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IMAGE ENHANCEMENT OF TEMPERATURE SENSING THERMAL PAINT COLOR CONTOUR USING A DESIGNED FILTER FOR EFFICIENT AUTOMATIC INTERPRETATION

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Abstract- Temperature sensitive thermal paints find a wide application in thermal mapping of engine components operating at high temperatures with a major reference to aerospace applications. In a view to increase the operating efficiencies the modern gas turbines are designed to operate at elevated temperatures which are just few degrees below the material withstanding temperature. An accurate thermal mapping technique is required to anticipate the behaviour of the engine component material to avoid failure before completion of the service life. A range of contact and non contact type of sensors are available for thermal mapping of gas turbine components but certain inherent disadvantages of these sensors make them unable to perform satisfactorily in the harsh and aggressive environment of the gas turbine. The literature survey reveals that the thermal paints have the advantages of both the contact and non contact sensors and can be qualified as a better alternative for thermal mapping of gas turbine engines. Thermal paints are identified as effective thermal sensors for thermal mapping of complex gas turbine hot section components compared to conventional thermometry techniques. Thermal paints change their color permanently when exposed to elevated temperatures generating a color pattern with distinguished color profiles with each color representing its formation temperature. Flow of exhaust gases over the thermal painted hot section modules deposit a carbon soot over their surface during testing. The color pattern obtained by heating the components gets distorted due to the soot deposition leading to discrepancies in the thermal paint data interpretation. This article presents the performance of a filter designed to denoise the degraded image of thermal paint color contour making it suitable for further data interpretation automatically.
Keywords- thermal mapping.

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Introduction

Operation of aero-engines at elevated temperatures to increase the working efficiency is a common practice in design of modern gas turbine engine leading to damage mechanisms like creep, low cycle fatigue, high cycle fatigue and thermo-mechanical fatigue causing premature failures. Exhaustive thermal mapping of the engine components operating in real conditions is essential to ensure a reliable performance of the engines in harsh environments. Conventional thermometry fails to generate a complete thermal map of the components with critical geometries and rotating at heavy speeds in aggressive environments. Labour intensive pains have to be taken to mount the contact type thermal sensors like thermocouples and thermistors on the components generating stresses within them and also are intrusive in nature. The cable network is quite complex and source of errors at the read out units. Non contact type of sensors like optical pyrometry is a quite challenging option for temperatures measurements due to limitations in generating a proper database of exact radiation emission characteristics of different materials for a range of temperatures. Thermal paints are comparatively preferred alternative temperature sensors due to their capability of generating a complete thermal gradient on the component surface. Also providing a visual record of the temperature distribution is an additional advantage. Thermal paints exhibit a range of color profiles when heated at different temperature with each color representing the temperature at which it is formed. Also there are no mounting issues even on the most complex geometries compared to the thermocouples and temperature plugs where mounting is quite difficult and permanently distorts the components geometry. Alternatively the thermal paints can be coated easily as good as regular paints and removed using common paint recovers without any damage to the component material and geometry. The tested components can be reused for further operation making it a cost effective solution.

During the engine operation for thermal paint test the exhaust gas flowing on the painted components deposits carbon soot on their surface distorting the transformed thermal paint color pattern leading to discrepancies in thermal paint data interpretation. An automatic interpretation algorithm is developed to interpret the thermal paint data by digital image processing technique. Image of the thermal paint color pattern after testing is acquired and given as an input to the developed software which analyses the image pixel by pixel and gives the temperature as the output. Deposition of the carbon exhaust on the paint colors during testing generates a noisy image incapable of data interpretation. A filter is designed to remove the effect of carbon deposition on the paint color, denoising the image and making it suitable for further interpretation.

Thermal paint data analysis

Conventionally the thermal paints are interpreted manually. The prominent colors are easily identified but the human vision system fails to identify the colors with weak contrast leading to incomplete interpretation. Furthermore the analysis varies with the interpreter resulting in a subjective mapping. An interpretation algorithm is developed using Digital Image Processing for a standard and accurate thermal mapping. The thermal paint is calibrated by applying it on the test coupons and heating every coupon at an interval of 15°C. The color profiles of all the coupons are recorded and stored in a calibration database file assigning every coupon color with its respective temperature value. On selection of a image pixel point on the thermal paint contour image for temperature identification, the pixel value is compared with the pixel values of the calibration database and its closest match is been found .The temperature value of this calibration database pixel is assigned to the image pixel point. Automation in thermal paint interpretation using Digital Image Processing generates a more accurate and reliable thermal map. Deposition of carbon soot and oil traces distorts the paint contour and lead to discrepancies in the data interpretation. A filter is designed to enhance the contour image by removing the effect of the soot and oil depositions.

