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Methodology for Design and Development of a Digital Image Processing Setup for Thermal Mapping of Gas Turbine Components Using Thermal Paints

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Abstract*— Engine efficiency increases with its operating temperatures which in turn are limited by the component material life. Accurate full field assessment of metal temperature of hot section components is essential for engine designers to produce reliable and durable engines. Conventional thermometry is not preferred as it fails to provide the thermal gradients and has errors in transferring the data from the measuring points to the read out unit. There is a change in the thermal transfer condition and the true temperature of the parts cannot be obtained. Thermal paints or temperature indicating paints undergo permanent color change when exposed to elevated temperatures. Conventionally the thermal paints are analyzed manually. Manual interpretation leads to inaccuracies due to lack of precise detection of isothermal boundaries concerning limitations to human vision. In this article a systematic approach developed for automatic interpretation of thermal paints is mentioned. A methodology for orderly procedure of image acquisition, image segmentation and image processing using a proper algorithm for surface temperature interpretation is been discussed.

Index Terms— **Digital Image Processing, Thermal Paints, Gas Turbine.**

I. INTRODUCTION

Aeronautical manufacturers and Maintenance Repairs and Overhauling agencies need to know the surface temperatures of gas turbine components with a reasonable accuracy. Surface temperatures are measured directly on the engine components through dedicated tests and are validated using various mathematical models. Accurate temperature data is necessary for efficient design and assessment of life span of operating engines. Consistent refinements in the design are done to increase the engine efficiency by increasing the turbine inlet temperature. The engines are designed to run at temperatures just a few hundred degrees below the component limiting temperature. In this context the knowledge of the actual thermal gradient to which the components are exposed is of vital importance. There are many measurement techniques like the optical pyrometry and thermocouple installation. But due to major drawbacks like requirement of specific knowledge of emissivity of the material at different temperatures and complexity of implementation of the sensors on the rotating engine components these techniques tend to be more inferior. Moreover these techniques give local temperatures only. Comparatively thermal paints are an effective alternative to get temperature gradients across the surface of the engine components. Thermal paints are paints that change their color permanently when exposed to elevated temperatures. Their interpretation is still majorly manual processes wherein isothermal contours are drawn by skilled are drawn by skilled and experienced human interpreters. Due to human vision limitations in identifying the various minute color shades the process becomes subjective and leaves room for human error. Researchers are taking efforts to automate the interpretation process. A methodology for design of an automatic interpretation technique of these thermal paints right from image acquisition to image processing and final interpretation using digital image processing is discussed in detail.

II. SURFACE PREPARATION

In context with gas turbines the paints are used to produce the thermal contours on the surfaces of axial and centrifugal flow compressors, combustor liners, combustion chamber casings, nozzle guide vanes, turbine rotor blades and vane cases. The surfaces of the components have to be properly treated before and after the application of the paints. Before application of the paints the components are dipped in anti-rusting or anti-greasing agents for about 45 minutes. Isochoric acid or acetone is recommended for the same. After rinsing the components using these cleansing agents they should be heated in a furnace or oven up to 200^0 C to burn out the oil traces if any. A very thin layer of the paint is then applied on the components using a spray gun. The painted coupons are again heated in the oven for a curing temperature of about 300°C for 2 hours. After completion of the curing cycle switch off the oven and let the components cool down to room temperature in the oven itself. It should be noted that a sudden withdrawal of these heated components from the oven and exposing them to room temperature weakens the paint bond due to the thermal shock and results in peeling of the paints. These painted parts are now assembled in the engine and the engine is allowed to run to carry out the test. After the test the parts are disassembled and their images with the thermal contours on them are captured.

III. IMAGE ACQUISITION

Images should be grabbed properly such that the component edges should be clearly recognizable while there should be minimal reluctance and illumination or shadow edges capturing the true colors.

