Review of Infrared Signal Processing Algorithms

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Abstract

The review of night vision and thermal image devices is covered to allow an in-depth understanding and appreciation of the challenges and inherent limitations on these devices that are the motivation behind image fusion. Infrared signal processing algorithms and architectures are equally important for the development of a high performance infrared imaging systems. Infrared signal processing deals with two types of processing sensor signal processing and infrared image processing for contrast enhancement and target detection. The sensor signal processing primarily deals with non-uniformity correction for infrared sensors. This arises because of differences in the photo response of the individual detectors of the focal plane array. Such a difference exists between neighboring detectors even if they are illuminated by the same radiance. Some researchers have described black body and calibration based non-uniformity correction methods and some have described the scene based adaptive non-uniformity correction algorithms.

Keywords:

I. Introduction

Calibration based method involve interruption in the operation of the infrared systems and do not provide the best result under different environmental conditions. Most of the scene-based methods described in the literature correct only offset non-uniformities and most of the methods cannot be implemented in hardware in real time, which is the fundamental requirement for an infrared imaging system. Thus, further investigations in non-uniformity correction algorithms and their implementation are needed. Infrared images are of poor contrast and high background noise, which result in poor visibility of the object. In addition, dynamic nature of the background and non-availability of background clutter characteristics affect the performance of the imaging system. The quality of an IR image depends on radiation pattern as well as the difference of temperature between the object and the background. Several researchers have described various types of algorithms based on histogram modification, logarithmic contrast enhancement, frame averaging, median filter, adaptive median fitters, kuwahara filter, high boost filtering, spatio-temporal [3,4,5] filtering, wavelet transform and Fourier transform based image processing.

However, these methods do not yield satisfactory results under different environmental conditions and also are difficult to implement in embedded hardware for real time applications. Hence further investigation will be useful to develop improved self-adaptive methods for infrared image enhancement and target detection systems. These methods should be capable of catering to most of the infrared scenarios over a wide dynamic range and real time implementation on a FPGA based embedded hardware. From the literature review it can be concluded that efforts to improve the performance of the infrared imaging systems will continue. More and more dedicated, intelligent and innovative sensor signal processing and infrared image processing algorithms will evolve. The real time implementation of these will result in the design of high performance next generation infrared systems.

II. Infrared imaging systems

Image Intensifier: One of the most extensively used imagery sensor systems is the night vision device or image intensifier. An image intensifier does have limitations due to the natural phenomena or characteristics of light propagation through the atmosphere. An NVD amplifies light photons in low light conditions through a series of electron photon conversion [1, 2].

A. Thermal Imager

The thermal imager is complementary to the image intensifier. Unlike the image intensifier, the history on the development of the thermal imager is not as exciting, partially due to the fact that the thermal imaging had sensitive military applications and was expensive when it first started out. The development of the thermal imager centered mainly on the techniques of detecting thermal radiation from the environment using different emerging materials and detector designs. The first detector technique used in the development of the thermal imagers was the scanning of single element detector to produce line images. The next major development was the micro-bolometer with its patent awarded in 1994. Subsequent developments focused mainly on incorporating the device into equipment systems such as the drivers' viewer for armored vehicles, weapons sights and hand portability. Some other improvements focused on the development of large scale focal plane arrays [6, 10].

B. Thermography

Thermography or thermal imaging is a form of thermal imaging that detects electromagnetic radiation in the thermal IR region, typically between the wavelengths of 3 and 15μm. Other familiar terms to define the regions may be Near IR (NIR – 0.7 to 1μm), Short-wave IR (SWIR – 1 to 3μm), Mid-wave IR (MWIR – 3 to 5μm) and Long-wave IR (LWIR – 8 to 12μm). These terms are defined based primarily on the atmospheric transmittance which affects the ability for the radiation to propagate through the air and be detectable. Other IR regions are greatly attenuated or absorbed by the atmosphere such that the study on these regions does not yield any benefits. As thermal imaging relies on thermal radiation emitting from targets in the background, it is therefore important to understand how this thermal radiation is generated and how it may be picked up by detectors.

