Bolometers Running Backward: The Synergy Between Uncooled IR Sensors & Dynamic IR Scene Projectors

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ABSTRACT

The leading IR scene projection (IRSP) device technology, resistive emitter arrays, has grown from its early roots in the uncooled microbolometer community into a separate and highly specialized field of its own. IRSP systems incorporating "microbolometers running backwards" are critical tools now ubiquitous in laboratory testing and evaluation of high performance IR sensors and their embedded algorithms. Adoption of IRSPs has reduced the scope of flight/field testing, producing dramatic resource savings and strong system development advantages.

Modern IRSP systems provide the capability to project high-resolution (1024 x 1024), high-temperature (750 K) dynamic MWIR-LWIR imagery at frame rates up to 200 Hz, with 16-bit input resolution. Novel IRSP systems are now being developed to test advanced FPAs and sensors requiring wide-format (768 x 1536), cryogenic background (50-80 K), fast-framing (400 Hz), and/or very high-temperature (2500 K) dynamic IR simulation in order to be properly evaluated.

The ongoing cycle of sensor improvement and test system evolution is perfectly illustrated by the parallel development of IRSP and emerging FPA/sensor technologies. The cross-pollination of technology between the sensor and projector domains continues to bring innovation to both communities. Technological trends related to semiconductor and micro-electrical-mechanical system (MEMS) device fabrication, real-time digital video processing, and EO system design are being exploited by both sensor and projector developers alike – with advantages realized by both.

This paper presents a lighthearted overview of the technical evolution of IRSP from its early microbolometer roots, discusses current and emerging IRSP capabilities, illustrates the device-level to system-level synergy between sensors and projectors, and offers a peek into the advanced EO simulation capabilities and technologies which will be required to address emerging FPA and sensor trends.

Keywords: Emitter Array, IR Scene Projection, Micro-Bolometer, MEMS Fabrication.

1. INTRODUCTION

Uncooled micro-bolometer technology is now ubiquitous in the infrared sensor world. Ever-improving radiometric performance and the emergence of multiple component- and system-level producers has turned this niche thermal imaging market segment into a growing and competitive marketplace. Utilizing 3-D bridge structures to suspend individual resistor elements above a CMOS readout array, modern microbolometers typically require a combination of licensed and proprietary MEMS materials, fabrication processes, and design techniques. To enable the advancement of next-generation thermal imaging devices, microbolometer R&D continues at a rapid pace, with smaller and higher-performance MEMS pixel technologies at the cutting-edge.

IR scene projection (IRSP) development began in the 1970s, with early filaments and Bly cells eventually replaced with

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resistive arrays based on the same core microbolometer MEMS pixel technology originally developed for IR sensing applications. Resistive arrays provide a unique IR simulation capability, due to their combination of wide radiometric dynamic range and high thermal resolution. Now commonly used in a variety of hardware-in-the-loop (HWIL) test applications, resistive array based IR scene projection (IRSP) systems have benefited greatly from the development of microbolometer technology. Interestingly, IRSP technology has now reached the point at which unique innovations in MEMS pixel design and fabrication are flowing back into the IR world, with applications and potential benefits in both sensor and projector communities.

2. FROM BOLOMETERS TO EMITTERS

(or, "Hey, I wonder if we could run these bolos in reverse…")

During the 1970s, it was recognized that a dynamic IRSP capability was required in order to effectively evaluate the latest and greatest IR imaging systems of the day. Static infrared targets were not adequate for true characterization of the emerging sensors and algorithms, and field tests were too time consuming, risky, and costly. This T&E gap prompted a series of studies to identify and evaluate potential dynamic IR simulation technologies. As we will discuss in section 2.4, resistive arrays emerged as the leading technology for all but a few IR scene projection applications. Before we review the history of IRSP device research and the chronology of resistive array development, we turn our attention to the MEMS – or more accurately, the micro-<u>optical</u>-electrical-mechanical system (MOEMS) – structure of microbolometers and resistive emitters, a review of pixel thermal physics, and a comparison of FPA device and system drivers for both classes of device.

2.1. Pixel Operation & Key Interfaces

For both microbolometer and resistive emitter pixel structures, a resistor element is suspended above the IC substrate by two support legs. An optical etalon is formed between the absorptive layer and a reflective layer typically deposited onto the top surface of the substrate/IC. In the case of microbolometer pixels, incident radiation causes a temperature (and hence resistance) increase within the pixel, thereby producing an irradiance-dependent current integrated and processed by the readout IC (ROIC). In the case of resistive emitter pixels, the thermally sensitive resistor film used in the microbolometer device is replaced with a unique resistive film capable of handling the extreme thermal excursions required by IR simulation applications.

During scene projection, a unique drive current is applied to each emitter pixel via a read-in IC (RIIC). This applied current causes power to be dissipated in each pixel body ($P = I^2R$), and the pixel temperature to rise dependent upon dissipated power and thermal losses (neglecting radiative losses). Depending on the physical temperature of the emitter and the in-band emissivity of the resonant pixel structure, IR radiation is emitted ($L_{out} \alpha\ T_{phys}, \varepsilon$) – and subsequently projected to the UUT by a collimator.

A typical resistive emitter pixel structure and RIIC drive topology is illustrated in Figure 1.

