Addressing the Challenges of Thermal Imaging for Firefighting Applications

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ABSTRACT

By providing visibility through smoke and absolute darkness, thermal imaging has the potential to radically improve the effectiveness and safety of the modern firefighter. Some of the roles of thermal imaging are assisting in detection of victims; navigating through dark, smoke-filled structures; detecting indications of imminent flash-over / roll-over; identifying and attacking the seat and extension of a fire; and surveying for lingering hot spots after a fire is nearly extinguished. In many respects, thermal imaging is ideally suited for these functions. However, firefighting applications present the infrared community some unique and challenging design constraints, not the least of which is an operating environment that is in some ways more harsh than most aerospace applications. While many previous papers have described the benefits of thermal imaging for firefighters, this paper describes several specific engineering challenges of this application. These include large ambient temperature range, rapidly changing scene dynamics, extreme demands on AGC, and large dynamic range requirements. This paper describes these and other challenges in detail and explains how they were addressed and overcome in the design of *Evolution 5000*, a state-of-the-art thermal imager designed and manufactured by Mine Safety Appliances (MSA) using Indigo System's Omega™ miniature uncooled camera core.

1. OVERVIEW OF FIREFIGHTING CHALLENGES

The most obvious challenge associated with designing a thermal imaging product that will be carried into a fire is the extreme thermal environment. Inside a burning building, firefighters and their equipment are routinely exposed to ambient temperatures between 150 ^{o}C and 350 ^{o}C (300 ^{o}F and 660 ^{o}F). During a flashover or back draft, the air temperature can suddenly climb to well over 500 ^{o}C (932 ^{o}F). Few electronic systems can survive in such conditions, even for short periods of time. But this is the setting in which a firefighter's thermal imager must not only survive but continue to operate flawlessly.

The thermal environment inside a burning structure also places a tremendous emphasis on effective dynamic range control. In one instance, a firefighter might be using thermal imaging to navigate through a dark, dank basement several floors below the fire. In this scenario, thermal contrast is measured in fractions of a degree, and high sensitivity is required. Then moments later, when the firefighter arrives at the heart of a raging blaze, the imager is likely to be exposed to scene temperatures exceeding 500 ^{o}C. This is the thermal equivalent of stepping from pitch darkness into full midday sunshine. As this example suggests, thermal contrast in a fire scenario can change rapidly and dramatically over several orders of magnitude. Providing adequate sensitivity and scene range demands a sensor with exceptional dynamic range as well as robust image processing algorithms to display the thermal information effectively. Traditional automatic gain control (AGC) algorithms are problematic in this situation because they distort radiometric truth. A firefighter often needs to size-up potentially dangerous conditions quickly, such as the fact that the door in front of him is too hot to open. With typical AGC, it is not readily apparent if the door is dangerously hot or merely warm. The displayed brightness depends upon too many other variables.

A primary concern for all handheld applications is minimizing size and weight, but this is particularly important for firefighting. After donning protective clothing and a self-contained breathing apparatus (SCBA), the typical firefighter is weighed down under approximately 50 lbs of gear, and that estimate does not include the added burden of carrying an axe, a hose, or an incapacitated victim. His manual dexterity is further encumbered by thick gloves and turnout gear. The last thing a firefighter wants to drag into a fire is another heavy, cumbersome piece of equipment, particularly if it has to be manually adjusted or is too complicated to use properly. Regardless of its performance, a thermal imager provides no benefit to a firefighter if he leaves it on the truck. An effective design must emphasize ergonomics and intuitive operation.

Yet another challenge of equipping a firefighter with thermal imaging capability is the harsh, sometimes violent handling to which his equipment is subjected. In the midst of hazardous and chaotic conditions, it is unreasonable to expect that a thermal imager will be treated as a delicate instrument. Instead it will be dragged, dropped, splashed, sprayed, and scorched on a routine basis. Firefighters are trained not to rely on thermal imaging – they should never get into a situation with the imager that they cannot get out of without it. That said, the advantage of navigating through darkness and smoke with a thermal sensor is tremendous, and the firefighter's safety is undeniably compromised if his equipment breaks down in the middle of a fire. Durability and reliability are paramount concerns in this application.