C. Thermal signature

The primary motivation for the exploitation of thermal imaging is the emittance of electromagnetic signatures in the 3-5μm and 8-12μm bands either by reflection of solar radiance or thermal-emittance by military targets, i.e., vehicles, soldiers and equipment. The thermal emittance part of the signature is independent of day or night conditions. At the same time, it is difficult to suppress thermal signatures using conventional methods of military camouflaging and in most cases these signatures are generally higher than that of the environment.

D. Wien's Displacement Law

The peak emitted spectral radiance is as described by Wien's Displacement Law. German physicist Wilhelm Wien stated that the wavelength carrying the maximum energy is inversely proportional to the absolute temperature of the source black body. This property means that the hotter a body is, the shorter the wavelength will be. This relationship is derived from Planck's blackbody radiation and states that

$\lambda mT = 2897.8 \pm 0.4\mu$ K ($\mu m \times$ K)

where λm is the wavelength of maximum spectral radiant emittance and T is the absolute temperature in degree Kelvin. For example, at temperature T equal to 300K, the wavelength of maximum intensity max λ is 10μm. So at a temperature of 30°C, below which most targets are found, objects would be emitting at a wavelength that falls within the 8-12μm band of the transmission window. Fig. 1 illustrates the Wien's Displacement Law, Spectral radiant flux versus wavelength [7, 8, 9].

Infrared imaging systems depend on thermal contrast between the target and background to generate real time video picture. These systems create pictures utilizing the infrared energy emitted by the objects as a result of their temperature difference with background and emissivity. These systems exploit two atmospheric windows i.e. 3-5 µm and 8-12 µm, in which atmosphere is transparent to infrared radiations. The transmission window dictates the choice of wavelength used for infrared sensor design.

The radiations at a specific temperature T has an intensity peak at the wavelength given by Wien's displacement Law which is $\lambda mT = K$ where T is the temperature in °K, λm is the wavelength in micrometers, at which a maximum occurs and K is a constant of value 2896. It can be seen that as the temperature increases, the peak of the radiant flux characteristics shift towards shorter wavelength. Radiation emitted by the target is either scattered or absorbed as propagated through the atmosphere. Fig. 2 illustrates Electromagnetic spectrum & Fig. 3 illustrates thermal image as a function of energy radiation. These systems are used for wide variety of military and civilian applications. These applications include night vision systems for ground, air and naval application, surveillance, airborne reconnaissance, infantry and armored fighting vehicles (AFVs), fire control and sighting systems, and medical applications [11].

They offer a number of advantages over passive image intensification based night vision systems Firstly they can be used in complete darkness, while for their operation the image intensifies based systems require some form of ambient light, be it starlight or else. The Infrared systems are partially affected by smoke, dust or haze. They can detect objects even through camouflage nets and cannot be blinded by searchlights, flares and fires. They can reveal details that even the human eye cannot detect and can detect to a certain extent tank targets hidden in woods or behind bushes in daylight or darkness. Thermal imaging system can detect objects at considerably longer distances than image intensification based night vision systems.

III. Infrared Imaging Trends

Research efforts are taking place at various places to develop more sophisticated and smarter infrared focal plane arrays (IRFPA). The major driving force is the military requirements for high performance infrared systems. It is generally agreed that most of the next generation military infrared systems require very large format focal plane arrays operating in 3-5 µm, 8-12 µm and also in dual spectral bands. The prime reasons for such developments are suppression of clutter, increase in target contrast that lead to longer detection and recognition ranges, improved resistance to counter measures such as decoys and camouflage, and improved target acquisition capabilities.

Research efforts are going on for the development of high performance IRFPA having pixel array format such as 1024 x 768,

1024 x 1024 and 2048 x 2048 pixels FPAs. The next generation infrared systems require higher spatial resolution for target acquisition at longer ranges. Such requirement can be met by FPAs having smaller pitch. However, in order to keep the same field of view of the thermal imaging systems, numbers of pixels are required to be increased. Hence FPAs with a large number of pixels arc required.

Efforts are being made for the development of lightweight infrared systems based on quantum well infrared photo sensors (QWIP) These sensors are potentially sensitive to radiations over 5-100 µm band and are fabricated using alternate layers of AlGaAs and GaAs. Advanced version of next generation infrared imaging systems will use smart sensors that will combine multi-spectral imaging, signal processing using optical neural networks and micro lens optics in the same focal plane-All these types of IRFPAs require cryogenic cooling to 77°K to reduce the dark current Further efforts are taking place to operate sensors at elevated temperatures [12]. Micro bolometer arrays having pixel format 320 x 240 have also been designed and are available. The advantage of these arrays is that they can be operated at room temperature. These sensors are finding applications in the development of handheld thermal imagers for short-range applications. However, for high demanding systems without cooling requirements it will take another 10-15 years before they can match cooled systems.

