FOURIER TRANSFORM TECHNIQUES FOR IMAGING PERFORMANCE EVALUATIONS OF THERMAL IMAGING CAMERAS USED BY THE FIRE SERVICE

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INTRODUCTION

Infrared (IR) technology for fire fighting applications has matured to the point that most first responder organizations in the U. S. either have purchased or are considering the purchase of thermal imaging cameras. Thermal imagers can provide first responders with critical information to size up a fire incident, track fire growth, and to locate victims, other first responders, and egress routes. While these devices represent a significant investment, typically on the order of $10 K per camera, first responders have little guidance on instrument performance beyond manufacturer literature and recommendations from other users[1]. These issues are further complicated because the demands placed on thermal imagers are application dependent. The end users may have very different ideas about which imaging properties are most important: sharp image contrast may be sufficient for some fire fighting applications, such as finding the source of a fire, but high thermal sensitivity may be required to locate a person or structural component when flames and water are in the imager's field of view. Currently, there are no standardized performance guidelines available to aid end users in making purchasing decisions.

Over the past several years, the Fire Research Division at the National Institute of Standards and Technology has been developing a suite of performance metrics and test methods for inclusion in a national consensus-based standard on thermal imaging cameras used by first responders[2]. The performance metrics are related directly to the environment in which the imagers are used and tasks typically performed by first responders. Measurements of contrast, effective temperature range, spatial resolution, image uniformity, thermal sensitivity, and the ability to penetrate obscuring media such as smoke and water vapor are currently included in the draft standard. The test methods associated with two of these performance metrics, e.g., spatial resolution and effective temperature range, may benefit from a careful analysis of the frequency content of the images that appear on the imager's display screen. As a subset of the overall project, NIST is working with the College of Optics and Photonics at the University of Central Florida to investigate two techniques for transferring the essential characteristics of complex images generally seen in the fire environment to relatively simple bench top target configurations for use in standardized performance tests.

METHODOLOGY

A Fourier transform is a mathematical procedure in which the spatial (or temporal) fluctuations in contrast in an image (or sequence of images) are converted from the spatial (or time) domain to the frequency domain. For a two-dimensional image, this transformation is accomplished using the following equation:

$$F(m,n) = \sum_{l=-\frac{N}{2}}^{\frac{N}{2}-1} \sum_{k=-\frac{M}{2}}^{\frac{M}{2}-1} f(k,l) e^{-2\pi i\left(\frac{mk}{M}+\frac{nl}{N}\right)} \quad [1]$$

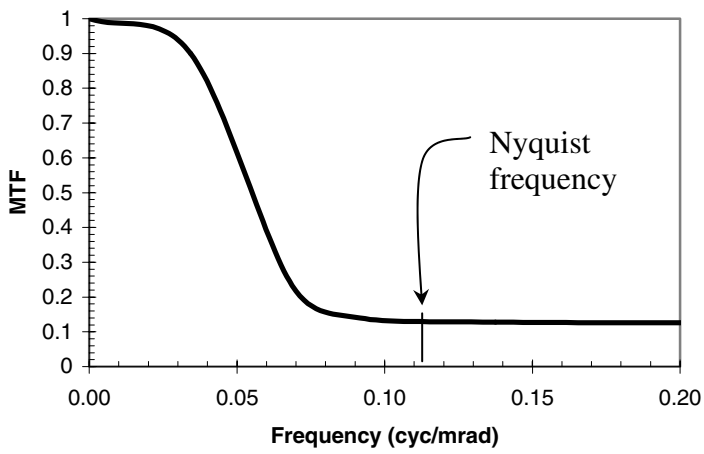
Where F is the Fourier transformed image, m and n are the dependent variables in the frequency domain, in this case contrast magnitude and phase, and k and l are the respective quantities in the spatial domain, in this case pixel intensity and position[3]. We shall use Fourier transforms in two ways in this discussion: first, as an expedient way to assess a thermal imaging camera's spatial resolution; and second, as a way to extract vital spatial frequency information from realistic images in order to design bench-scale test targets for use in other proposed performance tests.

Modulation Transfer Function (MTF)

All image forming optical systems suffer from the same performance degradation: as objects get smaller they become less distinct and more difficult to discern. An object's decrease in size is equivalent to an increase in spatial frequency. A pure spatial frequency can be thought of as a periodic change of light and dark features in an image. A plot of these changes in image pixel intensity would be sinusoidal in nature and exhibit a common peak-to-peak distance (wavelength) the inverse of which is the spatial frequency of the feature. This sinusoidal fluctuation in intensity is known in optics as modulation.