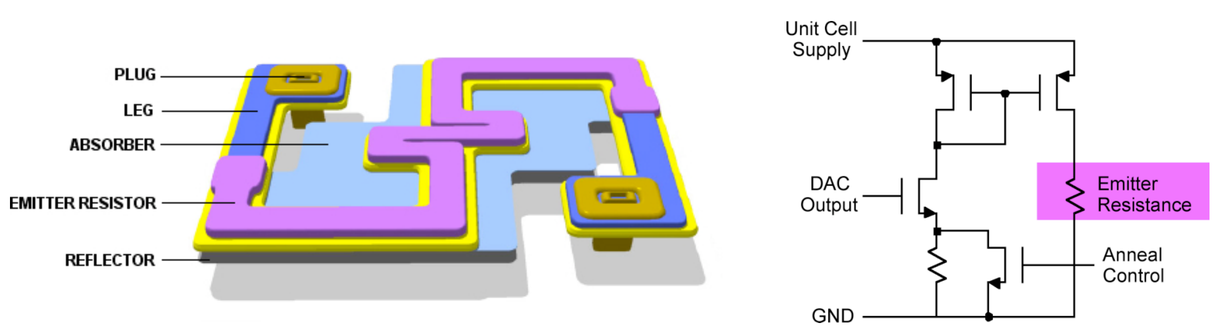

Figure 1 – Typical Resistive Emitter Pixel Architecture (left) & Electronic Drive Scheme (right)

Microbolometer and resistive emitter arrays usually require thermal stabilization, although for different reasons. Self-heating and/or thermal drift in microbolometer arrays results in image artifacts, and thereby limits radiometric performance. As we will discuss in more detail later, the large drive currents employed in running resistive arrays to useful simulated IR temperatures give rise to very high levels of array power dissipation and spatial power density. For reasons associated with both elimination of image artifacts and prevention of overheating/damage to the scene projector, resistive emitter arrays are generally liquid-cooled.

The optical interfaces to bolometer and emitter arrays are similar in that they both require specific optics with sufficient transmission, low aberration and distortion, high MTF, etc. Microbolometer optical systems are typically designed to strike a balance between performance, mass, cost, and other constraints associated with development of high-performance, compact EO systems. IR scene projection optics, on the other hand, are usually driven by the need for the IRSP system to introduce minimal degradation into the imagery, with mass and cost often considered secondary to performance. As such, the worlds of sensor and projector optics share much of the same basic technical emphasis, with a dramatically different emphasis on size, weight, and cost. As we will discuss later, novel designs incorporating modularity and zoom functions are facilitating the development of sensors and projectors alike. Figure 2a shows a typical emitter pixel and projected image, while Figure 2b shows a typical mircobolometer pixel and core imagery.

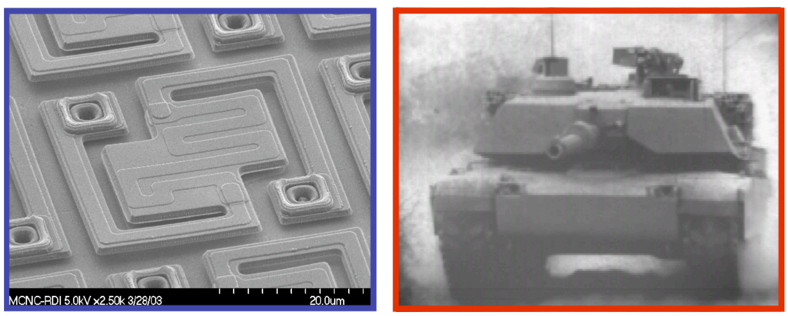

Figure 2a – Resistive Emitter Pixel (left) & Projected MWIR Image (right)
(courtesy of Santa Barbara Infrared)

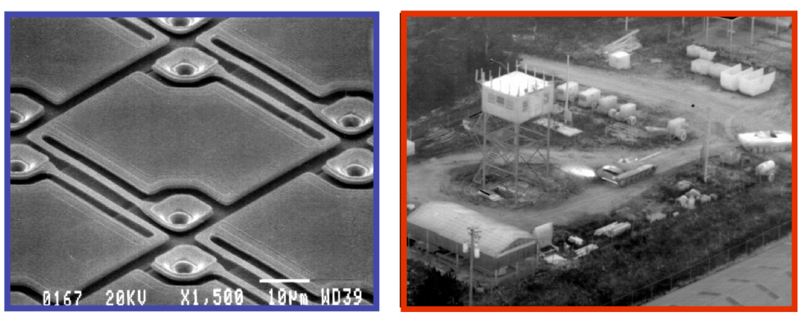

Figure 2b – Uncooled Micro-Bolometer Pixel (left) & LWIR Image (right)
(courtesy of Raytheon Vision Systems)

While most microbolometer arrays convert photons into analog video signals, emitter arrays convert 16-bit digital scene data into an array of unique analog current levels applied to each emitter. Although the sensor community is increasingly incorporating A/D conversion into ROIC designs, IRSP arrays have included on-chip, 14- or 15-bit DACs since the 1990s. This early shift to an all-digital data interface was driven by the difficulty of optimizing the analog interface between a high frame rate emitter array and a remotely located DAC (or even multi-DAC) subsystem.

