Design Challenges and Considerations for Image Fusion in Multi-Spectral Optical Systems

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Abstract

Data from multiple spectral wavebands can significantly increase the information available to the observer. Of particular utility is combination of images into a single multi-spectral image. When such images are combined properly, the resulting image can be an extremely powerful tool, sometimes offering more information than the imagery from either waveband individually.

Substantial care must be taken in the combination of these images, however, since mis-registration of the two images can cause significant confusion and image degradation when combined into a single image. Mis-registration from sources such as relative lateral or rotational shift, differences in image size, and differences in distortion can cause significant degradation in the combined image. Special care must be taken in both the optical and mechanical design to minimize these effects and to maximize the utility of multi-spectral image fusion.

Overview

Observation of a scene in different spectral wavebands can provide a great deal of additional information over that present in any single waveband. For example, visible imagery provides information about the color of an object, while infrared imaging of that same object provides information about the object's thermal emission. Each spectral waveband provides useful information; however by observing images of the object in both spectral wavebands, one can know both the object's visible color as well as its apparent temperature. If humans could sense both visible imagery as well as thermal imagery, it is unlikely that anyone would ever make the mistake of touching a very hot object, since its temperature would be directly observable.

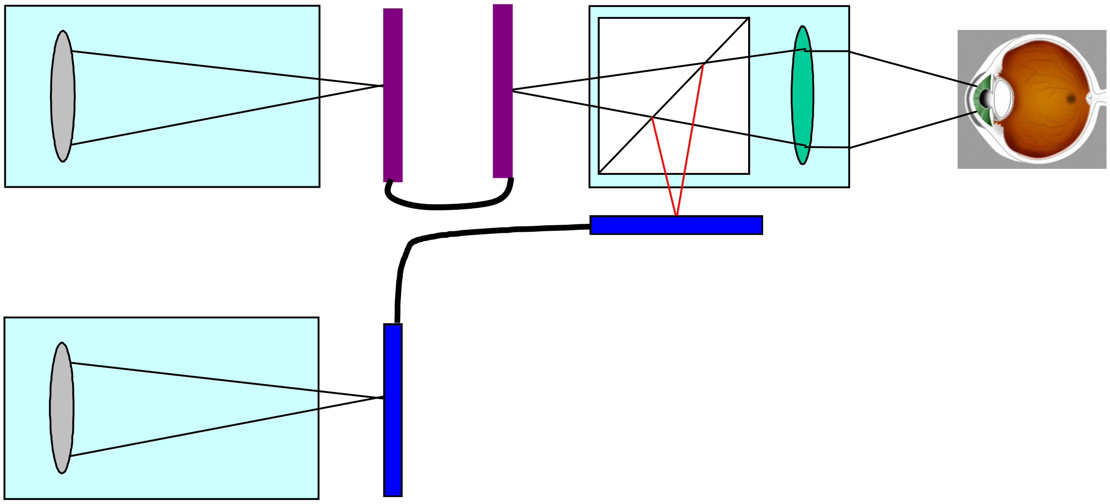
Combination of imagery in multiple spectral wavebands has been achieved, primarily in military systems, for several years. These systems began as vehicle or airborne assets due to physical size and weight; however recent advances in technology have allowed advances that can now make such systems easily man-portable. Miniaturization to head-mounted systems and weapon-mounted systems can now be realized. The following describes several methods used for combination of multi-spectral images and the special design considerations that must be taken to maximize the benefit of multi-spectral image fusion.

Image Fusion Methods

Image fusion methods generally fall into two major categories – electronic fusion and optical fusion. For the purposes of this paper, this author will differentiate each fusion method by one principal difference – electronic fusion involves observation of displays for all spectral images, whereas optical fusion involves the direct observation of at least one channel (i.e. no display). Each method has it own advantages and limitations and is discussed below.

Electronic Image Fusion

As defined above, electronic image fusion systems present two different spectral waveband images to the observer via discrete displays. This is generally achieved through two separate imaging systems that may be physically separated by any desired distance, though common-aperture systems are also possible for this system type. The images captured are then electronically relayed to displays, one for each spectral band to the observer. These displays may be presented to the observer in a combined eyepiece such that the images are overlaid before observation or each spectral image may be presented to separate eyes allowing the eye-brain to combine the images. A block diagram of this system type is illustrated below.

