Imaging IR sensors: future directions for test and evaluation

Glenn D. Boreman

University of Central Florida, Department of Electrical Engineering
Center for Research in Electro-Optics & Lasers
Orlando, Florida 32816

ABSTRACT

This paper is a review of present state-of-the-art and future technologies for infrared scene projection, including both target and background simulators. We will address the need to develop appropriate figures of merit for comparison and evaluation of these test methods. Test methods we will review and compare include: raster-scanned laser, liquid-crystal light valve, deformable membrane, reflective deformable-mirror spatial light modulators, thermal emitter arrays, and infrared halftone transparencies.

1. INTRODUCTION

Infrared scene projection (IRSP) is a technology for creating realistic infrared imagery, which is used for hardware-in-the-loop (HWIL) performance testing of thermal imaging systems. Actual field testing of system performance with real IR scenes is time-consuming and expensive. Field testing also lacks a quantitative basis, because natural scenes are ill-defined in terms of the specific characteristics of their radiation signatures. However, the performance of a system in response to real scenes is the final criterion. Methods are desired for the creation of realistic IR scenes that can be precisely described and calibrated, and which are of sufficient quality to measure the performance characteristics of the system under test.

In the past, IR scenes had been created by computer, or recorded from videotape of real IR scenes. Typically, the resulting video was injected behind the detectors in the system (Fig. 1) to exercise the image processor, tracker, and display of the system. This approach did not exercise the optics, detector, and electronics subsystems, and therein lies the need to develop IR scene-projection techniques instead of synthetic IR scene generations for end-to-end system characterization.

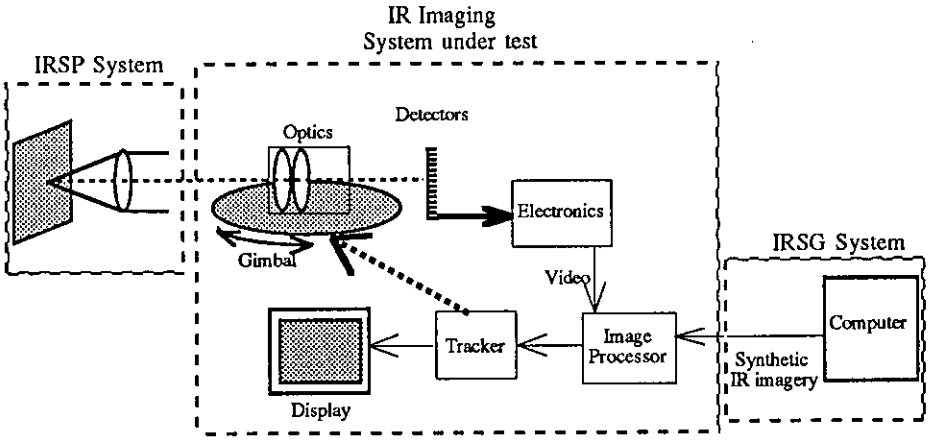

Figure 1. Schematic of IR imaging system under test.

2. REQUIREMENTS FOR INFRARED SCENE PROJECTION

Successful IRSP systems have rather demanding requirements. The scene projector system must be able to access the pertinent performance characteristics for the thermal imager system. Ideally, the scene projector system must have significantly higher performance than the system under test (a factor of ten or so better performance in all aspects). Given the current state of the art in IR imager systems, this requirement is increasingly difficult to meet in an across-the-board manner, which may necessitate the development of test hardware with specific functionality optimized for certain tests. The main technical requirements for IRSP systems fall into the following categories:

Spatial resolution
Dynamic range
Spectral bandwidth
Frame rate
Spatial uniformity
Noise
Flux transfer efficiency.

These requirements parallel the corresponding performance characteristics for IR imaging systems, with some being more important that others for any given application. For example, most current IR imaging systems simply respond to "in-band" flux, but more sophisticated imaging radiometer systems will have spectral discrimination capabilities. The development of an overall figure of merit framework for IRSP systems will necessarily include weighting factors that emphasize the level of system performance being tested for any given parameter.