Filtration Issues

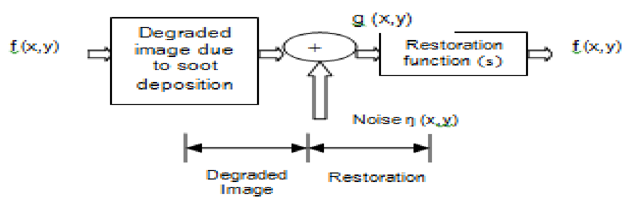


Fig. 1- Image Filtration

Image enhancement is the process of manipulating an image so that the result is more suitable than the original for a specific application. The word "Specific" is specific because the enhancements techniques are problem oriented. Thus, for example a method that is quite useful for enhancing x-ray images may not be the best approach for enhancing satellite images taken in the infrared bond of electromagnetic spectrum[(1)]. There is no general theory of image enhancement. During visual interpretation the viewer decides which is the best method for image enhancement by his inherent judgement and while dealing with machine perception, for example, in an automated character recognition system, the most appropriate enhancement method is the one that gives the best recognition ratio. There are two different approaches of image enhancement, the spatial domain approach and the transform (frequency) domain approach. The image processing in the spatial domain category is based on direct manipulation of pixels in an image while in a transform domain category the image is first transformed into the transform domain, processed there and brought back in the spatial domain through a an inverse transform applications. As far as our application is concerned the image processing in spatial domain is preferred as it is more efficient computationally and requires less processing resources to implement. Spatial domain processing is carried out either in intensity transformations or spatial filtering. Image transformation operates on single pixels of an image, principally for contrast manipulation and image thresholding. While spatial filtering deals with performing operations, such as image sharpening, by working in a neighborhood of every pixel in an image.

The spatial domain process can be donated by the expression

$$g(x,y) = T\,[\,f(x,y)\,] \qquad \text{(i)}$$

Where f (x,y) is the input image, g (x,y) is the output image and T is an operator on f defined over a neighborhood of point (x,y). The point (x,y) is an arbitary location in the image and the region containing the point is neighborhood of (x,y) which is rectangular and centred on (x,y). The origin of the neighborhood is moved from pixel to pixel and the operator T is applied on the pixels in the neighborhood to yield the output at that location. Thus for any specific location (x,y), the value of the output image at those coordinates is equal to the result of applying T to the neighborhood with origin at (x,y) in f. For example, consider the neighborhood is a square of size 5 x 5 and the operator T is defined to compute the average intensity of neighborhood. Then for a certain location f (x,y), assuming that the centre of the neighborhood is at (x,y) then the result g (x,y) at that location is computed as the sum of f (x,y) and its 24 neighbors, divided by 25 (i.e. the average intensity of the pixels encompassed by the neighborhood).The origin of the neighborhood is then moved to the next location and the procedure is repeated to generate the next value of the output image g. The procedure start from the extreme left of the input image and moves ahead pixel by pixel till the end of the image domain. The procedure is called spatial filtering in which the moving neighborhood is called spatial filter, mask, kernel, template or window. Thus a spatial filter essentially consists of a neighborhood (typically a small rectangle) and a predefined operation that is performed on the pixels of the neighborhood. A new pixel is created after filtering whose coordinates are equal to the coordinates of

the centre of the neighborhood calculated by the filtering operators. A filtered image is generated as the filter visits each pixel in the input image. The type of operation performed on the image pixel classifies the filter as a linear or non linear spatial filter.
The filter is odd size and the general expression of a linear spatial filtering is given by

$$g(x,y) = \sum_{s=-a}^{a} \sum_{t=-b}^{b} w(s,t)\, f(x+s, y+t) \qquad \text{(ii)}$$