2.2. Hardware-in-the-Loop (HWIL) Testing

IR scene projectors are used in an increasing number of HWIL test environments. These applications include the test and evaluation of FLIRS, imaging IR seekers, IR countermeasures, infrared search and track (IRST) systems, IR threat warning sensors, and space/strategic sensors.

The IRSP is typically employed within a dynamic, feedback-controlled architecture, as illustrated in Figure 3. In this type of HWIL installation, the IRSP receives digital video from a scene-generation computer – typically an SGI machine, but increasingly based on desktop PC technology. The IRSP mounts on the outer arm of a flight motion table and projects imagery to the UUT located at the table's center. UUT image/tracking data and guidance commands are sent to a simulation processor, which performs real-time coordination of UUT line-of-sight (LOS) and scene generator imagery.

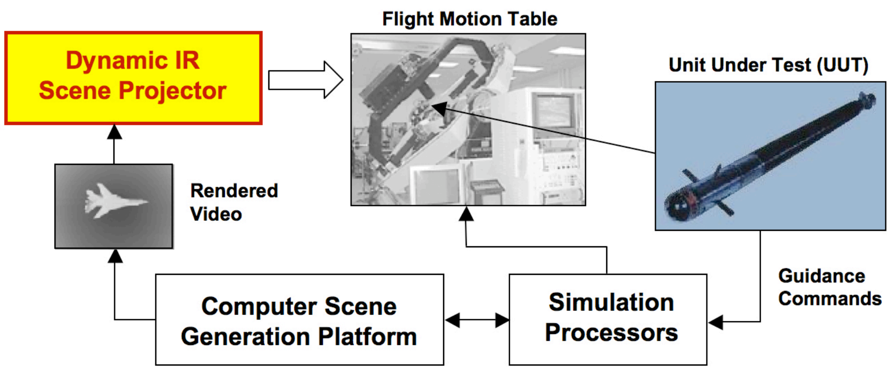

Figure 3 – Typical Hardware-in-the-Loop (HWIL) Simulation Architecture

Latency compensation is often implemented as a set of real-time azimuth/elevation/rotation parameters sent from the simulation processor to a point near the output of the IRSP data path, enabling x, y, and rotation to updated based on current UUT attitude.

2.3. IRSP Performance Drivers
(or, "Scene projector performance: How much is enough?")

For modern IRSP systems, array format is often required to be at least 1024^2 in order to support the more stressing test applications. Pixel size has held constant at approximately 50 μm, due largely to concerns associated with LWIR output/diffraction and pixel fill factor. Frame update rates are typically supported in the range of 20-400 Hz, thereby allowing simulation at integer multiple of the UUT frame rate and minimizing spatial-temporal sampling artifacts. Both snapshot and raster update modes allow optimum synchronization with both scanning and staring sensors under test.

The maximum apparent (simulated) temperature of production IRSP systems is currently in the range of 700-800 K (MWIR) and 500-600 K (LWIR). Development is already underway to extend the upper end of the simulated temperature range to at least 2500 K – the effective temperature of a late M-class star! While maximum apparent temperatures are rising, some HWIL applications such as space-based interceptor T&E require minimum simulated temperatures in the cryogenic regime. This of course requires an array specifically designed to operate with very low substrate temperature, yet with top-end radiant output comparable to traditional systems.

Typically, each pixel's radiance rise/fall time must be less than approximately 5 ms, and scene-dependent cross talk must be less than 1-3%. Operability must be greater than 99%, and cluster defects maintained to an acceptable level. Pixel substitution and interpolation functions available to sensors offer nothing to improve imagery projected by IRSP systems – no photons at a given emitter location means no radiant output, period. IRSP operability is thus a tremendous challenge, exacerbated by increasing array formats and the inherent difficulty of fabricating MEMS devices monolithically onto CMOS wafers.

2.4. History of IRSP Technologies

(or, "There's more than one way to make Max Planck happy…")

As mentioned previously, the quest for suitable IRSP technologies began in the 1970s. Initial candidate technologies for IRSP use included the Bly cell, the liquid crystal light valve, resistor arrays, Texas Instruments' digital micromirror device, deformable mirror devices, scanned laser devices, the infrared CRT, a vanadium dioxide spatial light modulator and later, laser diode arrays. Most of these devices had one or more limitations precluding their use in the most stressing HWIL environments, and resistive arrays emerged as the leading technology for all but a few IR scene projection applications. Figure 4 shows a historical overview of IRSP device R&D, from the early days of the Bly cell, to the current generation of systems relying predominantly on resistive arrays, to the ongoing research in the areas of VCSEL arrays, plasmas, and quantum/photonic crystal devices.