3. TYPICAL PERFORMANCE RANGES FOR IRSP SYSTEMS

Spatial Resolution

Current IR imaging systems operate at typical resolutions of 512 by 512 pixels, with 1024-by-1024 systems on the horizon. The general requirement of factor-of-ten overkill on IRSP performance versus IR imaging system performance is probably not achievable here in the near term. A one-for-one pixel match is an achievable compromise. However, a one-for-one pixel match has the additional complexity of matching nonsquare-format pixel arrays. If both the IR imaging system pixel arrangement and the IRSP pixel arrangement are square arrays, then a one-to-one match will work, given that the systems are aligned precisely so that the pixels overlay precisely. If the IR imaging system is gimballed where the system field of view moves over a larger field of regard, a strain is placed on the number of pixels required for the IRSP, as well as tight requirements on the pixel alignment. Scanned laser systems can achieve an oversampling to some degree, just in terms of number of resolvable elements, but even those systems have limited data bandwidths. A particularly troublesome problem for scanned laser systems is that they will not work with scanned IR imaging systems without a synchronization of scan. The scan velocity is a hard parameter to vary independently, both for IR imagers and IRSPs. Especially for test equipment that must have flexibility to adapt to different IR imaging systems, a scanned laser IRSP should have a variable scan rate and ability to synchronize to an external source.

Dynamic Range

Testing of imagers intended for air-to-surface, surace-to-surface, and air-to-air engagement scenarios have different dynamic range requirements.

Dynamic range requirements are most often stated as N:1, or as a given number of bits. For IR imaging systems that eventually display to a human observer, the use of 8 bits (256 gray levels) is the usual dynamic range. However, many IR imagers are being built with higher dynamic range requirements, such as 12 bits (4096 gray levels). The main requirement for IRSP systems is to be able to simulate both the hot plume of a missile and the earth-temperature background clutter. Dynamic range has a number of common specifications.

Contrast ratio is the usual measure of dynamic range, though it has no universally accepted definition. Contrast ratio is expressed in terms of the maximum and minimum output levels the IRSP is capable of achieving. It is also commonly expressed as

$$\text{Contrast} = \frac{\text{output}_{\max} - \text{output}_{\min}}{\text{output}_{\max} + \text{output}_{\min}} ,$$

or as

$$\text{Contrast} = \frac{\text{output}_{\max}}{\text{output}_{\min}} .$$

Another way of specifying dynamic range is the range of temperatures that can be simulated. This requires a conversion from flux units to temperature through the Planck radiation equation. A universal means of specifying dynamic range would be the maximum output achievable, divided by the noise-equivalent output (output for $S/N=1$, or RMS noise expressed in output units).

The dynamic range is limited at the low end by noise in the IRSP system. These noise sources can arise in various ways: temporal noise in the modulation or emission mechanism, spatial noise (pixel-to-pixel variation), stray radiation (crosstalk or leakage), or quantization noise. Dynamic range is limited on the high end by saturation effects in the mechanism that generates the IR energy. For example, the radiance produced in the image plane of a system can not exceed the source radiance being imaged.

Typically the linearity of the IRSP system within its dynamic range is not specified, that being correctable by a look-up-table operation of the desired input data.

Spectral Bandwidth

Laser-based systems provide acceptable testing for systems that operate on in-band flux. To test broadband systems using lasers, several laser channels are often used, taking advantage of the somewhat limited choices one has in IR lasers (e.g., CO, CO_2, and HeNe). Practical problems in testing systems arise primarily in two areas: speckle effects and anti-laser coatings.

Laser speckle is a coherent multipath interference phenomenon that causes the projected image to be received with additional noise. Rotating diffusers are commonly employed to average out the effects of the speckle, with the period of the rotation being much shorter than the integration time of the sensor under test.

Some systems are hardened with interference coatings (optical filters that reject specific wavelengths) against specific laser wavelengths. These coatings effectively block laser radiation that might harm the sensor element in a battlefield scenario, but for convenient in-situ testing of real systems, these coatings also exclude the lasers used by IRSP systems.

In some specific instances, the use of lasers is indicated for IRSP applications, but for the majority of targets upon which the IR imaging systems will be asked to operate, the radiation will be incoherent, and the use of lasers introduces a degree of artificiality into the test, which should be avoided if possible.

Lasers are useful is in the creation of high-brightness regions in the projected image, corresponding to the plume of a missile or other high-intensity target. Often, the background clutter and low brightness targets are projected using a thermal source, while the plume is simulated using the high radiance available from a laser source. The IRSP system is essentially two separate systems with beamsplitter optics used as beam combiners. This effectively increases the dynamic range of the aggregate IRSP system, because the range of temperatures that can be simulated is greatly increased by having a laser take the task of the high-brightness regions.

Frame Rate

While standard video systems operate at 30-Hz frame rates, the requirement for endgame simulation, where the sensor has closed in on the target, is typically in the range of 400-Hz frame rates. This high frame-rate requirement precludes some classes of thermal-emitter IRSPs where the radiation emission mechanism cannot respond sufficiently. Laser-based systems can generally operate at this rate without problems, as can some of the spatial-light-modulator-based systems.