IV. Infrared Signal Processing
The development of new and high performance sensors requires the innovation of signal processing algorithms and architectures for efficient target detection and engagement capabilities.

A. Sensor Signal Processing
Sensor signal processing is processing of low amplitude raw sensor output to display it in a suitable format In recent years the performance of infrared imaging systems has improved considerably due to the availability of larger format focal plane arrays (FPA) having larger number of pixels at the focal plane, smaller pitch & better noise equivalent temperature difference (NETD). However, it has also resulted in several problems and most serious of them is sensor non-uniformities. The performance of FPAs is strongly affected by the spatial non-uniformity in the photo-response of the detectors in array, also known as fixed-pattern poise, which becomes particularly severe in mid to far-IR imaging systems. Despite the advances in detector technology, non-uniformity continues to be a serious problem reducing the quality of the acquired infrared images [13,14].

Non-uniformity is because each individual detector in the array has a different photo response from its neighboring detector even if the two detectors are illuminated by same radiance The pixel-to-pixel fluctuations can be attributed to a number of factors such as 1/f noise associated with detector and the corresponding readout integrated circuits (ROIC), and the non linear dependence of the detector gain on the photon flux incident on it. All these factors result in spatial and temporal non-uniformities, thereby, degrading the image quality significantly. Furthermore, the spatial non-uniformity fluctuates slowly in time due to changes in FPA temperature, unstable bias voltages and the change in scene irradiance. This temporal drift is manifested in the acquired image in the form of a slowly varying pattern superimposed on the infrared image, which degrades the spatial resolution, radiometric accuracy, and therefore, reduces the temperature resolving capability of the FPA Moreover, what makes the non-uniformity correction (NUC)

problem more challenging is the fact that spatial non-uniformity drifts slowly in time. Thus a one-lime factory calibration will not provide a permanent remedy to the problem. Consequently, the task of any non-uniformity correction technique is to compensate for the spatial non-uniformity and update the compensation as needed to account for the temporal drift in the detector response. There are two types of non-uniformity correction techniques, namely. Calibration based techniques and Scene based techniques [15,16].

B. Calibration based techniques
Calibration based techniques depends on calibrating the focal plane array (FPA) at distinct temperatures by use of flat field data generated from a uniformly calibrated target source such as black body radiation source. In a calibration based technique the operation of the camera is discontinued during calibration.

V. Image Processing

A. Digital Image Processing
Image processing is the improvement of the image for human perception and image enhancement is the processing of image to increase their usefulness. Methods and objectives vary with the application. When images are enhanced for human viewers, the objective may be to improve perceptual aspect, image quality, Intelligibility or visual appearance. Fig. 4 shows the block diagram of a general image processing system. An image obtained from a sensor is first digitized and stored in the memory. This digitized image is then processed and displayed This has a wide range of applications in remote sensing, medical image processing, robotics, automated inspection of industrial parts, infrared imaging and night vision systems for automatic target detection.

Sharpening of image feature such as edges, boundaries or contrast to make a graphic display more useful for display and analysis is image enhancement The enhancement process does not increase the increase information content but it does increase the dynamic range of the chosen features so that they can be detected easily. Image enhancement includes gray level and contrast manipulation, noise reduction, edge crisping and sharpening, filtering and interpolation and magnification, pseudo coloring and so on. The greater difficulty in image enhancement is quantifying the criterion for enhancement. Therefore, a large number of image enhancement techniques are empirical and requires iterative procedures to obtain satisfactory results. The following are some of the common image enhancement techniques.