A final challenge that must be overcome in the quest to equip every firefighter with thermal imaging is the financial constraints under which most fire departments operate. In the eyes of veteran firefighters, thermal imaging is a luxury whereas helmets, turnouts, hoses, vehicles, and other basic equipment are absolute necessities. For thermal imaging to become ubiquitous in the firefighting community, product costs must come down. Pricing likely needs to be comparable to other individual-issue items, such as SCBA equipment, before outfitting each firefighter with a thermal imager becomes standard practice.

2. ADDRESSING THE CHALLENGES

Until very recently, infrared technology was not sufficiently mature to facilitate a thermal imaging design capable of addressing all the challenges of the firefighting application. That is not to say that thermal imaging has not had a positive effect on the fire-service industry in the past decade, and firefighters are generally excited about the technology because of its obvious potential. However, initial products on the market were too heavy and too clumsy, and image quality on at least some of these products was less than adequate. Of course the most significant barrier to widespread adoption of infrared imagery in the firefighting community has been cost. It has only been in the last year that firefighters have had opportunity to experience thermal imaging products truly capable of meeting their needs at relatively affordable prices. The quantum leap in quality and cost is due largely to advancements in infrared imaging technology, combined with exceptional product design to integrate imaging cores into robust, ergonomic total systems. The Evolution 5000 (E5000) manufactured by Mine Safety Appliances (MSA) is a case in point. The heart of the E5000, shown in Figure 1, is Indigo Systems Omega™ sensor (Figure 2), the smallest infrared imaging core in commercial production today. The remainder of this paper describes engineering solutions employed in the design of Omega™ and the E5000.

Figure 1: MSA Evolution 5000

Figure 2: Indigo Omega™ imaging core

TEC-less Operation

Historically, uncooled thermal detectors have been incapable of operating without active temperature stabilization of the focal plane array (FPA), usually in the form of a thermoelectric cooler (TEC). Reliance on a TEC is undesirable in many imaging applications, but it is especially problematic for firefighting because of the extreme ambient temperature range. The most obvious disadvantage of a TEC is that it consumes ever-increasing power as the rest of the system heats up in a fire. A second, more-subtle concern is the erosion of dynamic range caused by system heating relative to a fixed FPA temperature. The loss of dynamic range is the result of out-of-field irradiance (i.e., flux from the enclosure, optics housing, and other sources outside of the imaged field of view, collectively referred to as the "camera case"). For f/1.2 optics, the out-of-field solid angle is five times greater than that subtended by the imaged scene. Consequently, relatively small temperature differences between the FPA and the camera case consume a substantial portion of available sensor dynamic range. This point is illustrated in Figure 3. When the case and FPA are at the same temperature (30 °C in this example), no signal is generated from out-of-field irradiance, and a large scene temperature can be imaged without saturation. But as the case heats, an increasingly large proportion of the available signal range is wasted. As a result, the maximum scene temperature drops rapidly, rendering the system essentially useless in a firefighting scenario. For applications that require operation over a wide temperature span, elimination of a TEC is crucial for power management and conservation of dynamic range. Only recent advances in uncooled sensor technology have made TEC-less operation possible.