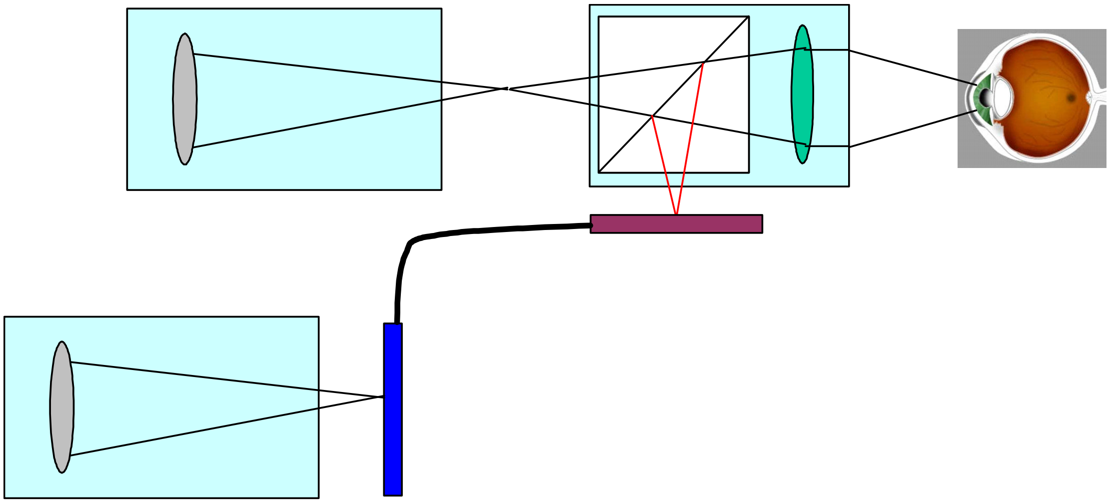


Electronic Fusion Systems Offer Packaging Flexibility

This system type offers a great deal of packaging flexibility, since the imaging lenses and detectors can be remotely located. However, several potential limitations accompany this flexibility such as parallax and display resolution limits. Each of these considerations is discussed in detail below.

Optical Image Fusion

Observing the same definitions, optical image fusion systems present two different spectral images to the observer, with at least one image being directly viewed (no display). This system configuration may use either separate imagers or common-aperture imagers. The constraint on this system type that one image be directly observed places a significant limitation on the packaging flexibility allowed, since it demands that the objective lens and eyepiece be aligned in front of the observer. As with electronic imaging systems, the eyepiece may be designed to accommodate combination of the images directly, prior to presentation to the observer, or the separate images may be displayed – one to each eye.



Optical Fusion Systems Offer Maximum Resolution

The principal advantage of the optical fusion configuration is the high resolution possible with such systems, particularly wide-angle systems. Depending on the system application, the observed field of view may be anywhere from several degrees (narrow field, high resolution system) to many tens of degrees (wide field of view, panoramic system). For man-portable systems, the system imaging requirements generally favor moderately wide fields of view to increase situational awareness. Other vehicle-mounted applications also favor fairly wide fields of view, such as driver's sights to allow modest "peripheral vision" to which humans are accustomed.

For systems with wide field of view requirements, optical image fusion is critical to maintain good resolution in at least one waveband. Consider a typical goggle field of view of 40 degrees (32H X 24V degrees). For a sampled system using displays, most current systems use 320X240 displays, with some newer systems using 640X480 displays. For the smaller display, it is seen that the field is sampled at a pitch of 10 per degree, giving a pixel size of 0.1 degrees or approximately 1.75 mrad in object space.

Such a system is considered to have a resolution of 2X this pitch (one complete cycle or two pixels) or 3.5mrad. Similarly for the larger display, the displayed pixel size is 0.05 degrees or about 0.875mrad (provided that the image captured by the objective assembly and detector contains at least this resolution) and the system resolution is 1.75mrad.

This sampled resolution is compared to a non-sampled system that can be achieved with an optical fusion system as follows. The generally accepted angular resolution of the human eye is 1.0 arc-min. Provided the optical system in from of the eye is reasonably well corrected, the overall system resolution can be the eye resolution itself. This resolution is equivalent to 0.0167 degrees or about 0.3mrad. This resolution can only be achieved, of course, in the visible spectrum, where no image sampling is required on either the detection or display of the image. However, even some systems that are sampled on the detection side can benefit significantly from the optical fusion approach. For example, current state of the art night vision systems use an image intensifier that has resolution on the order of 60cyc/mm. This resolution, when used with a typical goggle eyepiece focal length, results in a system resolution that is slightly above eye-limit, but considerably better than the sampled systems described above.