The MTF is a measure of an imaging system's ability to reconstruct an image from a target over all spatial frequencies, and varies in value from 0 to 1, where 0 indicates no distinguishing characteristics in the image whatsoever. MTF decreases with increasing frequency due to blur that affects image contrast as objects become smaller and closer together[4]. In other words, the MTF is a measure of an imager's spatial resolution, or ability to see the details in a scene or target. The MTF is conventionally presented as a curve, with MTF plotted as a function of frequency, an example of which is shown in Figure 1. Typically, sharply contrasting adjacent areas are imaged, then Fourier transform analysis is used to examine the transition in pixel intensity, or blur, as a function of distance from the contrast edge.

Figure 1. Typical MTF curve for a first responder thermal imaging camera having a 320 x 240 pixel detector array.



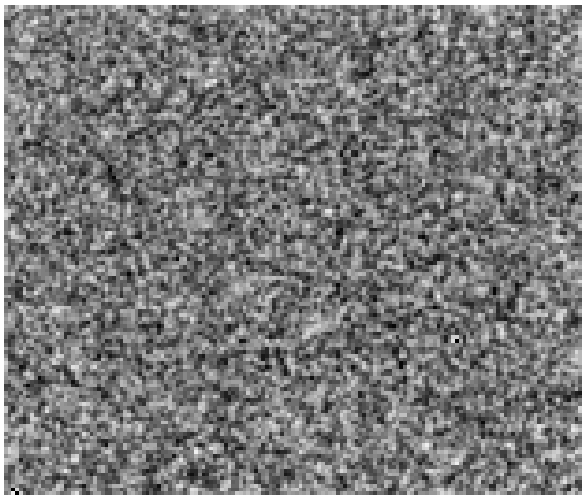
An MTF curve is normalized with a value of 1 at the ordinate, or zero spatial frequency, and is usually carried out to the Nyquist frequency, which is the frequency at which the sampling rate causes signal aliasing and can introduce image artifacts such as moiré patterns[4]. The Nyquist frequency depends on the geometric design of the optics and detector of the camera under test.

MTF is regarded as the one of the most valuable figures of merit for optical imaging systems and is being considered as the basis of the spatial resolution performance metric developed in this work.

Random MTF target

The Random MTF target uses random features distributed in a specific pattern to yield a uniform distribution of spatial frequency power over a range of frequencies that are determined by the pixel size and configuration of the imager detector under test. An important advantage of the Random MTF target approach over other techniques is repeatability. The theory of MTF is inherently based on Linear Shift Invariance (LSI). LSI implies that small movements or positional differences of the object or test pattern with respect to the imager detector under test do not yield different MTF results. Commonly used MTF targets such as points, lines, bars, and knife-edges all have sharp edges; these methods require that the target must be carefully aligned with the rows and columns of the detector array of the imager under test in order to produce repeatable results. The degree of uncertainty in the test results depends on the detector position and design, a small movement or shift of the target in these tests can result in significantly different measurement results because the sharp target edges may partially fill the camera's detector pixels in non-repeatable ways. The Random MTF target, shown in Figure 2, utilizes random features and incorporates an averaging technique during processing, which results in a test method that is immune to shifts of the target and is in fact LSI.

Figure 2. Image of a Random MTF target. This target is linear shift invariant due to the randomized nature of the contrasting areas. All frequencies of interest are represented equally.