A. Image Acquisition Procedure:

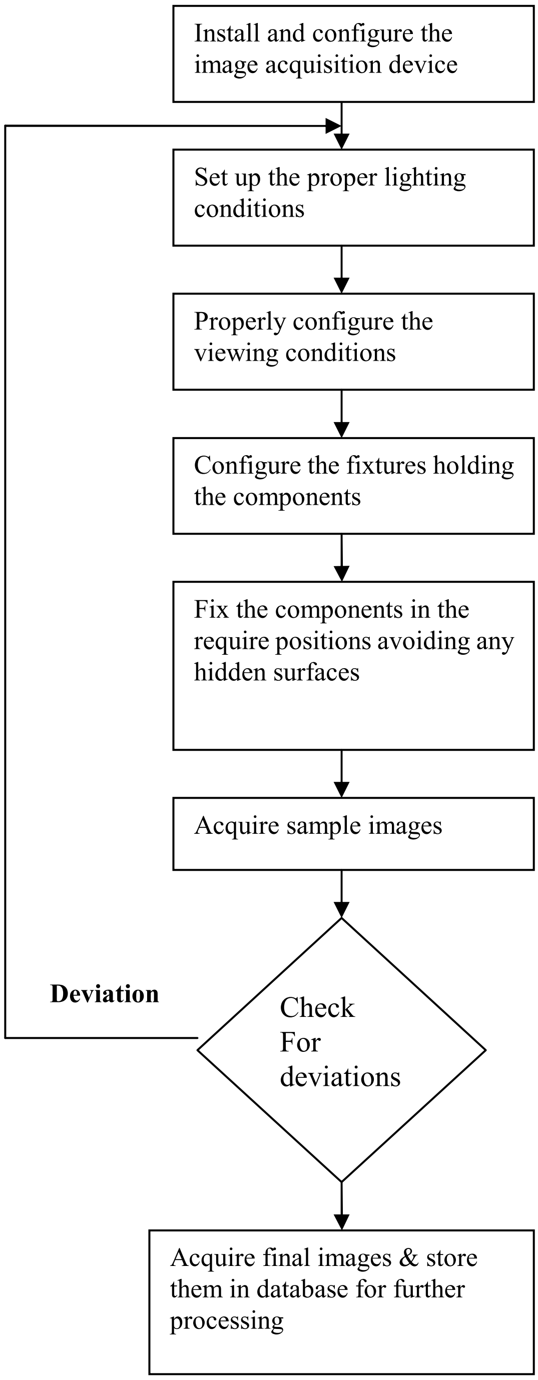

Fig.1. Flow Chart of System

B. Image Acquisition tool kit: The image acquisition tool kit consists of a i) 3 CCD camera ii) Camera tripod iii) Turntable with fixtures mounted onboard iv) Proper lighting appliances. High end digital cameras produce images that have superior image quality in terms of resolution, sharpness and accuracy of color reproduction compared to normal digital cameras which produce inferior quality images depending on the amount of interpolated data used, the type of color filters used, patterning of the color filters on the CCD chips, the response of the CCD pixels, noise sensitivity and so on. Digital cameras include one or more charge coupled device (CCD) chips, which are divided into a number of pixels. In conventional cameras each pixel is responsive to one red green or blue light and produces an output signal which is proportional to the intensity of the red, green or blue light falling on it. These output signals are referred to as 'R','G' and 'B' for red, green and blue light respectively. "Single chip" cameras include one CCD chip, having a distribution over the surface of the chip of different pixels. One set of pixels is responsive to red light, one set to green light and one set to blue light. The pixels in the various set are spread relatively even over the chip, although there may not be the same numbers of pixels of each color (as one color may be used to supply luminance levels common to all three sets of pixels).At each pixel in the image, information is therefore provided about one color of light, namely red, blue or green light. For each pixels information relating to remaining colors must be extrapolated from the color information obtained in respect of neighboring pixels. A "three chip" camera uses a prism to split the image into three separate images: a red image, a blue image and a green image. Each image is received by a separate chip such that red, green and blue light information is available for every pixel on respective chip. These cameras therefore provide superior image resolution and less ambiguous color information. As an alternative to either of the above, a black and white camera may be used with red, green and blue filters placed in front of the camera in turn to thereby provide color information for each pixel, a separate image being recorded for each color. Overall a three chip camera is preferred. It is not essential to use red, green and blue sensitive cameras, but these are commonly available thus convenient to use. The added advantage is that since the images are captured at high resolution, it is possible to magnify the displayed images considerably without losing details for a thorough analysis.