Special Design Considerations

Special consideration must be given in image fusion systems to system parameters that can cause poor alignment of the images. If such errors are present, the observer may experience loss in resolution or may fail to detect objects in the field of view that would normally be observed. Several design and fabrication parameters are discussed below and the potential impact each has on the fusion of imagery from different spectral wavebands.

Image Offset

When two images are overlaid, one critical parameter for image registration is relative image offset. Such offset can be either lateral offset or rotational offset. Lateral offset between images will cause an apparent blurring or loss in resolution in the direction of the offset, provided the object or scene being viewed is observable in both wavebands. For example, the overlay of visible and infrared images in a daytime image would experience degradation in resolution if the images were offset laterally. This same overlay would, of course, not experience degradation (from the image combination) in a night time image, since the visible image would not be present. This offset must generally be controlled to substantially less than the resolution of the waveband with the coarsest resolution (if the resolution is different between the two spectral wavebands) in order to eliminate degradation of the fused image resolution. Lateral offset can generally be minimized by electronically shifting the images relative to each other on a pixel to pixel basis.

Relative rotation between the two images can also contribute to the degradation of combined images, however the result of this offset is different than the lateral offset in that objects near the center of the image experience little offset, while objects near the periphery of the image undergo relatively large offset. This type of offset is significantly more difficult to eliminate, if present. Generally this type of offset is controlled through opto-mechanical tolerances, though a rotational image transform can, in principal, be applied to the data to rotate the displayed image.

Image Magnification

Even if the centers of the two images to be combined are perfectly registered, differences in magnification can cause mis-registration of the images for off-axis portions of the image. This error is nominally zero at the center of the image, but gets progressively larger towards the outer edges of the image. Typical variation in focal length due to tolerance stack up can be several percent of the nominal focal length. For short focal length systems, this change is quite small. However for long focal length systems the absolute variance in focal length can be quite large, causing substantial changes to the image size.

An example of this variance can be demonstrated by examining a potential system with the following nominal parameters:

System Effective Focal Length (EFL) = 100mm
Detector Format = 1280 X 1024, 6µm pixels
Field of View = 4.398 X 3.519 degrees (5.631 deg diagonal)

If the actual system is built and the focal length is longer than nominal by 2.0%, then the actual system parameters are as follows:

System EFL = 100*1.02 = 102mm
Detector Format = 1280 X 1024, 6µm pixels
Field of View = 4.312 X 3.450 deg (5.520 deg diagonal)

If two images with this same resolution are combined, the resulting magnification change due to the change in focal length is 0.043 degrees in the horizontal dimension and 0.055 degrees on the diagonal. Given the nominal pixel extent is 4.398 deg/1280 pixels = 0.0034 deg/pixel, this difference in magnification is 12.5 pixels of image mis-registration at the horizontal edge of the image. It is seen that even near the center of field, focal length differences this large can cause several pixels of image mis-registration. This mis-registration can cause image degradation by making the edge of objects appear “smeared” and causing a reduction in the system resolution.

Image Distortion

Since differences in focal length are very important, it is no surprise that distortion must also be carefully controlled. Distortion is defined as a change in focal length with field angle and therefore can cause image mis-registration must like that seen in the focal length differences. The principal difference between the errors introduced by magnification change and those from distortion is that while the magnification change tends to produce image shift that is linear in magnitude with field, distortion can produce non-linear shift with field. The end result is similar, however with distortion mismatch, the image may be significantly better (or worse) over a significant portion of the central viewing zone and worse (or better) closer to the image edges.

An example of image mis-registration due to distortion is detailed below.

Imager #1
EFL = 20mm
Detector Format = 320 X 240, 20μm pixels
Distortion = -2.0%
FOV = 18.545 X 13.962 degrees

Imager #2
EFL = 20mm
Detector Format = 320 X 240, 20μm pixels
Distortion = +1.0%
FOV = 18.004 X 13.551 degrees

This small distortion mismatch causes one-half degree of difference in horizontal field of view. This difference equates to approximately 4 pixels of image mismatch at the edge of the field of view.