Where x and y are varied so that every pixel in ω visits every pixel in f. A linear filter can be operated in correlation or convolution. Correlation is the process of moving a filter mask over the image and computing the sum of products at each location. Convolution mechanics is the same, except the filter is first rotated by 180^{o}. Non linear spatial filters are order statistic filters which order (rank) the pixels contained in the image area encompassed by the filter and then replaces the value of the center pixel with the value determined by the ranking result.
Median filter, Maximum and Minimum filter and Mid point filter are the types of non linear spatial filters out of which the median filter is the best rated filter as they provide excellent noise reduction capabilities with considerably less blurring than linear filters of similar size. This type of filter replaces the value of a pixel by the median of the intensity values in neighborhood of that pixel including the original value of the pixel while computing the median. The median filter represents the 50^{th} percentile filter of ranked set of numbers. The filter which uses 100^{th} percentile is called maximum filter and is useful for detecting the brightest point in the image while the 0^{th} percentile filter is the minimum filter and is used to find the darkest point.
A max filter is given by

$$f(x,y) = \max_{(s,t) \in S_{xy}} = \{g(s,t)\} \qquad \text{(iii)}$$

and the min filter is given by

$$f(x,y) = \min_{(s,t) \in S_{xy}} = \{g(s,t)\} \qquad \text{(iv)}$$

A mid point filter computes the mid point between maximum and minimum values in the area encompassed by the filter.

$$f(x,y) = \tfrac{1}{2}\left[\max_{(s,t) \in S_{xy}} \{g(s,t)\} + \min_{s,t \in S_{xy}} \{g(s,t)\}\right] \qquad \text{(v)}$$

Filter Design

median filter is designed for the image processing of the thermal paint contour image. The median ξ , of a set of values is such that half the values in the set are less than or equal to ξ and half are greater than or equal to ξ . The median filter is designed to sort the values in the neighborhood determine their median and assign the identified median value to the corresponding pixel in the filtered image. For example, if a 3 x 3 neighborhood has values (25,30,40, 30,50,40,60,20,90) these values are sorted as (20,25,30,30,40,40,50,60,90) which results in a median of 40 (the 5^{th} largest value for a 3 x 3 neighborhood). For a 5 x 5 neighborhood the median would be the 13^{th} largest value.
Thus a median filter gives an output image in which the pixels with distinct intensity levels are forced to be more like their neighbors. The neighborhood is designed at least as large as the noise or even larger to encompass the effect of unaffected pixels in the domain. For small initial noise levels it is recommended to specify a minimal number of neighbors in order to permit stable linearization. It is been observed that in successful cases most of the filtering is done either in the first one to three iterations. Going further is potentially dangerous since further correction may lead to distortion. The rms correction in each iteration is monitored and the process is stopped as soon as it does not decrease substantially any more.

Filter Implementation and testing

Two different thermal paints are applied on two test plates and exposed to a heating flame for a fixed predefined time one after the other. Contours are obtained on the test plates with different colors embedded within them, exhibiting the range of temperatures to which they were exposed.
The images of the contours are taken and are referred as original images. The test plates are further exposed to an engine exhaust allowing a considerable amount of carbon to be deposited on the contours distorting their structure. The images of these degraded contours are further taken and referred as noisy or degraded images. The filter is applied on these noisy images to filter the effect of the carbon soot deposition. The filtered images are termed as denoised images. The filter is also designed to give the histogram output to check the filter performance. Analysis of the figures 2 and 3 reveal that the filter is quite efficient to remove the noise upto a considerable extent. The histograms of the red, green and blue planes of the noisy and denoised images approve the reliable performance of the filter.

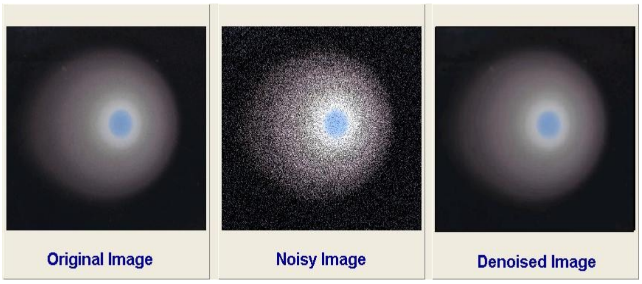
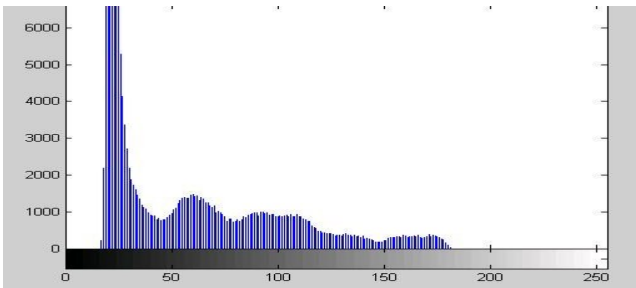
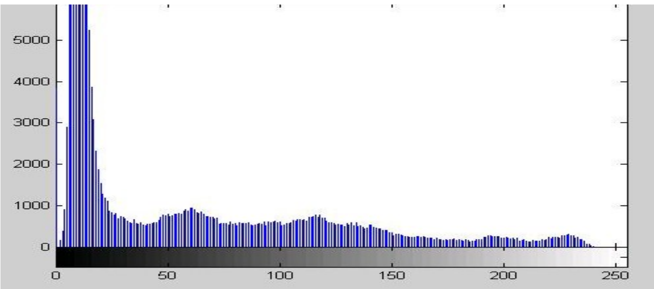


