image cube is then transformed into a matrix A with dimensions $M \times N_t$, where $M = N_xN_y$. The column vectors of M are standardized to correct for individual detector pixel characteristics. This standardization is achieved through

$$\hat{A}(n,m) = \frac{A(n,m) - \mu_n}{\sigma_n} \tag{33}$$

where

$$\mu_n = \frac{1}{N_t} \sum_{n=1}^{N_t} A(n,m) \tag{34}$$

$$\sigma_m^2 = \frac{1}{N_t - 1} \sum_{n=1}^{N_t} (A(n,m) - \mu_n)^2 \tag{35}$$

Any $M \times N$ matrix can be decomposed through Singular Value Decomposition (SVD) into the following elements

$$A = U \Gamma V^T \tag{36}$$

where Γ is a diagonal matrix containing the singular values of matrix A, U and V contain the left and right singular vectors of A. In this application, the matrix U contains a set of orthogonal basis functions that describe the spatial variations within the data and the matrix V^T contains the corresponding characteristic time behavior which can be used to estimate defect depths. By reversing the raster transformation applied to create A on U, the empirical orthogonal functions (EOF) of the data are produced. An analysis was done showing the first two modes tend to contain 99% of the variance within the data, although some leakage does occur in the following modes [44]. The first mode describes a response similar to that of a uniform slab. However, the second mode, characterizes a nonuniform field created by material anomalies, and therefore has been named the primary contrast mode or PCM. A drawback of the PCT algorithm is that it may enhance some defects at the cost of other defects [45].

The flaw depth is estimated from the second principle component (PC), contained in the matrix V^T, and by knowing the thermal diffusivities of the material using the technique developed in [43][46]

I. Dynamic Thermal Tomography (DTT)

Two versions of the DTT algorithm were implemented, those referred to as classical and reference free [47][48][45]. In the classical algorithm, an operator must define a reference region. In the implementation here, the operator selects five pixels identifying the background and the time sequences of those pixels are averaged to reduce noise in the created reference signal, T_{ref}. The frames were first normalized by dividing each frame with the first post-flash frame. The difference between each pixels time sequence and the reference signal is taken

$$\Delta T(x,y,t) = T(x,y,t) - T_{ref}(t) \tag{37}$$

Next, the maximum difference (C_{max}), and the time which that maximum occurs (t_{max}), is found to create a maxigram and a timegram. This creates synthetic images that samples the values at their “optimal” time. The corresponding transit times in the timegram can be used to create tomographic slices of the document.

The reference free approach is similar to the classical approach with the need for having an operator choose pixels removed. Instead, different order polynomials are fitted to the (normalized) temperature response. The low order polynomial will only reflect general behavior of the material, where a higher order will include the behavior of defects. In this case, a third and a sixth order polynomial was used. The difference for each pixel can be found through

$$\Delta T(x,y,t) = T_h(x,y,t) - T_l(x,y,t) \tag{38}$$

The corresponding maxigram and timegram can now be found from the new ΔT. The defect depth can be found using the procedures described elsewhere [49].

J. Pulse Phase Thermography (PPT)

PPT is a combination of two forms of thermography, flash (pulse) thermography and modulated thermography. Flash thermography deploys a pulse of heat energy into the specimen and analyzes the transient decay of surface temperature. Alternately, in modulated thermography the specimen is submitted to a sinusoidal temperature stimulation in which standing thermal waves are created within the material. These standing thermal waves are analyzed by their magnitude components and phase shift with respect to the reference modulation. The magnitude images are proportional to local optical and infrared surface features; however, the phase shift images are relatively independent of these features. As a result, the phase image can probe roughly twice the thickness given by the magnitude image and are therefore the output of interest [50].

PPT uses the principle that a pulse of energy in the time domain contains all frequencies in the frequency domain. Since the input pulse is not an ideal delta function, but rather a rectangular pulse, the resulting frequencies are given by a sinc function [30]

$$F(f) = A_p T_s \operatorname{sinc}(\pi f T_s) \tag{39}$$

where f is the frequency variable, A_p is the pulse amplitude, and T_s is the sampling rate. In effect, all frequencies are being analyzed simultaneously in PPT rather than a single frequency as in modulated thermography [51]. In PPT, the discrete Fourier transform of each pixel's time series is computed using the well known equation.