B. Point operations
They are zero memory operations, where a given gray level it u $\in \{0, L\}$ is mapped into a gray level v $\in \{0, L\}$ according to a transfer function v = f(u). Several such transformations are:

* Contrast stretching
* Noise clipping
* Window slicing
* Histogram modeling

C. Spatial operations
These enhancement techniques are based on the spatial operation performed on local neighborhood of input pixels. Often such image is convolved with finite response filler called spatial mask. Some of the common operations are:

* Noise smoothening
* Median filtering
* Un-sharp masking
* Low pass/band pass and high pass filtering
* Zooming

D. Transform operations
They are zero memory orations enhancement techniques and performed on a transformed image followed by the inverse transform. Some common techniques are:

* Linear filtering
* Root filtering
* Homomorphic filtering
* Pseudo coloring

Human can distinguish many more colors than that gray level coding complex information in color can effectively increase the perceptual dynamic range of a display. Pseudo color refers to mapping a set of images ui (m, n); i = 1, 2...............I into a color image. Usually the mapping is determined such that different features of the data set can be distinguished by different color. Thus a large data set can be presented comprehensively to the viewer.

VI. Infrared Image Processing
Infrared image processing technology and phenomenology is inherently different from that of visible spectrum. Visible sensors are silicon based sensors with very low floor noise of few electrons whereas infrared detectors are fabricated using materials like InSb or mercury cadmium telluride (MCT) having energy band gap significantly lower than the materials used for the fabrication of visible sensors and therefore, are of large dark current. Cryogenic cooling though reduces dark current but does not eliminate this effect. Infrared optics typically has point spread functions several times larger than visible optics because of longer wavelength photons and related diffraction effects. The most important parameter for an image quality is the image contrast level, which is the actual signal of interest compared to the flux level. Typically the contrast is much less in infrared image than in visible image. Furthermore, infrared image does not have color information and does not depend on the ambient light.

The quality of image depends on radiation pattern as well as temperature difference between object and background. There world be multiple radiation patterns in a real time scenario where the objects and surrounding would be emitting different IR wavelengths. Under this dynamic environment one has to come up with adaptive methods for IR image processing for optimum results. These methods should be such that they should be able to enhance the image for maximum number of infrared images and computational complexity of these is optimized to ensure their real time implementation. Histogram modification is one of the very important techniques for image enhancement. In histogram modification the original image is rescaled so that the histogram of the enhanced image follows some desired form.

VII. Conclusions
It is dear from the literature survey that infrared signal processing algorithms and architectures are equally important for the development of a high performance infrared imaging systems. Infrared signal processing deals with two types of processing sensor signal processing and infrared image processing for contrast enhancement and target detection. The sensor signal processing

primarily deals with non-uniformity correction for infrared sensors. This arises because of differences in the photo response of the individual detectors of the focal plane array. Such a difference exists between neighboring detectors even if they are illuminated by the same radiance. Some researchers have described black body and calibration based non-uniformity correction methods and some have described the scene based adaptive non-uniformity correction algorithms.

Calibration based method involve interruption in the operation of the infrared systems and do not provide the best result under different environmental conditions. Most of the scene-based methods described in the literature correct only offset non-uniformities and most of the methods cannot be implemented in hardware in real time, which is the fundamental requirement for an infrared imaging system. Thus, further investigations in non-uniformity correction algorithms and their implementation are needed. Infrared images are of poor contrast and high background noise, which result in poor visibility of the object. In addition, dynamic nature of the background and non-availability of background clutter characteristics affect the performance of the imaging system.

The quality of an IR image depends on radiation pattern as well as the difference of temperature between the object and the background. Several researchers have described various types of algorithms based on histogram modification, logarithmic contrast enhancement, frame averaging, median filter, adaptive median fitters, kuwahara filter, high boost filtering, spatio-temporal filtering, wavelet transform and Fourier transform based image processing. However, these methods do not yield satisfactory results under different environmental conditions and also are difficult to implement in embedded hardware for real time applications. Hence further investigation will be useful to develop improved self-adaptive methods for infrared image enhancement and target detection systems. These methods should be capable of catering to most of the infrared scenarios over a wide dynamic range and real time implementation on a FPGA based embedded hardware. From the literature review it can be concluded that efforts to improve the performance of the infrared imaging systems will continue. More and more dedicated, intelligent and innovative sensor signal processing and infrared image processing algorithms will evolve. The real time implementation of these will result in the design of high performance next generation infrared systems.