From a system specification point of view, the high-frame-rate requirement must be considered in terms of its effect on all other performance specifications. For example, a system with adequate resolution (MTF) at low frame rate may well have insufficient image contrast when required to operate at these high frequencies.

Also, simply the data bandwidth of the system must be considered in those situations where a high-resolution image needs to be projected at high frame rates. For example, an 8-bit, 512-by-512 image projected at a 400-Hz frame rate requires nearly 1 Gbit/sec data rate. This will generally require parallelism in the drive electronics for the modulators in the IRSP.

For a scanned system with many pixels, the requirement of a certain integrated energy over a frame time can lead to damaging level of power during the short dwell time. This is particularly true for laser-based systems.

Spatial Uniformity

Spatial uniformity is not currently a parameter of major concern, as the current IRSP struggle to meet other more basic requirements. However, as the performance improves in areas of resolution and frame rate, spatial uniformity will become a factor that sets the lower limit of the dynamic range, in much the same way as spatial uniformity sets the lower limit on noise-equivalent temperature difference in staring IR imaging systems today. Uniformity of response of the modulation or emission mechanism is an area that must be addressed as the performance of the IRSP systems eventually improve.

Noise

Similarly, the temporal noise of the projected image is not often specified in current IRSP systems. This is a result of dynamic range usually being specified on the basis of image contrast, rather than as a noise-equivalent flux. All modulation or emission mechanisms have some inherent noise sources, and these, for the most part, remain to be addressed.

Flux-Transfer Efficiency

One issue that is largely ignored in the specification of IRSP systems is the overall flux-transfer efficiency. While specified parameters such as contrast may be reasonably high, if the overall flux level reaching the detectors of the IR imaging system is too low, the dynamic range of the imager will not be adequately tested. Indeed, the contrast levels can often be optimized at the expense of overall flux-transfer efficiency. Again, the system tradeoffs would be clearer if a noise-equivalent flux density were employed, rather than simply contrast ratios.

Development of Global Figures of Merit

The comparison of developmental IRSP systems will be facilitated by more meaningful figures of merit than simply the use of contrast ratios. A signal-to-noise-ratio-based figure of merit will address several of the concerns noted above regarding correct normalization of projected flux values to the noise level of the IRSP.

In addition, meaningful IRSP figures of merit will likely be multivariable combinations of performance parameters, in a functional form that emphasizes their interdependence. A current problem in "specmanship" for IRSP systems is that one performance number is quoted at a time, while the remaining parameters are allowed to be at whatever value optimizes the one performance characteristic being specified. For example: contrast ratios are often quoted for static scenes, or MTFs are quoted for situations where the overall flux transfer efficiency of the system has been compromised.

An approach to specification of IRSP systems may be a signal-to-noise ratio, as a function of both temporal and spatial frequency, along with a specification of the maximum projected flux levels as a function of wavelength. A figure of merit of this sort would account for spectral fidelity, contrast, frame rate, resolution, noise, and flux transfer efficiency.

As the approach shifts from comparison of developmental IRSP systems to the choice of which IRSP system is best for a given application, the framework within which the figure of merit is expressed may be expanded to include weighting factors that emphasize the level of imaging system performance being tested for any given parameter. For instance, for any given imager to be tested, a different importance will be attached to resolution, frame rate, spectral fidelity, etc. The weighting factor applied to a given parameter in the IRSP selection process should be proportional to the performance level of the imaging system to be tested on that parameter.

4. COMPETING APPROACHES

This section discusses the mechanisms for some competing approaches and will compare the advantages, drawbacks, and future directions of each.

Static IRSP Systems

For projection of static scenes, the current practice is quite rudimentary. Outline masks are frequently fabricated as cutouts in metal, and backlit by a blackbody or laser source. If the scale of the target needs to change to simulate endgame scenarios, an IR zoom lens is used to change scale corresponding to target closure. If groups of targets are required to have relative motion, separate cutouts are placed on movable positioner rails.

This class of target can simulate high dynamic ranges, but the drawback is that the cutout is a binary image, either bright or dark.

A recent development in this area that stands to provide more sophistication for static scene projection is the use of infrared-transmitting halftone screens.[1-3] These targets are still constructed of the binary materials characteristic of IR targets, but have sufficient spatial resolution that groups of pixels can be placed within a given resolution element of the IR system to be tested, producing an effective gray-level response. The transmission of any given pixel is determined by the size of the photolithographically defined hole in the opaque material coated on the substrate. As an example of the current capabilities of this technology, a transparency that operates in the 8- to 12-μm band, produced by CI Systems, Inc., is shown in Fig. 2.