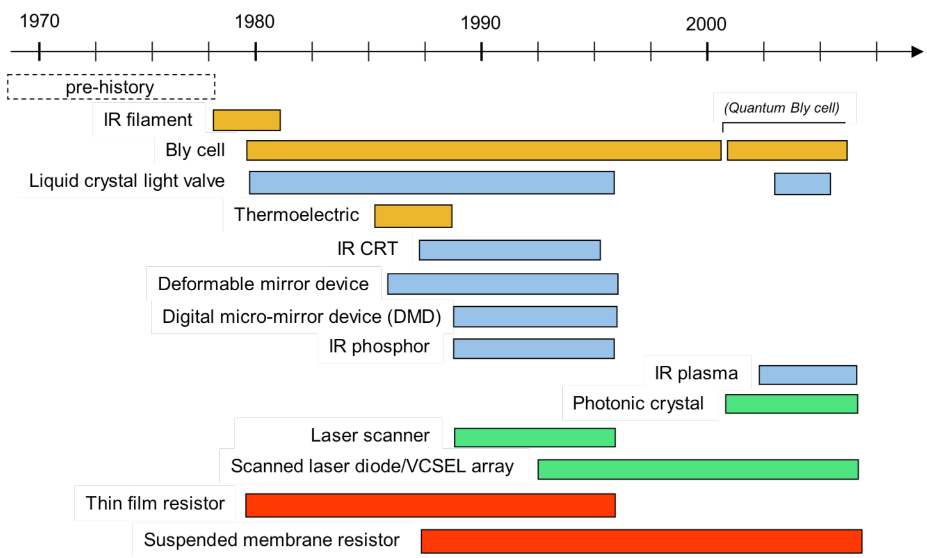

Figure 4 – Historical Overview & Time Line of IRSP Technologies

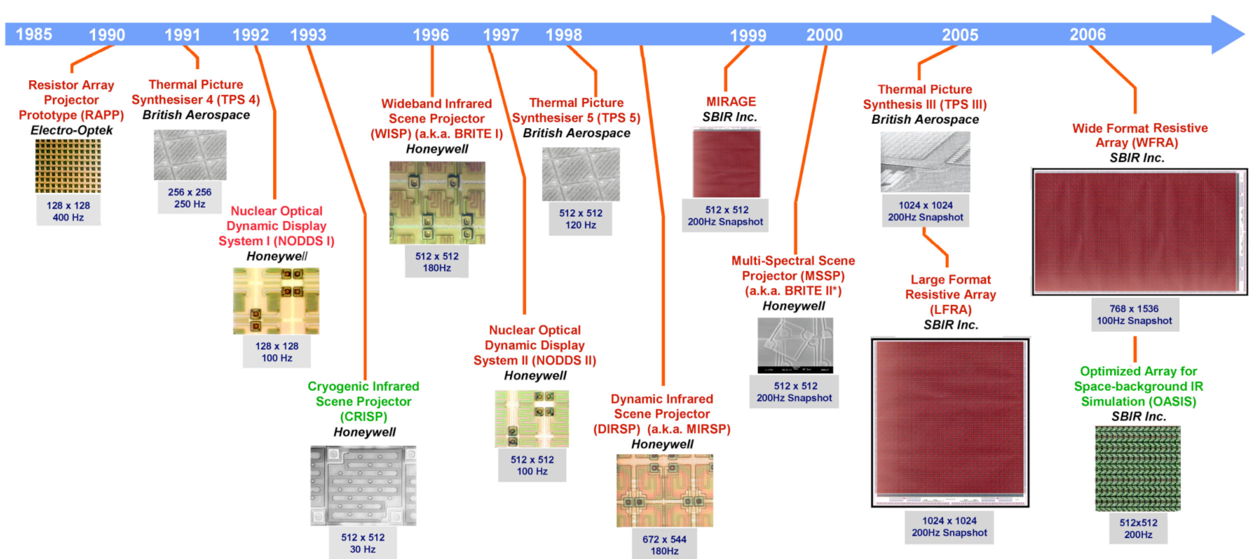

Figure 5 – Chronology of Resistive Emitter Array Development for HWIL Applications

Figure 5 illustrates the chronology of resistive array development for IR scene projection. The history of resistive arrays began with the early 128 x 128 Electro-Optek device, and evolved to the 128^2, 512^2, and 1024^2 offerings from BAe and the 128^2, 512^2, and 672 x 544 (DIRSP) configurations produced by Honeywell. After purchasing an exclusive license to the Honeywell MEMS/emitter technology in 2001, Santa Barbara Infrared is now the industry leader in IRSP, with 512^2 cryogenic 512^2, and 1024^2 systems in production, and a wide-format 768 x 1536 system in development.

3. PIXEL-LEVEL DEVICE PHYSICS

(or, "Foiled by Conservation of Energy, Once Again…")

Although microbolometers and emitters rely on different methods of modulating resistor temperature (radiative absorption vs. electrical heating), the fundamental thermal performance of both types of device relies upon the same type of heat (or power) balance equation.

3.1. Pixel Performance

For an emitter pixel suspended above a substrate with temperature T_{sub} and driven by a constant current, the relationship between pixel power, conductive and radiative losses, heat capacity, and the thermal derivative of pixel physical temperature with respect to time is given by:

$$C(T)\frac{dT_{phys}}{dt} = I^2R(T) - G(T)[T_{phys} - T_{sub}] - g[T_{phys}{}^4 - T_{bg}{}^4] \qquad [1]$$

where key parameters are defined as follows:

$T_{app} \equiv$ *Apparent Temperature*	$R(T) \equiv$ *Emitter Resistance*
$T_{phys} \equiv$ *Physical Temperature*	$C(T) \equiv$ *Heat Capacity*
$T_{sub} \equiv$ *Substrate Temperature*	$G(T) \equiv$ *Thermal Conductance*
$T_{bg} \equiv$ *Background Temperature*	$g \equiv$ *Geometric/Radiative Factor*