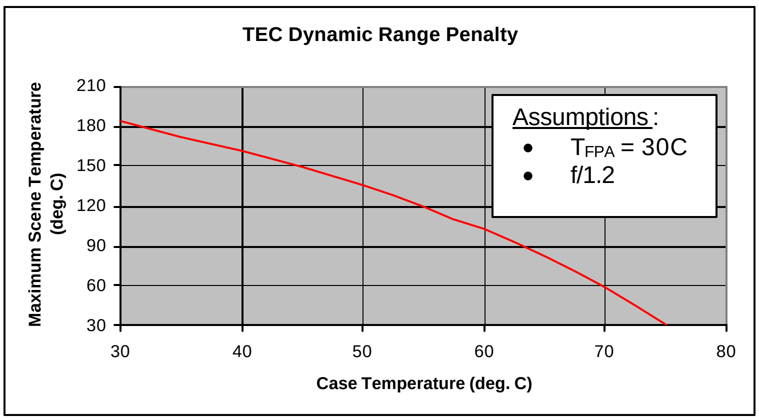

Figure 3: Erosion of dynamic range from temperature differences between case and FPA.

The challenge of eliminating a TEC is maintaining uniformity as the FPA heats or cools. Generally speaking, uncooled detectors are highly sensitive to temperature change, and if parameters vary even slightly from pixel to pixel, image quality can degrade radically with temperature. The Omega™ camera used in the E5000 is a pioneer in TEC-less operation. Using a novel combination of proprietary read-out circuitry and non-uniformity correction (NUC) algorithms, it is one of the first infrared cameras to solve the uniformity problem. Omega's advanced temperature-compensation algorithms minimize variations in pixel behavior over very wide spans of temperature, as shown in Figure 4. This figure shows an identical scene imaged at three different values of case temperature: 35 °C, 55 °C, and 75 °C. It is clear that image quality remains high across this full range, demonstrating the effectiveness of Omega's advanced approach to TEC-less operation.

The full operating temperature range of the Omega™ firefighting configuration is -20 °C to +75 °C. To span this range, Omega™ requires only 3 NUC tables each of which subtend approximately 35C. (Most other TEC-less cameras require many tables, which negatively impacts memory requirements, size, cost, calibration, and system complexity.) Omega™ automatically transitions from one table to the next as the camera heats or cools, and the transition is transparent to the user. The NUC tables are overlapped by several degrees, which prevents the camera from oscillating between tables at a boundary.

(a) T_{case} = 35 °C (b) T_{case} = 55 °C (c) T_{case} = 75 °C

Figure 4: Nearly identical scene imaged at three values of camera case temperature. Excellent image quality is maintained using advanced correction techniques.

Optimized Gain States

In the midst of a burning building, objects in the sensor field of view can easily exceed 500 °C. On the other hand, there are low-contrast thermal imaging tasks, such as navigating through smoke, that demand sensitivity less than 1/20th of a degree (50 mK). In terms of signal at the FPA, these two extremes represent an instantaneous dynamic range approaching 2^{15}. Yet it should be recognized that the high-temperature scenario and the low-contrast scenario represent two distinct modes of operation; the firefighter often needs high temperature range *or* high sensitivity but not both simultaneously. Consequently, an effective solution to the challenge of large dynamic range is a thermal imager with two operating states – a high-gain state for low-contrast conditions and a low-gain state for large scene temperature. This is the approach employed by Omega™ and the E5000. Figures 5 and 6 show example images in the high-gain and low-gain states, respectively, while Table 1 compares maximum scene range and noise equivalent temperature difference (NEdT).

Figure 5: High-gain state

Figure 6: Low-gain state

Table 1: Evolution 5000 sensitivity and max. scene range

	High-gain	Low-gain
NEdT	$\leq$ 50 mK	$\leq$ 390 mK
Max. scene temp.	$\geq$ 135 ^{o}C ($\geq$ 275 ^{o}F)	$\geq$ 500 ^{o}C ($\geq$ 932 ^{o}F)

The dual gain-state strategy is not unique to the E5000. In fact, it has been adopted by most manufacturers of firefighting imagers. However, several implementation details must be considered for this approach to be effective. The transition between gain states must be completely automatic with no user intervention. Furthermore, the imager's current state must always be obvious. Most importantly, the switching logic must transition appropriately and efficiently such that the firefighter is never forced to contend with a saturated image in high-gain state, a washed-out image in low-gain state, or a continuous hunting for the proper state due to slight changes in scene content. The E5000 uses two thresholds as the basis for gain-state determination: a temperature threshold and a population threshold (i.e., percentage of the scene above/below the temperature threshold). Hysteresis in both the temperature and population thresholds prevents oscillation. Transition between states is completed in less than 0.5 sec, and the user is alerted to the change by a difference in the color of on-screen symbols as well as an explicit low-gain indicator – an "L" displayed in the lower-left corner of the display (see Figure 6).