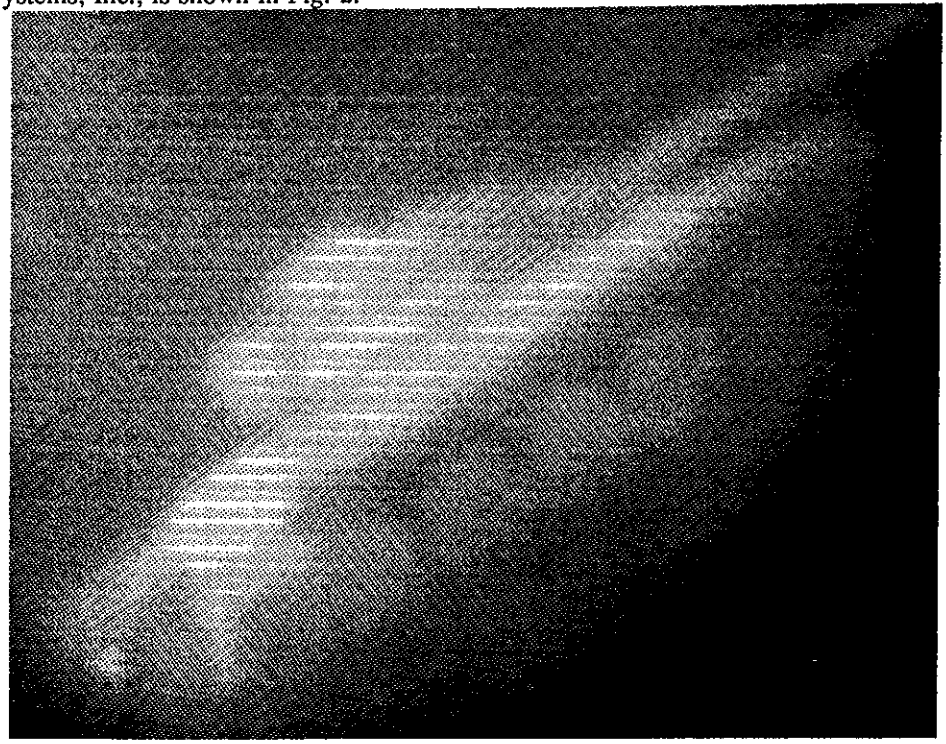

Figure 2. Tank in 8- to 12-μm band. (Courtesy of CI Systems, Inc.)

Dynamic IRSP Systems

The choices for implementation of dynamic IRSP systems are more numerous than the choices for static systems.

Raster-scanned laser. One system approach that has progressed quite far to practical application is the raster-scanned laser, seen schematically in Fig. 3. The laser radiation can be modulated simply as a flying spot scanner, or can be modulated in scophony[4,5] format, which has a larger illuminated aperture in the acoustic cell, and hence a better resolution. Large-scale systems of this type have been built (for example the KHILS projector, built by Aura Systems, El Segundo, CA, installed at Eglin AFB, FL).

That particular system uses four different IR laser channels to cover the long-wave IR, with acousto-optic Bragg cells performing both modulation and scanning functions. Dynamic range, frame rate, and resolution are good, as would be expected of a laser-based system. Effects of laser speckle on the projected image have been noted and are being addressed with a rotating diffuser.

One issue that remains with this type of system is that although this approach is well-suited for testing of staring systems that integrate received power over a frame time, the testing of scanned imagers is hampered by a lack of scan synchronization. Generally, the image from a scanned FLIR system is not useful, consisting of only intermittent bright spots. Future generations of these systems should be designed with programmable scan flexibility in mind, because the IR systems to be tested have many different scan formats.