VIII. Applications
Infrared Imaging Systems are used for various applications extending from surveillance and reconnaissance to long range target acquisition, engagement and missile guidance. Night Vision Systems for ground, air and naval applications, infantry and armored fighting vehicles, fire control and sighting systems and medical applications. Infrared systems can be used in complete darkness. They are partially affected by smoke, dust or haze. They can detect objects through camouflage nets. They cannot be blinded by searchlight, flares and fire. Fig. 5 illustrates the basic block diagram of a typical Automatic Target recognition (ATR) system. Black box represents the scope of this thesis.

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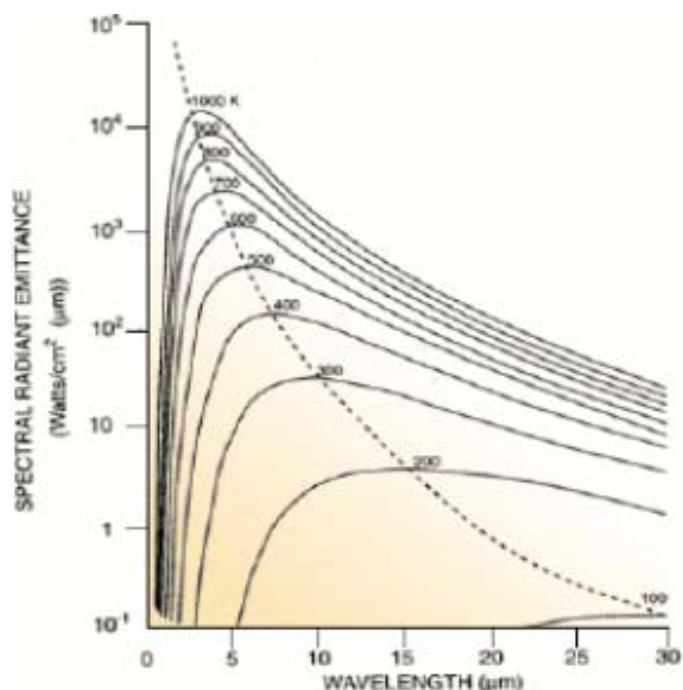
Fig. 1: Wien's Displacement Law, Spectral radiant flux versus wavelength
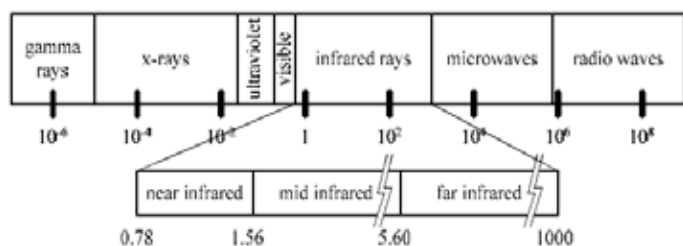

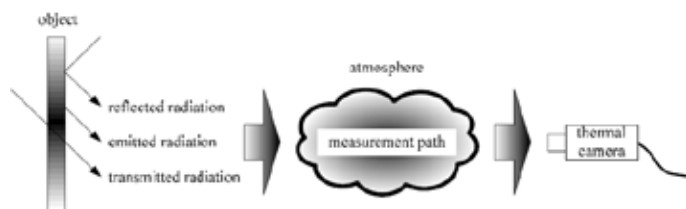Fig. 2: Electromagnetic spectrum

Fig. 3: Thermal image as a function of energy radiation
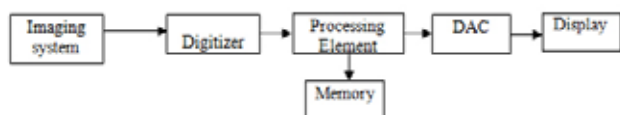

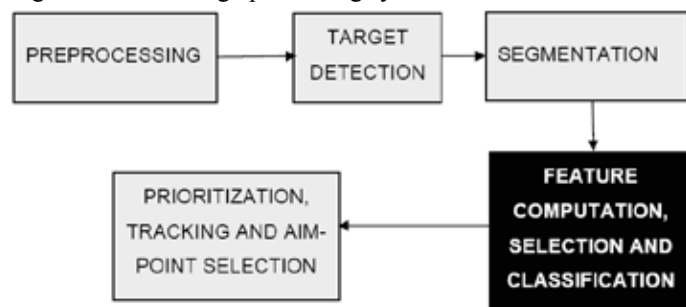Fig. 4: General image processing system

Fig. 5 : Basic block diagram of a typical ATR system. Black box represents the scope of this paper