C. Important Practices to avoid general Problems: Proper practices with right equipments can successfully lead to obtain high quality images. The guide lines are not rules of photography but are formulated by series of experimental iterations.

1. ***Location of the Object:*** It is suggested to fix the object at the centre of the table to get a sequence of views with every view equipped with the required details. The object distance and camera position can be varied with proper spinning of the turntable to obtain appropriate containment of the object in the field of view. The rotation angle of the turntable for each view is subjective that depends majorly on the object geometry.

2. Camera Position: Various iterations have to be taken to select the height, angle and distance of the camera. Different views of the object should be considered to determine these parameter. The best position is such that the parts of the object do not hide each other and also the reflection of the light incident on the surface does not create unnecessary noise in the image. Depending upon the geometric complexities of the object, multiple angles of elevation may need to be used. A polarizer may be used to polarize the light while the directly

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reflected light may be filtered using a cross polarizer.

3. ***Viewing:*** The proposed viewing environment is a LCD monitor of a laptop/PC. The computer should be equipped with a sound graphic card for better quality images and no flicker problem. A dim lighting condition is preferred for accurate color representation.

4. Lighting and Illumination: The ambient illumination in indoors and outdoors often is a compound of fluorescence and daylight. Hence it is proposed to illuminate the surrounding by a fluorescent light source and an incandescent lamp. Quartz halogen lamps 150 W are also found effective for better image results. Proper lighting is important for accurate color reproduction and should be maintained constant for multiple object rotation. All round illumination is not suggested due to reflection issues. Inclined illumination at 45 degrees avoids glazing and hence can be preferred. Comparatively normal illumination with proper camera angle is a better alternative to get good images. It should be seen that the component to be analyzed is illuminated in such a way that there are no reflection or shadow issues. At elevated temperatures the paint binding starts fusing reflecting back the light incident on it. Such images have less color information and appear white and glazy. In this case a polarized light is suggested to avoid glazing with a cross polarizer across the camera. This reduces the glazing problem but at the cost of brightness of the image.

IV. CALIBRATION DATABASE

A calibration database containing set of reference calibration color values corresponding to particular temperature values associated for a certain thermal paint is to be created. This calibration data base is retrieved and compared with the color of the component image so that the particular temperature value is assigned. This is done by using calibration coupons. Coupons are metal sheets which are cut in to 1"x 2" pieces and painted with a paint of specific type after applying surface preparation. These coupons are exposed to over a range of temperature which are best suited to that paint type by heating them in a furnace, thereby obtaining different colors for different range of temperature. Next the images of the coupons are taken using a digital camera with high resolution and these images are stored as JPEG or BMP files. To include a coupon into the database, user can select any arbitrary point on the coupons to display the RGB value of the color, enter the temperature and include into database for a particular paint type.

V. IMAGE PROCESSING AND INTERPRETATION

This stage consists mainly of following stages.

i) Image Filtration and Enhancement.

ii) Boundary Detection.

iii) Interpretation.

A. Image filtration and enhancement: In the primary phase the image processing algorithm should consist a filter code to denoise the images before interpretation. Filters and Signal enhancement modules are developed to remove a noise from the acquired image to transform it to a more usable one for a particular study objective for which it intended. Filtering is an essential part of an image processing algorithm to yield rich images for accurate automatic analysis. In past decades several color image processing algorithms have been proposed for filtering the noise in particular additive impulsive and Gaussian noise, speckle noise, additive mixture noise and stripping noise. A comprehensive class of vector filtering operators have been proposed, researched and developed to effectively smooth noise, enhance signals, detect edges and segment color images which is used for thermal mapping. In present case as these paints are applied on the gas turbine engine components to get the thermal gradient, the exhaust gases flow over them during testing. This in turn deposits carbon soot on the components and distorts the image with the carbon color superimposed on the paint color and the true transformed color profile cannot be exposed leading to discrepancies in interpretation. The deposition of exhaust soot causes a major problem in reading the thermal paint contours.