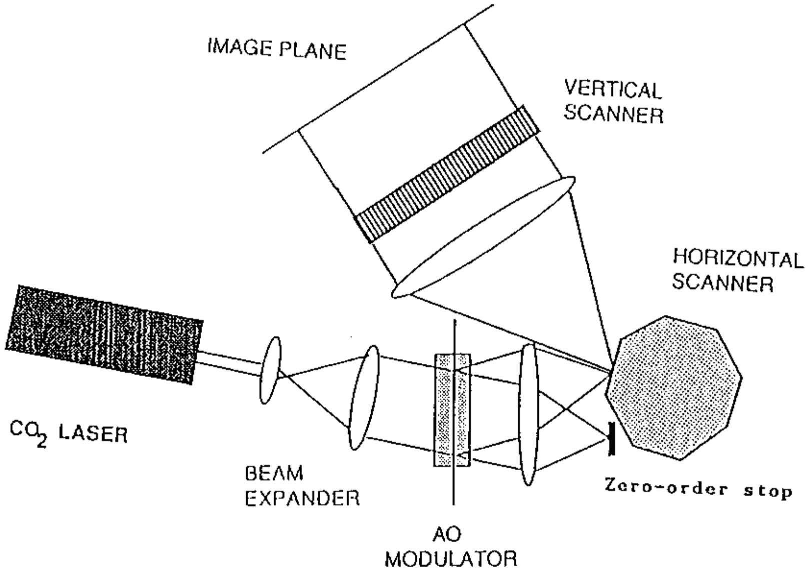

Figure 3. Scophony IRSP system.

Liquid-crystal light valves (LCLV). The technology exists[6] to implement an optical-to-infrared converter using liquid crystal display properties of polarization rotation in the IR. As seen in Fig. 4, the write-side of the LCLV is coupled to a visible CRT display, driven by standard video. The reflection of broadband IR radiation from the read-side of the LCLV is polarization modulated and, after passing through a polarizer, the radiation is intensity modulated. This technology has been demonstrated by Hughes Research Labs in the 8- to 12-μm range. These devices have approximately TV-compatible resolution and frame rate, but the main drawback has been the relatively low contrast ratios produced, in the range of 20:1.

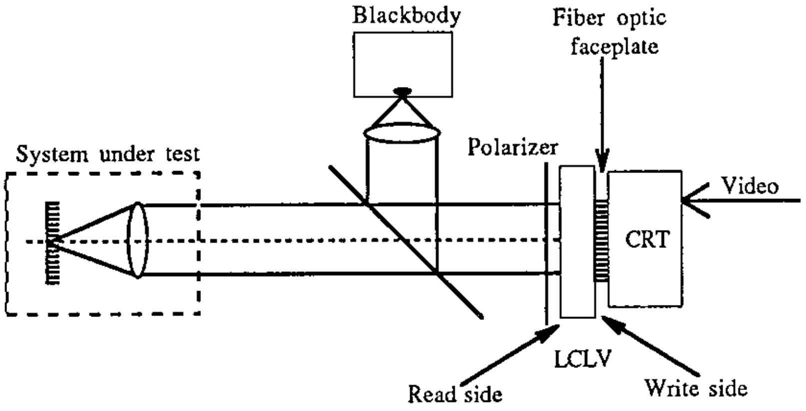

Figure 4. LCLV-based IRSP system.

Thermal-emitter arrays. Substantial activity[7-10] has occurred recently regarding arrays of resistive elements, which would emit their radiation directly in the IR by incandescence. Thermal-emitter technology faces problems in the areas of time response and pixel-to-pixel crosstalk. These issues are addressed by the construction thin-film resistors. The mass of the elements remains small, to minimize their heat capacitance and to improve the time response.

The resistors are fabricated to have small electrical leads, and are commonly operated in a vacuum enclosure. These design features ensure that the main heat loss term is caused by radiation, and minimizes pixel-to-pixel heat flow, but at the cost of a longer response time for cooling. Some designs use a heat sink contacted to the back of the elements, with control of lateral heat transfer and pixel-to-pixel crosstalk by the use of air-filled slots between elements. Some of the systems constructed have extensive cooling systems associated with the heat sink function.

Arrays up to 100 by 100 have been reported, with larger arrays currently under development. The spectral radiance of the emitters is characteristic of a thermal source. Thus, one of the spectral fidelity requirements is met, that of a broad source spectrum.

However, when the finite size of the elements is considered (non-unit fill factor) and the finite flux-transfer efficiency of the projection system is considered, the temperature of the resistive elements must be considerably higher than the temperature of the scene to be simulated, to produce an appropriate amount of in-band flux at the detector plane.

Thus, the radiation spectrum, while proportional to that of a blackbody, does not have the true spectrum corresponding to the temperature of the desired target scene.

Reflective spatial light modulators. Reflective modulators are attractive for IRSP applications because they modulate reflected power rather than emitted power, and thus the issues of frame rate, resolution, and crosstalk are more tractable. In recent years, both membrane-based and movable mirror-based spatial light modulators (SLMs) have been developed, largely for optical processing applications,[13-15] rather than for IRSP applications. The movable mirror modulators have greater capacity for angular tilt in the individual mirror elements, and thus provide higher contrast ratios than the SLMs where the reflective surface is a continuous faceplate. A schematic of a torsion-mirror SLM developed by Texas Instruments is seen in Fig. 5.