As (a) the thermal derivative goes to zero and (b) the device is operated in a temperature regime limited by conductive losses (*i.e.* – real world temperatures for current microbolometers and emitters), we are left with the fundamental steady-state equation relating pixel power to conductive losses:

$$I^2R(T) = G(T)[T_{phys} - T_{sub}] \qquad [2]$$

For an emitter driven to a given physical temperature per equation [1] or [2], the pixel's simulated (apparent) temperature may be computed by solving for the variable T_{app} in the following equation:

$$\int_{\lambda 1}^{\lambda 2} B_\lambda(T_{app})d\lambda = ff\int_{\lambda 1}^{\lambda 2} \tau_{opt}(\lambda)\cdot\varepsilon(\lambda)\cdot B_\lambda(T_{phys})d\lambda \qquad [3]$$

where λ_1 and λ_2 are the lower and upper spectral band edges, $B_\lambda(T)$ is the spectral radiant emittance (Planck function), ff is the pixel's optical fill factor, τ_{OPT} is the transmission of the projection optics and package window(s), and $\varepsilon(\lambda)$ is the pixel's spectral emissivity. The design of emitters – as with microbolometers – is complicated by the fact that critical material parameters such as heat capacity and thermal conductance are sensitive to process variations. Emitter design is further complicated by the fact that (a) multiple parameters depend upon instantaneous physical temperature and (b) each pixel must operate over a temperature range of 700-800 K.

3.2. Mo' Betta' Emitters

(or, "It's gettin' hot in here…")

As indicated previously, each emitter must be able to slew 700-800 K in 3-5 ms to be useful in modern IRSP applications. This obviously places extreme demands upon the emitter material set (*i.e.* – bridge dielectric, leg and resistor metals, etc.) and operating environment (*i.e.* – temperature and vacuum). The latest generation of 1024 x 1024 emitter arrays provides a maximum apparent temperature of approximately 700-750 K, draws 100 A peak current, and dissipates over 1 kW, peak! A new high-temperature emitter development program is striving for apparent temperatures of ~ 2500 K, and hence physical temperatures of approximately 3000 K! Figure 6 illustrates a high-temperature BAe emitter array driven to incandescence.

Figure 6 – Resistive Array Driven to Incandescence
(courtesy of BAe)

In addition to handling the extreme temperature environment required for IRSP, emitters must also provide a high degree of physical robustness, good radiometric stability, and high array operability. As with bolometers, a successful emitter design and material set must provide high IR emissivity (absorption), suitable thermal conductance to substrate, and low pixel heat capacity. Who said it would be easy?

4. IRSP SYSTEM CHALLENGES

(or, "Honey, Where Can I Dump this Kilowatt?")

With the current generation of 1024 x 1024 emitter arrays drawing 200 A and dissipating over 1000 W, cooling and thermal stabilization are crucial to system survival and simulated performance. Power density for the current and emerging emitter arrays is approximately 40 W/cm^2, thus requiring novel thermal design solution to remove heat (and return current) from the package. To achieve this, each emitter array is reflow soldered to a specialized heat spreader within the device package. The heat spreader is soldered to a meso-channel fluid plenum/cooler, through which a special coolant (typically HFE 7100) is controlled and re-circulated by a high-capacity chiller. Figure 7 illustrates a 1024 x 1024 projector core, and shows the typical 2-D distribution of heat across the emitter substrate during active projection.

The 200 A maximum emitter current is sourced to the array through hundreds of parallel wire bonds on the RIIC surface, and returned through the backside-metalized RIIC substrate, through the heat spreader and meso-channel cooler, to a copper heat sink. From the heat sink, low inductance buss bars route the emitter supply and return nodes to switching power converters located in the projector head. Power converter inputs are connected to a main power supply in the remote command and control electronics (C&CE) rack.

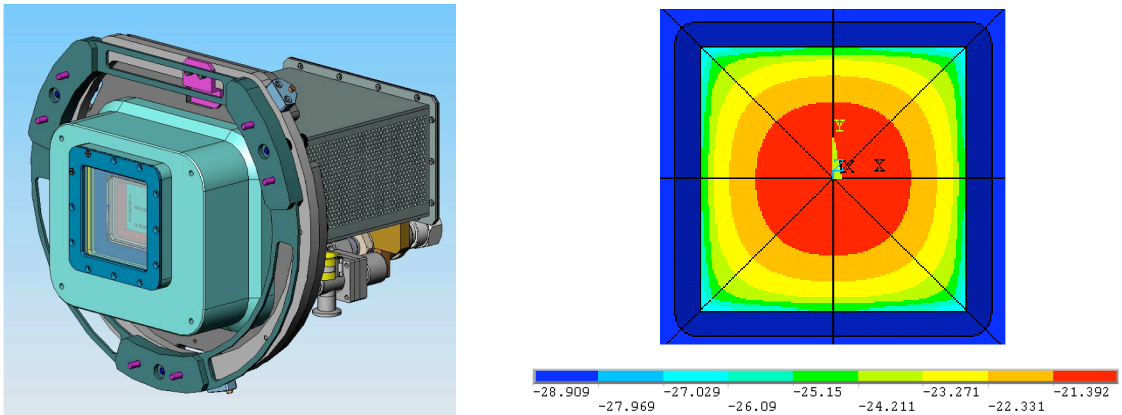

Figure 7 – 1024 x 1024 Scene Projection Core (left) & Thermal Distribution Across Array (right)
(courtesy of Santa Barbara Infrared)

As temperature requirements become more stressing – and emerging sensors demand higher-resolution emitter array formats – it is clear that these thermal and electrical design solutions must continue to improve for future IRSP systems.