Color Temperature Thresholds / Spot Meter

The traditional strategy for mapping the large dynamic range of a sensor to the much lower range of a display is through a nonlinear AGC algorithm. AGC optimizes the use of gray shades, revealing subtle details in low-contrast scenes and preventing the background from washing-out in scenes containing hot objects. But one drawback of AGC which is inconsequential in many thermal imaging applications but important to a firefighter is the distortion of absolute temperature information. For example, a smoldering heap of embers will be displayed in bright white if it is the hottest object in the scene, but its brightness will be reduced to a darker shade of gray if a hot flame is burning in the background. This inconsistency in the display of an object can be extremely confusing. The ability to gauge temperature accurately and reliably is an important asset to a firefighter. It provides information that can potentially make the difference in such life-or-death actions as identifying structural features weakened by heat, avoiding flash-over and backdrafts, discovering lingering hot spots before flare up, and directing water spray.

The E5000 provides two valuable features to overcome the issue of temperature distortion. The first of these is a "heat seeker" capability in which sufficiently hot objects are colored yellow or red. With the rest of the image displayed in gray, colored objects stand out vividly and provide unambiguous indication that they are dangerously hot. In high-gain state, temperatures above 135 ^{o}C are painted yellow while temperatures greater than 142 ^{o}C (288 ^{o}F) are shown in red. In low-gain state the yellow and red thresholds are 450 ^{o}C (842 ^{o}F) and 475 ^{o}C (887 ^{o}F), respectively. A second useful feature that augments the colored heat seeker is an on-screen spot meter. As shown in Figures 5 and 6, the temperature of the spot in the center of the image is indicated in real-time via a thermometer graphic on the right edge of the screen. As the thermometer "fills", its color changes to yellow and then red at the temperatures corresponding to the yellow and red heat-seeker thresholds. Unlike a numerical display, this graphic allows the firefighter to gauge temperature intuitively without shifting his focus from the center of the display.

Ergonomics / Human Factors

From the firefighter's point of view, the most noticeable difference between thermal imaging products available today and those of just a few years ago is that weight and size have been reduced considerably. Including its battery, the E5000 weighs just 1.25 kg (2.75 lbs), less than half of its predecessor, the Evolution 4000. The primary enabler of this remarkable improvement is the Omega™ core, which has total volume less than 74 cm^3 (4.5 in^3) and weighs only 101 g (3.6 oz). The obvious ergonomic benefit of reducing size and weight of a thermal imaging product is that it is far more comfortable to carry. Less obvious, but perhaps equally important, is that a firefighter's maneuverability is not sacrificed when the imager is strapped to his turnout gear. The E5000 housing provides an attachment point for a carabiner so that the imager can be clipped to a belt, D-ring, or grommet, as shown in Figure 7.

Figure 7: Attachment via a carabiner.

While small size and weight are the highlights of an ergonomic design, several other features are essential for a handheld product to be comfortable and easy to use. The center of gravity must be located above the grip to minimize fatiguing torque. Because the imager is sometimes shared amongst two or more firefighters, the handle must be sized for easy hand-off. The display must be sufficiently large and bright, and its angle must facilitate a natural viewing position. None of these details have been overlooked in the design of the E5000.