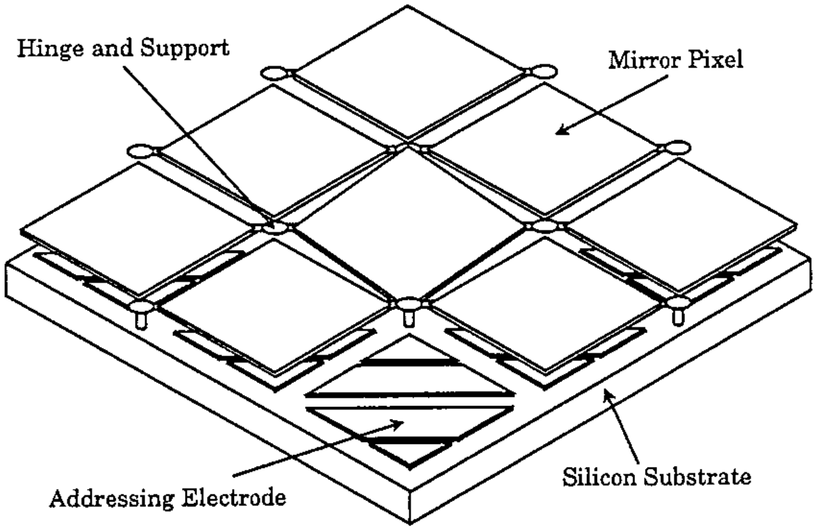

Figure 5. Torsion-mirror SLM.

A schematic of a proposed IRSP based on this SLM is shown in Fig. 6a,b. This IRSP would operate in the binary mode, where an individual pixel is either on or off, with gray levels achievable by temporal pulse-width modulation (PWM) of the mirror tilt within one frame time of the sensor under test. These SLMs are capable of frame rates of 7 kHz, so the PWM approach is capable of providing 8 bits of resolution to a 30-Hz sensor.

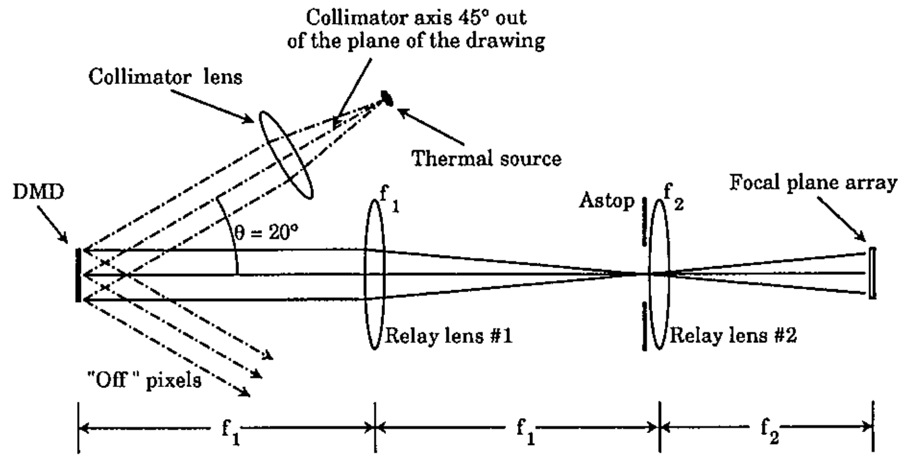

Figure 6a. Layout of proposed IRSP

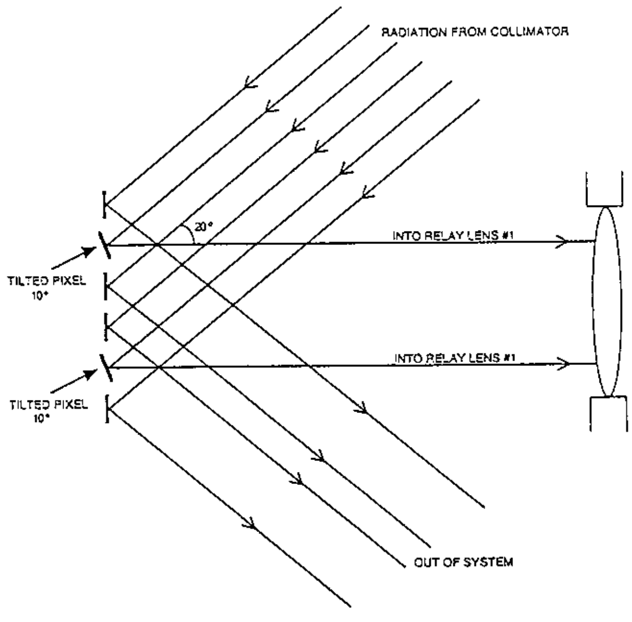

Figure 6b. Close up of modulation mechanism (geometrical optics model).