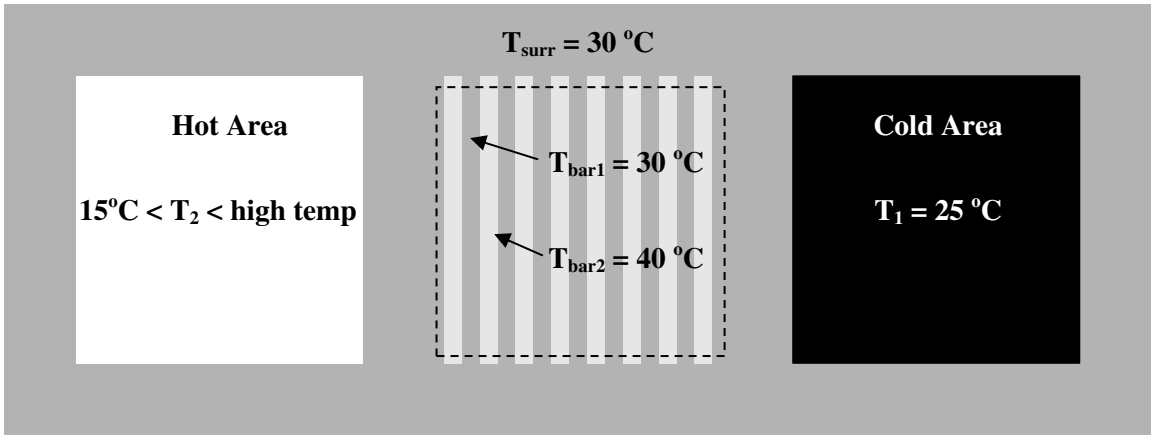


An MTF test using the Random MTF target is performed by imaging a backlit transparent target. The backlight in this case is an extended area infrared blackbody set to a nominal temperature. For this application, the thermal imaging cameras operate in the 8 µm to 14 µm wavelength range, therefore the target substrate must be transparent in this range. Zinc selenide, which transmits approximately 65 % - 70 % in this wavelength range, is the material of choice for this project. Chromium is deposited on the substrate to form the random pattern. The image of the target produced by the thermal imaging camera under test is then processed using Fourier transform image analysis techniques[5].

Image frequency content

In the development of a consensus standard, as is this case, performance metrics and test methods are created in a process in which many diverse parties, such as first responders, thermal imaging camera manufacturers, and fire researchers, all participate. The goal is to form a consensus on test methods that are meaningful to first responders, useful to manufacturers, and are also scientifically defensible. For example, in the proposed effective temperature range test, the imager views a scene, shown in Figure 3, in which a large hot area (representing flames and heat) and a large cold area (representing water and ambient conditions) are in the field of view, along with a bar pattern having intermediate temperatures (representing a human).

Figure 3. Test target for the proposed effective temperature range test. The high value of T_2 is the temperature at which the camera no longer responds to increasing temperature.



This test measures the visibility of the bar pattern in the center of the target as the temperature of the hot area increases through a range. The frequency of the bar pattern is important in this test because of the wide variation in thermal imaging camera design. Some cameras may not have sufficient spatial resolution to see the bars clearly, even under optimum thermal conditions. In order to avoid biasing this test method toward any particular camera technology, the bar frequency was determined by the needs of the users. Input from first responders on the type and size of image that best characterizes their most pressing needs in this type of thermal environment led to the development of a bar pattern based on frequency analysis of images of people dressed in turnout gear and in street clothes standing at several distances from the camera under test. This process yields target design information that greatly simplifies the test method and reduces the uncertainty of test results while retaining meaningful characteristics from realistic images.

Bar frequency determination

Infrared images of two people, a woman and a man, dressed in street clothes and in firefighter turnout gear were collected and analyzed at distances of 2 m, 3 m, 5 m, and 10 m from the thermal imaging camera, resulting in a total of 64 images. An example of a pair of images taken at 3 m is shown in Figure 4. Given a known distance that appears in every image, the frequency content of the image can be extracted using a Fourier transform; for the purpose of this work the contrast magnitude is of interest and the phase component is disregarded. A 1-dimensional horizontal Fourier transform was used, with each column summed along the length of the image. The images of each person were processed separately for each distance. In the plots shown in Figure 5 the magnitudes of the frequencies obtained for a single thermal imaging camera provide an indication of the frequencies that contribute the most to the overall image.

Hand calculations of the frequencies of dominant features, such as the head, arms, torso, and shoulders were performed to check the accuracy of the plots. The magnitudes of the frequencies in these plots may be somewhat misleading in that they reflect summed values over the length of the image and also may include harmonic effects coming from lower frequency data. These issues will be resolved in the near future. In the meantime, the location of the peaks (but not the magnitude) is useful for the determination of bar target frequencies to be used in bench-scale test methods.

Figure 4. Infrared images of a person standing 3 m distant from a thermal imaging camera. He is wearing street clothes (left) and firefighter turnout gear (right).