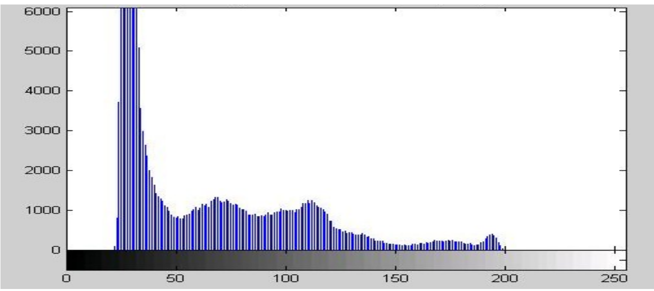
Fig. 2 (a)- Contour 1



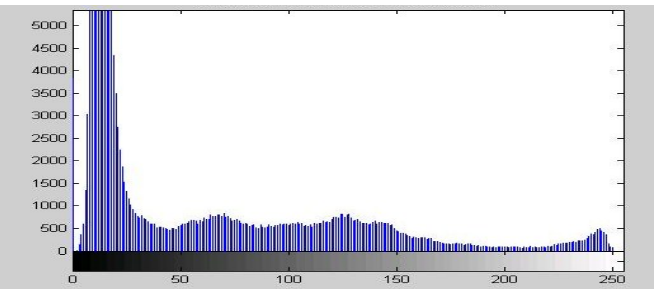
Histogram of Green Plane of Noisy Image



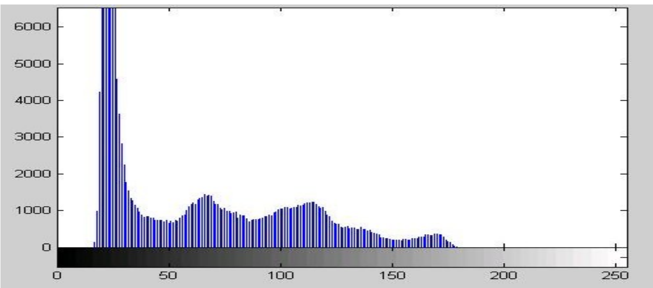
Histogram of Green plane of Denoised Image