The main limitation to these devices is the crosstalk caused by diffraction. For IRSP applications, large pixels are desired. Prototypes have been made with 50-µm pixels, but the typical devices made by TI for HDTV applications (1K × 2K pixels) are 17-µm pixels. A diffraction cross-talk model has been developed[16] that predicts that contrast ratios of 256:1 are achievable with 50-µm pixels, and contrast ratios of 2400:1 are achievable with 150-µm pixels, for IRSP applications in the 3- to 5-µm band.

We performed a feasibility demonstration of the basic design seen in Fig. 6a, using a 17-μm pixel device with radiation in the 0.8- to 1-μm band. The actual configuration used is shown in Fig. 7. This should be indicative of performance obtainable in the 3- to 5-μm band with 50-μm pixels.

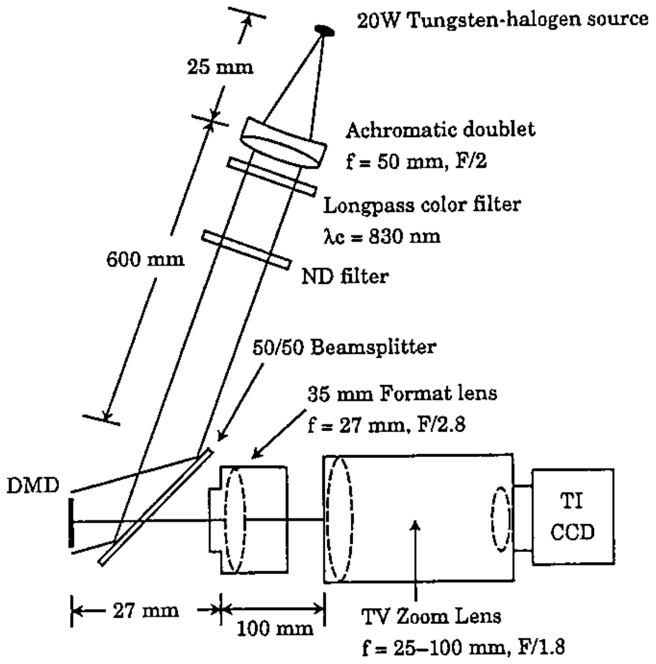

Figure 7. Layout for feasibility demonstration of IRSP with torsion beam DMD.

Notwithstanding a recent prediction that this configuration would not produce images of sufficient contrast,[17] we achieved the imagery seen in Fig. 8. Driving the DMD such that we isolated a single bright pixel, we measured the profile seen in Fig. 9 from one video line of the CCD output. The ratio of maximum signal level to RMS noise level in this measurement is around 100:1, which turned out to be limited by the clock noise of the CCD used to acquire the image. Thus, it appears from the first measurements that our diffraction crosstalk model predicts the correct magnitude of performance levels.

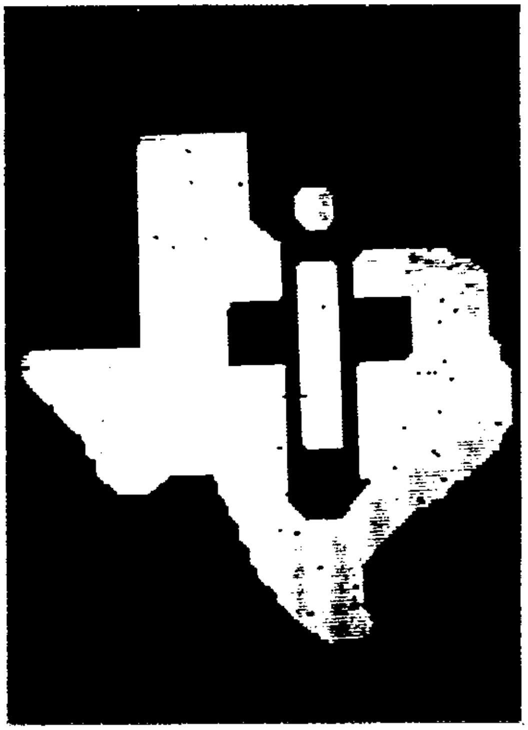

Figure 8. Image obtained using the apparatus shown in Fig. 7.