5. SENSOR/PROJECTOR SYNERGY

(or, "Two Niche Communities Are Better than One)

The continuing "arms race" between sensors and test systems has historically resulted in the cross-pollination of key MEMS, electronics, and optics technologies. Next-generation FLIRs, trackers, visible imagers, and laser range finders are contributing advancements to the scene projector realm and vice versa, as illustrated in Figure 8.

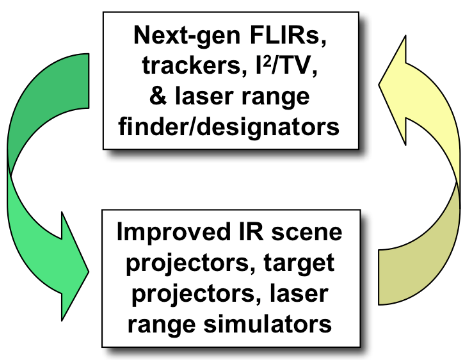

Figure 8 – The Cyclical Nature of IR Sensor and T&E Technology Advancement

Pixel uniformity, operability, and device architecture are evolving for both microbolometers and emitters. New high-speed digital video processing technologies are enabling new sensor and projector capabilities. Improvements in optical system design are facilitating the efficient development of new sensors, and improving the flexibility of IR scene projectors. Together, these complementary developments will continue to benefit both sensors and projectors.

5.1. Pixel Uniformity & Operability
(or, "Why is nobody else trying to make 2 x 2-inch bolo arrays?")

The monolithic MEMS fabrication processes used in microbolometer and emitter production are complex, sensitive, and costly. Fabrication time is generally on the order of 3-6 months, with many adjustment and tuning steps involved. Although many MEMS technology licensees work to improve and optimize the core process(es), numerous variability and defect mechanisms give rise to uniformity and operability limitations – which in turn drive yield, cost, and lead time. Non-uniformity correction (NUC) is applied in both sensors and projectors to improve spatial uniformity at the expense of dynamic range. However, the sophisticated pixel substitution and interpolation functions routinely implemented in modern sensors are simply not possible in the projector domain – no output, no projected pixel!

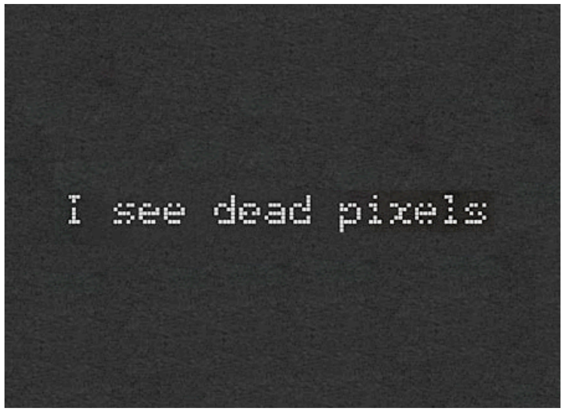

Figure 9 – The Importance of Array Operability!

5.2. Emitter & Micro-Bolometer MEMS Innovations

(or, "How much $#!% can we fit in this five-microgram sack?")

Figures 10a through 10d show examples of MEMS structure innovations created to improve bolometer and/or emitter performance, increase operational flexibility, and offer novel solutions to optical switching problems at the array level. These MEMS developments will surely continue, driven by the ongoing need to improve IR sensors and projectors.

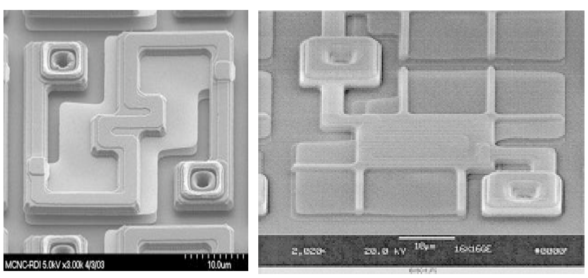

Figure 10a – Emitter Pixels with Reduced Mass & Low τ
Due to "Gossamer" MEMS Architecture
(courtesy of Santa Barbara Infrared)

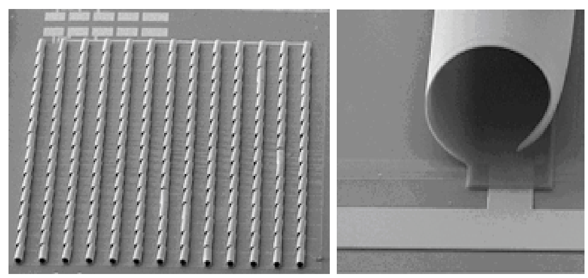

Figure 10b – Artificial Eyelid Actuator with
5-10 kHz Optical Switching Capability
(courtesy of RTI International)