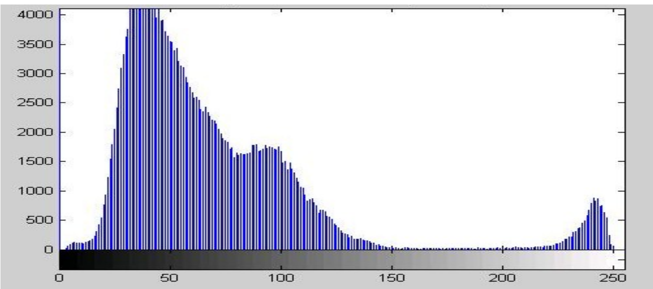
Histogram of Blue Plane of Noisy Image



Histogram of Blue Plane of Denoised Image



Histogram of Red Plane of Noisy Image



Histogram of Red Plane of Denoised Image

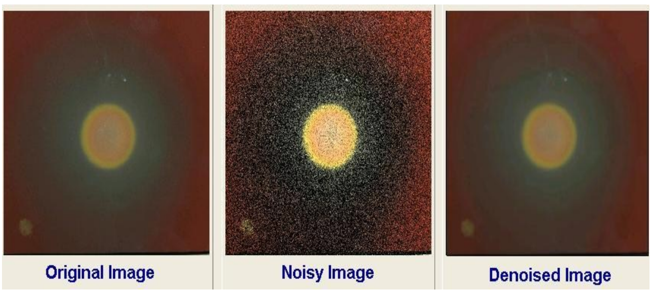
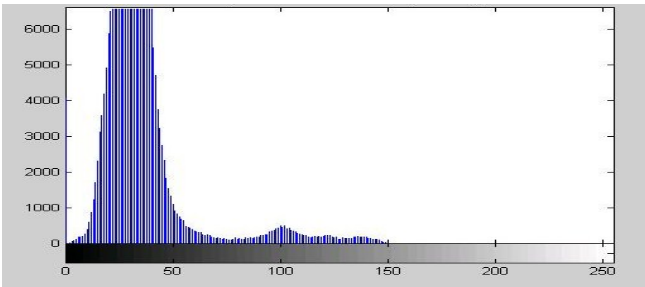
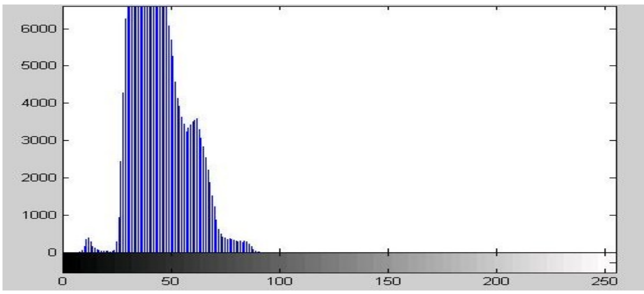


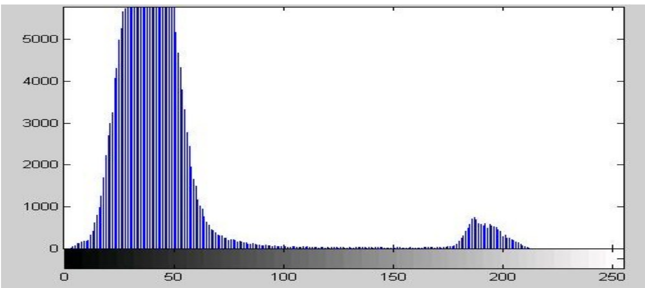
Fig. 3 (a)- Contour 2



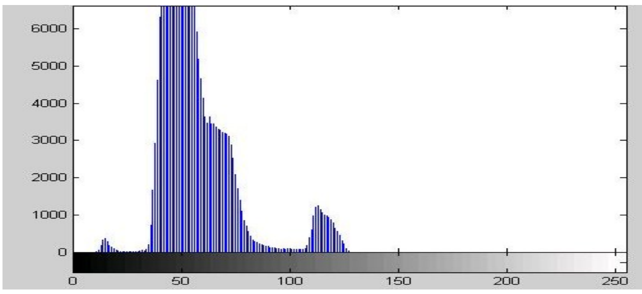
Histogram of Blue Plane of Denoised Image



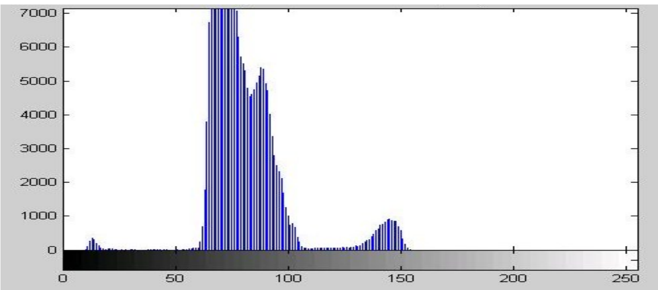
Histogram of Blue Plane of Noisy image



Histogram of Green Plane of Denoised Image



Histogram of Green Plane of Noisy Image



Histogram of Red Plane of Noisy Image
Fig 3. (b)- Histograms

Results and Discussions

The filter was applied to remove the noise and the denoised images were analyzed to understand the performance of the filter. The noise removal capability of the filter was tested and the resulting denoised images were compared with the original image which was quite encouraging. The visual observation of the noisy and denoised images shows the effective performance of the filter. The histograms confirm its reliable performance. It is observed that the filter gives a satisfactory performance on the images with 35 percent degradation. The median non linear filter is found to perform better in our case as compared to the other filters due to the appreciable noise removal capability and less computational structure. As filtering of the distorted image is a basic step in the automatic interpretation of the acquired data without which a reliable analysis cannot be expected, the designed filter assures to play an important role in the efficient interpretation of the thermal paints.

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