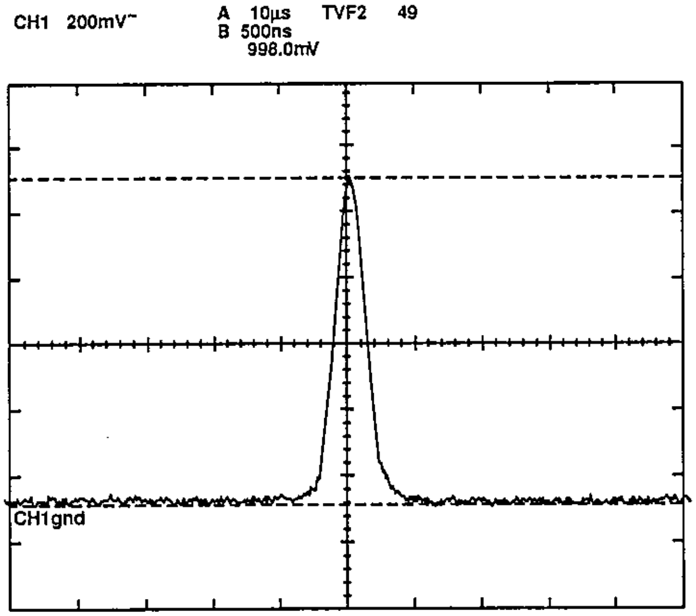

Figure 9. Oscilloscope trace of a selected video line containing a bright pixel.

The main disadvantages of this IRSP approach have been the relative scarcity of the devices, in that TI is presently the only production source of them in high-resolution arrays. However, it seems that the mirror-based SLMs can satisfy most of the requirements for IRSP. A prototype demonstration of IRSP should be done in both the 3- to 5-µm and 8- to 12-µm bands, to ascertain the ultimate performance envelope of this technology.

5. REFERENCES

1. J. W. Baer, "Infrared dynamic scene generator using halftone reflectance images," Proc. SPIE Vol. 940, 189-193 (1988).
2. S. Ghilai, U. Gera, D. Cabib, A. Lapin, Y. Liran, Infrared transparencies (thermoscenes) for simulation of infrared scenes as a tool to improve FLIR testing," Proc. SPIE Vol. 819, 80-86 (1987).
3. D. Cabib, J. Eliason, S. Ghilai, R. Bracha, "Accurate infrared scene simulation by means of a microlithographically deposited substrate," Proc. SPIE Vol. 1762 (1992).
4. R. V. Johnson, "Scophony light valve," Applied Optics 18, 4030-4038 (1979).
5. E. F. Schildwachter and G. D. Boreman, "Modulation transfer function characterization and modeling of a Scophony infrared scene projector," Optical Engineering 30, 1734-1738 (1991).
6. M. S. Welkowsky, "IR simulation using the liquid crystal light valve," Proc. SPIE Vol. 765, 89-93 (1987).
7. D. Stauffer, B. Haas, and B. Cole, "Performance of a thermal scene generator," Proc. SPIE Vol. 1050 156-164 (1989).
8. A. P. Pritchard and S. P. Lake, "Electrically heated pixel arrays for dynamic infrared scene generation," Proc. SPIE 940, 182-188 (1988).
9. J. L. Hester, "Thermal array target simulation technology," Proc. SPIE Vol. 940, 150-152 (1988).
10. L. Burriesci, D. Keezer, "A dynamic RAM imaging display technology utilizing silicon blackbody emitters," Proc. SPIE Vol. 765, 112-122 (1987).
11. E. R. Schildkraut, "IR image generation by thermoelectric elements," Proc. SPIE Vol. 765, 102-108 (1987).
12. M. Daehler, "Infrared display array," Proc. SPIE Vol. 765, 94-101 (1987).
13. L. J. Hornbeck, "128 × 128 deformable mirror device," IEEE Transaction on Electron Devices, ED30, 539-545 (1983).
14. D. R. Pape, L. J. Hornbeck, "Characteristics of the deformable mirror device for optical information processing," Optical Engineering 22, 675-681 (1983).
15. L. J. Hornbeck, "Deformable-mirror spatial light modulators," Proc. SPIE Vol. 1150, 86-102 (1989).
16. K. J. Barnard, "Crosstalk analysis of a deformable-mirror-based infrared scene projector," PhD dissertation, University of Central Florida, 1992.
17. O. M. Williams, E. J. Bevan, S. B. Mobley, "Optical aspects of infrared projector technologies for hardware-in-the-loop simulation applications," Proc. SPIE Vol. 1687, 49-63 (1992).