Parallax – Common vs. Multi-aperture

Parallax is a potential issue unique to multi-aperture sensors. From a design perspective, a system that utilizes separate objective lens/sensor assemblies is generally simpler, since the performance and critical parameters (such as those discussed above) need to be controlled for a single spectral waveband for each assembly. This simplification can cause parallax, depending on the separation of the objective assemblies and the range of distances over which the image fusion is to be accomplished.

An example of parallax introduced by separated sensors is illustrated as follows. Consider a sensor system with objective/sensor assemblies separated by approximately 10 inches, as might be the case when mounted on opposite sides of the head. If these sensors are oriented to point nominally straight ahead, then the angular position of a target is slightly different in each sensor, depending on range to the object. For example, for an object at 1000m the object appears shifted (toward the right for the left sensor and toward the left for the right sensor) by 0.127mrad. This shift is probably not perceptible, even for an image fusion system, unless the system has resolution of 0.25mrad or less.

The example above shows very small parallax due to the very large range to the object compared to the sensor separation. However, for shorter ranges the parallax can become quite apparent and can cause significant issues for image fusion. Consider a system with the same 10 inch sensor separation as that considered above, but an object distance of 200 meters. The apparent angular shift for the object at this distance is 0.635mrad. This shift will be noticeable for systems with resolution on the order of 1.0mrad and will cause degradation in image quality for overlaid images. At 100mm the effect is doubled causing significant degradation in a fused image due to the lateral offset of the images.

A common aperture system, by definition, will not experience parallax, since all or part of the objective lens assemblies are common to the two separate sensors. This arrangement can, in principal, achieve the best image fusion, without regard to object range. However, the designer's job may be significantly more difficult in a common aperture system since all of the principals outlined above must be met for both spectral wavebands simultaneously within a common optical train. Commonly the designer will need some degree of flexibility between the spectral paths and will use one or several optical elements in each path after the spectral separation to properly optimize the design to meet the stringent requirements demanded of the image fusion.

Large resolution or large field of view differences

Selection of the particular sensor used for each path in a fusion system is drive by many factors including system requirements, cost, and commercially available vs. state of the art sensor technology for the wavebands of interest. Image fusion can be extremely effective when the resolution of each spectral band is approximately the same. Additionally, while in general, the fields of view for each sensor is not identical (and possibly not the same aspect ratio or shape), it is generally most beneficial if both fields of view are close to the same.

Some combinations of wavebands, however, have potential to produce images with relatively large differences in either resolution or field. For example, visible sensors are readily available in large formats with very small pixel sizes (<5μm). By contrast, microbolometer technology is rapidly gaining popularity for thermal imaging, however many commercially available microbolometer sensors are quite modest format with relatively large pixels (50μm). Technology is rapidly progressing to both reduce pixel size and increase overall format size; however these devices are considerably more costly. As a simple comparison, if one considers a fusion system with visible and microbolometer sensors and if, for simplicity, we assume that the two objective assemblies have the same focal length, then the resolution in the two images will be different by a factor of 10. If these images are overlaid, the large difference in the resolution may cause significant confusion and be quite objectionable to the observer.

A potential compromise in such a situation might be to reduce the field of view for the thermal imager by a factor of 1/3. This reduction means that it is no longer possible to overlay the images over the full field of view for the visible (in this case) sensor. The thermal image will instead be fully within the visible image and cover the center 1/3 of the image. While the overlay is now over a reduced portion of the total field, the resolution difference is much smaller (3X) causing much less potential degradation in the combined, fused image. This compromise may offer significant improvement in the overall system performance even though the image fusion can only be achieved over a portion of the field of view.

Summary

Combination of images from different spectral wavebands can significantly improve the detection and imaging capability over either of two sensors individually. Careful overlay and registration is critical to gain full advantage of the fusion of the two images. In fact, if good registration between images is not achieved, substantial degradation can result. Many factors must be considered by the system engineer and by the optical designer in the development of an image fusion system, among them image offset and differences in image magnification and distortion. Additionally careful consideration of total field of view and resolution for each sensor must be incorporated to make sure gross differences are not present. Separate aperture and common aperture systems also present unique benefits and challenges that can impact image fusion systems.