$$F(u) = \frac{1}{N} \sum_{n=0}^{N-1} h(x) e^{-j2\pi ux/N} = R(u) + jI(u) \tag{40}$$

where $R(u)$ and $I(u)$ are the real and imaginary parts, respectively, of the transformed sequence, $F(u)$. The magnitude and phase responses is obtained from the transformed data through

$$\phi(u) = \tan^{-1}\left(\frac{I(u)}{R(u)}\right) \tag{41}$$

$$|F(u)| = \sqrt{R(u)^2 + I(u)^2} \tag{42}$$

resulting in a series of magnitude and phase difference output images. As previously stated, the phase images are usually of interest due to their increased resistance to surface features. The resulting series of images correspond to frequencies ranging from 0 to $1/\Delta t$, where Δt is the time interval between images. The lower the frequency, the deeper the image is able to probe. For the phase offset images, it was found most useful if the maximum phase offset, ϕ_{max}, was found for each pixel time history and output into a single resulting image [51].

Another form of PPT developed is computed using the Wavelet Transform (WT) in place of the Fourier Transform (FT). The advantage is that wavelets preserve time information of the signal and are correlated to defect depth, allowing quantitative evaluations [52][53]. Another technique uses the Hough Transform to retrieve the blind frequencies, which are correlated with the defect depth [54]. It was also found that pre-processing the images with the reconstruction technique given in TSR improved the depth resolution of PPT [55].

K. Fitting-Correlation Analysis (FCA)

The FCA algorithm [56] begins by reconstructing the signal using the technique specified in TSR. The reconstructed signals are then evaluated to see how closely they match either an "ideal" signal or a signal chosen by an operator. The ideal signal can be found using Equation 5 or Equation 23. Two methods are used to evaluate the closeness of the fit, the correlation coefficient and the angle cosine. The correlation coefficient is calculated as

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}} \tag{43}$$

and the angle cosine as

$$\cos\theta = \frac{\sum_{i=1}^{n} x_i y_i}{\sqrt{\sum_{i=1}^{n} x_i^2}\sqrt{\sum_{i=1}^{n} y_i^2}} \tag{44}$$

The resulting correlation coefficient image and the angle cosine image are output.

L. Other Techniques Not Included

There are many minor variations of the above techniques not included. Other techniques that are not included, but are the focus of future work, include techniques developed from the Hough transform [57][58], inverse transmission line matrix fitting [59], techniques which account for lateral diffusion within the document [60][61][62][63], flaw detection approach [47][64], neural networks [47], nonlinear fitting [47], adaptive thermal tomography [65][47].

VI. Conclusions

The conclusions drawn from the results of the test are outlined below. These results focus on the best parameters for acquiring the data with an emphasis on the effectiveness of the processing procedures.

A. Data Acquisition Parameters

Several flash thermography parameters were evaluated in acquiring the data sets and will be discussed in the following section.

1) Pulse Amplitude: The first parameter evaluated was the amplitude of the input energy pulse. In general, the deeper the ink or less thermally diffusive the covering layer is, the larger the amplitude flash required to stimulate proper depths. With a set-up of four synchronized flash units, ink was able to clearly be revealed, after processing, through layers of paper, cardstock, and papyrus. However, there was not enough energy to penetrate a thin cardboard layer.

For document strikeouts, it was found a large pulse amplitude was not necessary. Of more concern is the length of the input pulse.

2) Pulse Length: Although often modeled as an impulse function, in reality the energy input into the document tends to have a sharp rise followed by an exponentially decaying tail. For deeper subsurface writings, this tail doesn't have a strong negative effect on the detection process and can even aid in detection by allowing the document to absorb more energy. For document strikeouts, this pulse tail becomes a concern due to the high thermal diffusivities of common inks. It was found that using a shortened pulse better results were achieved.

3) Sampling Frequency: For the data set acquired, a sampling frequency of approximately 87 Hz was used. This was found to be fast enough for subsurface defects; however, a faster sampling rate is required for document strikeouts due to the higher thermal diffusivities of the inks.

B. Lens Filters

Two notch filters were evaluated in the collection of the acquired data set, a $3.42 - 4.05\mu m$ and a $2.65 - 3.24\mu m$ lens filter. The $3.42 - 4.05\mu m$ filter greatly outperformed the $2.65 - 3.24\mu m$ for subsurface defect detection. However, the $2.65 - 3.24\mu m$ filter showed some potential in better revealing document strikeouts. Further investigation is still needed.