To avoid this a customized filter is to be developed to remove the carbon soot noise retrieving the original color contour .The image is smoothened by setting the color value of a central pixel in a group of pixels to the average of all the pixels in the area. The performance of the filter is independent of the value of the temperature. The paint changes its color when exposed to temperature of different values and each color has a specific Hue, Intensity and Saturation (HIS) value. The filter uses these values for filtering the image degraded because of exhaust deposition. The performance of the filter to denoise the degraded thermal paint images can be further analyzed.

B. Boundary Detection or Segmentation and Interpretation: Proper compensations and corrections for brightness and non-uniform illumination must be applied before further processing. It should also be checked whether the image is filtered by the filter and suitable for further processing. This can be ensured by comparing the pixel values of neighboring pixels and checking for any irrelevant significant changes. Further the aim of image analysis is to see the temperature value assigned to the various color contours on the engine component image as the output. To achieve this every pixel of any point of the image must be allocated with the corresponding temperature. As is clear from coupon calibration database that every calibration point with a certain pixel value is associated with the corresponding temperature. An algorithm is to be developed to find the closest calibration point for each pixel point on the component image and thus allocate the temperature to the location represented by that pixel. Also if the pixel image point does not exactly match with the nearest calibration point, then the difference (x) is found and the corresponding temperature value is computed by a standard interpolation equation. Application of the above process for every pixel point on the image shall include heavy computations and in a view to minimize the number of calculations, image has to be properly processed. Primarily

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the boundaries of the colors have to be detected by a suitable algorithm.

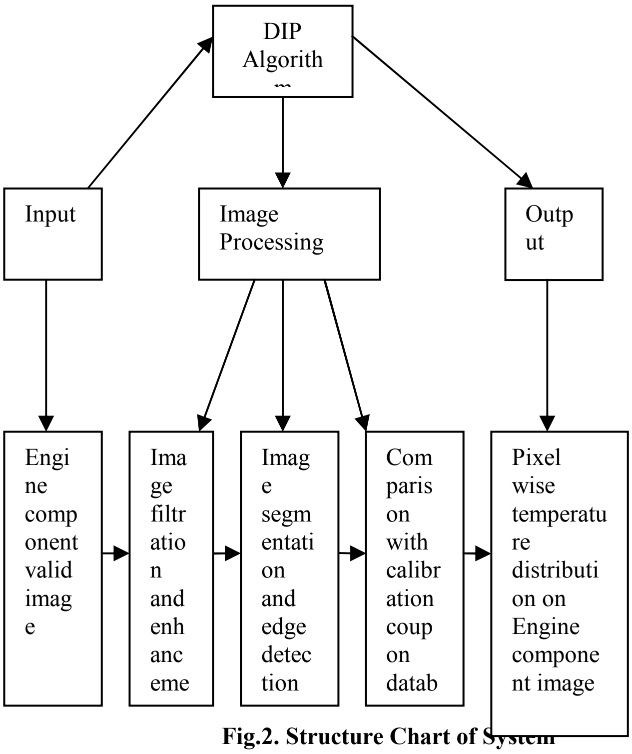

Fig.2. Structure Chart of System

This is a process of partitioning an image into different regions that are similar with respect to a certain image feature. Once the image is filtered boundary detection is the basic step of image analysis. All the subsequent tasks like feature extraction and image analysis depend on the segmentation quality. A good segmentation algorithm makes the image analysis more efficient and reliable. Care should be taken to avoid over segmenting and under segmenting. Further the areas within each boundary have to be divided in small parts assigning every part with a central pixel value which is a mean of all the pixel values within that area. This exercise shall divide each area of interest in to finite number of pixel values reducing the computational part with more uniform results.

VI. CONCLUSION

Compared with the available thermometry techniques, thermal paint is found to be a better alternative. An efficient DIP algorithm can separate the close color classes giving reliable temperature information and removing the manual errors. It should be seen that the images of the calibration coupons are properly captured as it forms the basic database for interpretation. Also at higher temperatures the visualization becomes difficult due to paint glaze. A proper attention should be given to the lighting and viewing conditions to capture the true colors. The components should be placed properly during image acquisition so as to capture the maximum area without any hidden surfaces. All the steps from surface preparation to image processing should be properly followed to get satisfactory results.

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