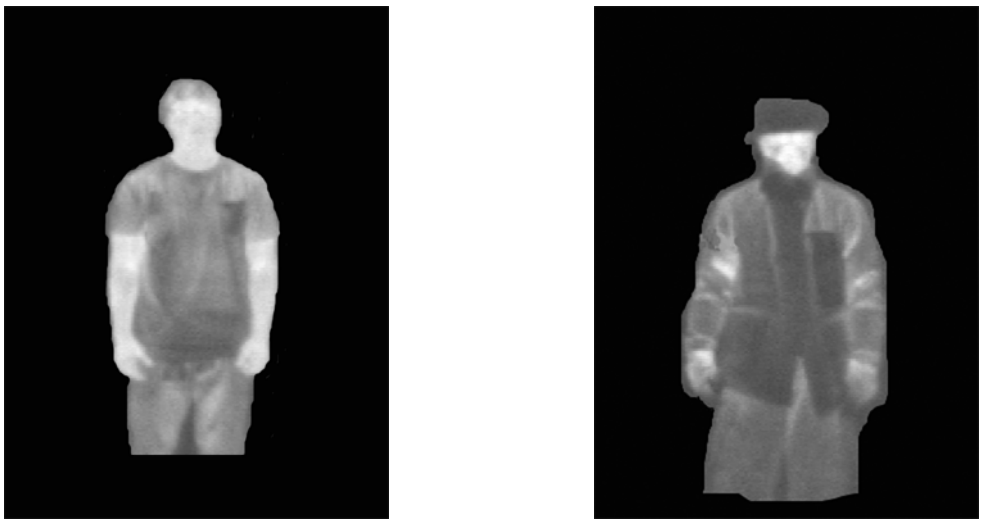
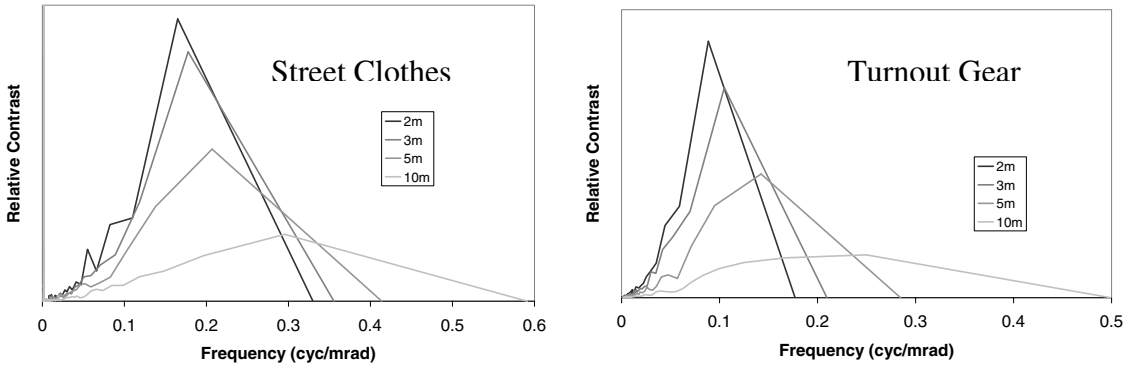


Figure 5. Frequency plots of infrared images of a person dressed in street clothes (left) and in firefighter turnout gear (right) at four distances from the thermal imaging camera.



Results show that, as the person moves further away from the camera position, she/he appears smaller and thus exhibits relatively higher frequencies. There was little difference in frequency plots between male and female targets. The images of people wearing street clothes showed more features (peaks) than the corresponding images of people wearing turnout gear. This was attributed to the fact that turnout gear tends to mask the heat signature of the person wearing it; body heat penetrates street clothes much more readily. Also, a difference in the frequency plots was noticed regarding the location of the peaks, with the peaks being shifted toward higher frequencies for street clothes. Compared to street clothes (jeans, tee shirt or blouse), turnout gear is large and bulky and would therefore present a somewhat larger, lower frequency target.

CONCLUSIONS

The advantages of using these techniques for image analysis are twofold: first, inherent difficulties related to the exact position of the test target with respect to the imager detector array can be alleviated if the elements of the target are numerous enough and are randomly arranged; and second, realistic images such as that of a firefighter standing nearby can be replaced with a simple bar pattern having similar frequencies for bench-scale image performance tests. These two image analysis techniques exploit these advantages and are being developed for evaluation of first responder thermal imaging cameras.

In addition to reducing the measurement error associated with linear shift invariance, a connection is established between the bench-scale test targets used and realistic images that a first responder might expect to see at an emergency event. Further work is underway in both these areas to assess the benefits of full implementation of these image analysis techniques.

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