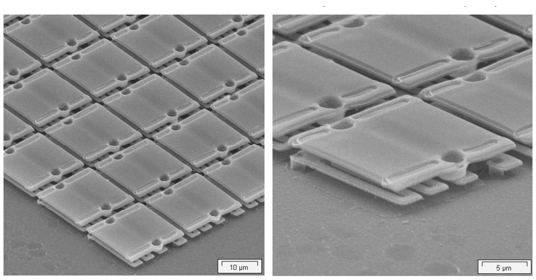

Figure 10c – Advanced Microbolometer Array
with Optimized Fill Factor and Conductance
(courtesy of Raytheon Vision Systems)

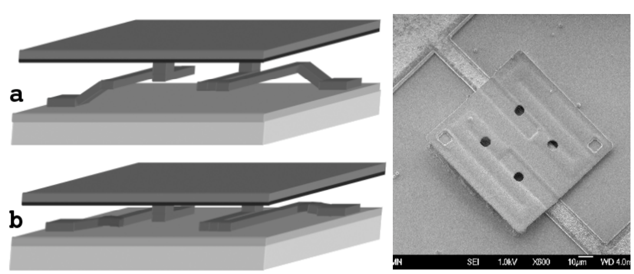

Figure 10d – Experimental Micro-Bolometer Structure with
Variable Responsivity/Tunable Thermal Conductance
(courtesy of University of Minnesota)

5.3. Signal Processing & Data Throughput

(or, "Digital video data rates: Too much of a good thing…")

In the sensor domain, data throughput and storage performance are typically driven by high-performance hyperspectral imaging applications. High-rate data streams are in the range of 50-100 MB, with resulting data cubes for typical collection scenarios in excess of 100 GB. Lossless data compression schemes, optical interconnection, high-bandwidth downlinks, and other technologies are striving to maximize sensor performance and mission utility. Real-time functions such as adaptive NUC and "smart" FPA processing promise to further improve sensor performance in the future.

In the projector domain, technical evolution is being driven by high-resolution IRSPs such as the Large- and Wide-Format Resistive Array (LFRA/WFRA) projects. To support 200 Hz simulations, these systems require data throughput of over 400 MB/s, with real-time implementation of NUC, translation/rotation, convolution, and other functions. Fiber optic links between C&CE and projector core improve performance and reduce electronic integration risk. Minimizing latency is important in IRSP applications, and projector systems now include real-time horizontal, vertical, and rotational (x, y, Θ) scene adjustment to compensate for changes in UUT attitude during scene data transfer. As with many other key performance parameters, the effectiveness of latency compensation depends upon the electronic architecture, data path, and firmware implementation. As of the last several years, the custom (and somewhat arcane) computing and video electronics subsystems utilized in IR scene projection are being replaced by COTS-based design-solutions.

Figure 11 illustrates the complexity of hyperspectral data cubes in the sensor world, and the importance of high-resolution, high-throughput video data paths to IR scene projector performance.

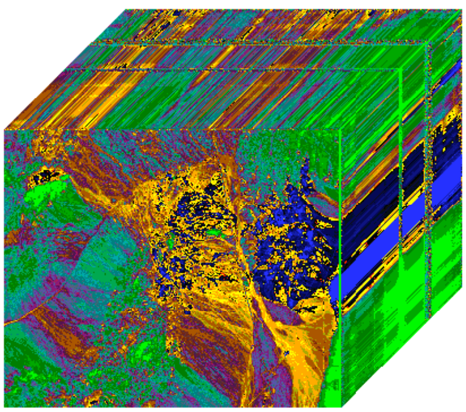
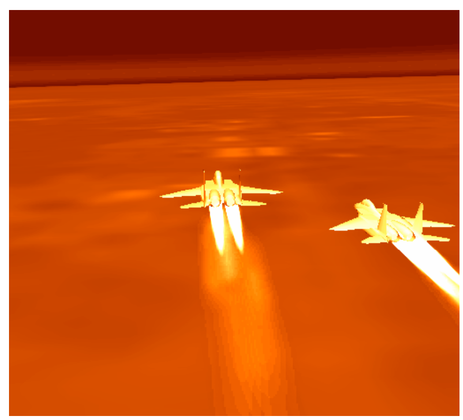

Figure 11 – Hyperspectral Data Cube (left) & High-Resolution IRSP Imagery (right)

5.4. Optical System Design

(or, "I've looked at photons from both sides now…")

Ongoing improvements in optical system design, modeling, fabrication, and coating improve the evaluation of new thermal imaging systems, and increasingly allow IR scene projection systems to be adapted to a variety of T&E applications and UUT types. Custom solutions such as modular and zoom architectures allow the improved in-process screening of thermal imaging cores, thereby minimizing failures at higher levels of assembly due to image artifacts. The same types of modular and zoom architectures are applied to IRSPs, enabling HWIL facilities to re-configure for testing of different UUTs and simulated scenarios without the need for unique refractive collimators.