C. Pre- and Post-Processing

Since many of the processing algorithms depend on the temporal surface temperature decay, care must be taken in preprocessing the image sequence to not alter the temporal decay. As such, the contrast stretching and enhancement techniques discussed cannot be used effectively as pre-processors. These techniques are essential post-processors to further enhance the processed results. If the document has a low spatial frequency and the ink writing is large enough (at least twice the filter window size), then a Gaussian or median filter can be used as a pre-processor to remove noise and the effects of dead pixels. A median filter is essential to remove noise when using the $2.65 - 3.24\mu m$ lens filter. These filters are useful in post-processing to remove outlying pixel values that sometimes occur in processing or to smooth any noise introduced in the processing. The signal reconstruction technique given in the TSR algorithm has proven to be an effective tool in noise reduction and can be used prior to any of the other techniques discussed. In addition, contrast techniques can be used as pre-processor or post-processing technique. A common preprocessing step is to subtract a pre-flash image from every frame within the data set to correct for any differences in ambient temperatures or surface thermal effusivity. Finally, another useful image visualization technique is to create false color images from the grayscale data. Since the human eye is more sensitive to color, using a continuous color map can increase the ability to visualize defects. This can be accomplished by using the `colormap` function in Matlab. A continous color map such as the *jet* colormap has been found to provide false color without a mosaic effect [30].

D. Processing

Each of the algorithms discussed were implemented and their effectiveness evaluated. Due to the nature of the work, a quantitative measure for effectiveness is not available. In addition, different processing techniques work better for different document structures. Therefore the results presented are generalized based off the experience of processing the flash thermography on a variety of constructed data sets using different parameters. All the algorithms were developed for and work best on homogeneous, single layer materials. Since ancient documents are often constructed with a variety of materials and may have multiple layers, the evaluation will focus on the effectiveness of processing the more complex structures. Each algorithm will be discussed in turn.

1) Contrast Stretching and Enhancement: The techniques discussed here such as image normalization and histogram equalization can be used to successfully process the raw images. However, the thermally based processing algorithms discussed in the following sections usually provide better defect visualization. The advantage of these techniques are when they are used as a post-processor.

2) Contrast Definitions and Differential Absolute Contrast : The Differential Absolute Contrast (DAC) technique proved to be the most effective contrast technique, depending on proper selection of the sound area by the operator. The advantage of this technique is that by choosing t' values relating to defects at different depths, certain defects could be emphasized over others. This is advantageous when applied to documents of complex structure because the writing layer can be selected and emphasized. DAC should be included in processing of flash thermography applied to documents.

3) Thermal Signal Reconstruction (TSR): The signal reconstruction and noise reduction of this technique proved to be immensely helpful in processing. The TSR algorithm proved to be one of the better techniques giving consistently good results and is better able to reveal some of the deeper defects. TSR also showed potential in revealing document strikeouts.

4) Principal Component Thermography (PCT): For single layer, homogeneous materials, PCT is very effective in revealing the sub-surface layer of ink. As the document structural complexity increased, the PCT algorithm tended to enhance some defect areas at the cost of others, proving to not give consistently good results in revealing the sub-surface ink.

5) Dynamic Thermal Tomography (DTT): DTT proved to be one of the least effective algorithms in revealing sub-surface inks or detecting document strikeouts.

6) Pulse Phase Thermography (PPT): The PPT phase images proved to be one of the deepest probing algorithms. Due to the increase resistance to surface features, the PPT phase images also proved to be effective in more complex document structures in revealing the sub-surface writing. As expected, the lower frequency phase images tended to probe the deepest. For document strikeouts, the opposite conclusions were drawn. The amplitude images were preferred over the phase images because of their sensitivity to surface features. In addition, higher frequency amplitude images were preferred because they did not probe the surface as deeply. PPT is an essential processing tool for analyzing documents.

7) Fitting-Correlation Analysis (FCA): The FCA algorithm performed moderately in all tests. In general, the TSR, PPT, or DAC algorithms outperformed the FCA algorithm.

E. Comparison With Multi-Spectral Imaging (MSI)

Flash thermography has been shown to enhance visibility of surface writings with similar effectiveness as MSI. In addition, flash thermography is able to reveal near surface writings which MSI fails to reveal.

VII. Future Work

The next step in this work is to acquire ancient documents of interest, such as a piece of Egyptian Cartonnage, to validate the process. Other existing processing techniques will be analyzed in addition to those presented here. Since the processing techniques do not always emphasize the ink over other flaws in complex document structures, then new techniques are being investigated.

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