Modular optics typically offer discrete adjustment of focal length to optimize projected IFOV for the UUT and/or simulation at hand. As IRSP systems are usually operated with multiple emitter pixels optically mapped to a single UUT pixel (to minimize spatial aliasing artifacts), the ability to tune projected IFOV is extremely useful. Zoom optics, while more costly to develop and manufacture, offer continuous variation of IFOV and FOV within the design range of the collimator. Full zoom capability provides maximum flexibility to match the projected image to the UUT – with ease of re-configuration and minimal re-alignment time. Figures 12a and 12b illustrate modular and zoom architectures

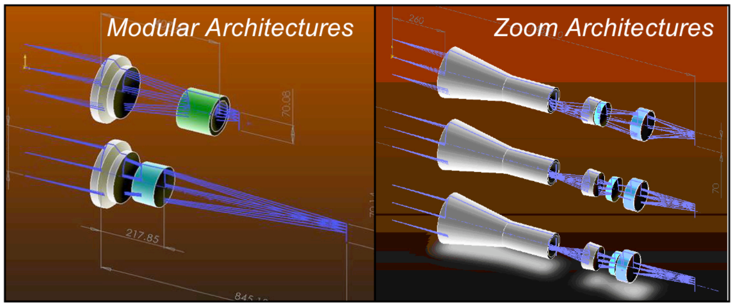

Figure 12a – Novel Approaches to Sensor & Projector Optics: Modular (left) and Zoom (right) Architectures
(courtesy of StingRay Optics)

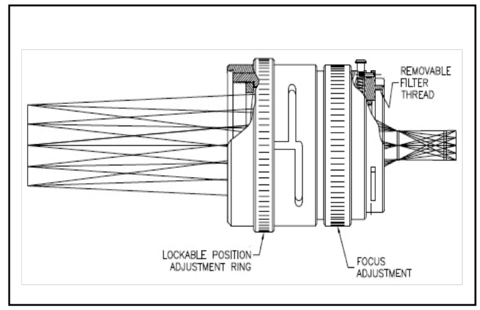

Figure 12b – Adjustable IR Lens for IRSP NUC and/or Camera Core Image-Based Screening
(courtesy of Santa Barbara Infrared)

6. SENSOR SIMULATION TRENDS

(or, "What Have You Done for Me Lately?")

As sensors incorporate increasingly advanced architectures and offer higher levels of performance and operational flexibility, EO simulation systems must necessarily keep pace in terms of FOV, spatial resolution, dynamic range, frame update rate and mode, temporal characteristics, and uniformity/operability. Table 1 lists a variety of emerging sensor trends and operational parameters, with their corresponding simulation/projection challenges.

SENSORS		SCENE PROJECTORS	
TREND	PARAMETERS	CHALLENGE	TECHNOLOGY
Increased Array Formats	1280 x 720 (and beyond)	Large, Wide-Format Arrays	1536 x 768, and beyond
Distributed Aperture Sensors	2048^2, micro-dithered	Multiple Wide-FOV, Low-Cost Projection Subsystems	Productized 1024^2 IRSP
3rd-Generation FLIRs	MW-MW, MW-LW, LW-LW	Simultaneous, Co-Registered Multi-Band Scenes	Optically-Combined IRSPs Photonic Crsytals Laser Diode Arrays
Broadband Imaging Suites	Fused UV-VIS-MWIR-LWIR	Combination of IRSP and UV-VIS Projection	
Hyperspectral Imagers	VIS-SWIR-MWIR-LWIR, ($\Delta\lambda/\lambda < 0.01$)	Hundreds of Unique Spectral Bands	Area/Line Projection with Arbitrary Spectrum Generation
Extended Dynamic Range	> 20-bit	Very High-Temperature Projection Capability	New Materials (T_{app} > 2000 K) Laser Diode Arrays/Scanners UV & IR Plasmas
Increased Frame Rate	~ 10 kHz	High Data Throughout or Sub-Image Processing	Fast Steering/Translation of Multiple Image Clusters
3-D Imaging/LADAR	Linear Arrays (1 x 256) Area Arrays (256 x 256)	Small Projected IFOV (200-400 μrad) High Temporal Resol. (250-500 ps)	Laser Diode/VCSEL Arrays with Vertically-Integrated Control

Table 1 – Summary of Emerging IR Sensor & Scene Projection Trends

High-resolution UUTs are being addressed by emitter arrays of 768 x 1536 pixels, and beyond. 3rd-gen FLIRs and broadband imaging suites are currently supported by optically combined IRSPs, with photonic crystals, laser diode arrays, and other simulation technologies in development. Hyperspectral sensors have spawned a series of novel "arbitrary spectrum generators", capable of projecting distinct tuned spectra for each pixel location in a line image, with area projection under development. Extended dynamic range sensors are currently addressed by resistive arrays combined with discrete, scanned laser spots. For the future, technologies such as laser diode/VCSEL arrays and UV-VIS-IR plasmas are in development. Laser-driven projection of sub-image "pixel clusters" – formed and steered by 2-D analog mirror-based MEMS arrays – will enable high frame rate simulation for emerging UUTs. 3-D imaging/LADAR simulation poses one of the most difficult scene projection challenges, although a variety of approaches are being explored including laser diode and VCSEL arrays with vertically integrated electronic control, leveraging ongoing developments in the sensor realm.

SUMMARY

Resistive arrays for IR scene projection evolved from the early days of microbolometer development, and currently offer a unique IR simulation capability. While bolometers and emitters are limited by the same thermal and physical constraints, MEMS advancements are pushing both bolometer and emitter technologies forward. The cross-pollination of electronic and optical technologies and architectures further increases the pace of development and the feasibility of the most challenging sensor and projector solutions. This trend will surely continue, to the benefit of sensor and simulation system developers worldwide.

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