Athermalized, Wide -FOV Optics

When fighting a fire, it is often impossible and always impractical to make manual adjustments to a thermal imager. Fully automatic operation is expected, and that includes focus control. Another requirement for the optical system is a wide field of view (FOV). In a typical firefighting scenario, there is rarely a need to see more than a few yards away. Resolution is therefore not a significant issue. Far more important is situational awareness. Being able to see from floor to ceiling and wall to wall allows a firefighter to size up a room quickly when he steps into it. The E5000 provides a 55^{o} x 41^{o} FOV (69^{o} diagonal), athermalized across the full operating temperature range (MTF within 10% of best focus).

Thermal Management

The physics of semiconductor devices simply do not permit electronics to operate at extreme temperatures. The goal of thermal management is to optimize the period of time that the system can be exposed to a high-heat environment before electronics and other critical components reach their temperature limits. This is accomplished by effective insulation (thermal resistance) and heat-sinking (thermal mass). These two quantities define the thermal time constant, which in turn determines how quickly temperature rises when the system is exposed to heat.

The firefighting configuration of the Omega™ camera is specified to operate to a maximum temperature of +75C. While this value is higher than most camera cores, exposure to a fire would quickly push it outside of its specified range were it not for effective thermal management. The Omega™ is enclosed in an expanded polypropylene foam shell shaped to fit snuggly in the E5000 housing, as shown in Figure 8. Not only does the shell provide thermal insulation, it also protects the camera core from shock and vibration. Furthermore, heat sinks have been strategically located in the housing to increase thermal mass. Both the camera core and the imager's liquid-crystal display (LCD) are instrumented with temperature sensors to detect overheating, and an indicator below the display flashes to alert the user when there is an overtemp condition. In virtually all operating scenarios, it is the display that limits E5000 runtime in a fire since it cannot be insulated as well as the camera core. Table 2 shows safe exposure time of the E5000 in various thermal environments. Generally speaking, exposure time of the E5000 is comparable to the maximum safe exposure time of the human firefighter in the same environments.

Figure 8: Omega™ removed from E5000 housing (enclosed in foam shell)

Table 2: Exposure time of E5000

Ambient Temperature	Exposure Time
80 °C (175 °F)	> 30 minutes
120 °C (250 °F)	> 10 minutes
260 °C (500 °F)	> 5 minutes

Robust Packaging

Aside from harsh thermal conditions, the housing design of a fire-service product must address several other environmental challenges, including flame, water spray, and handling shock. In the case of the E5000, these challenges have been met by a combination of best-engineering practices and proprietary materials. All shock-sensitive components are mounted in protective foam that dissipates impact force in the event of a drop. External protective bumpers, made from specially-developed flame-resistant neoprene, provide additional shock dampening. The front portion of the bumper is a pliable grip guard, allowing the firefighter to crawl while holding the E5000 in his hand. (See Figure 9.) The plastic portion of the enclosure is a proprietary polycarbonate / polyethylene (PC/PET) blend with additives that promote flame resistance. The housing is doubly sealed using custom gaskets and O-rings, and all sealing seams are flat. As a result of these measures, the E5000 has attained an IP67 rating (submersible under a meter of water) and is capable of surviving a 1.8 m (6 ft.) drop onto concrete.

Figure 9: Flexible front grip-guard

Cost

In addition to significant technical challenges associated with designing firefighting equipment, cost is also a critical requirement in this market. Most thermal imagers using uncooled FPAs are "low cost" when compared to high-performance cooled systems, but in comparison to other equipment issued to a firefighter, thermal imaging is very expensive. Clearly the infrared industry and the firefighting community have different perspectives, and this further exacerbates the challenge of designing a product inside the customer's price threshold. Small, incremental cost savings (such as design features to reduce assembly time) are important and cannot be ignored, but they are insufficient when the gap between supplier and consumer is so large. Quantum leaps were required to bring about a dramatic cost reduction in MSA's Evolution product line.

The most significant trade affecting the low cost of the E5000 was selection of a small-format camera (160x120) over a mid-format (320x240). As previously mentioned, firefighters do not require exceptional resolution from a thermal imager because it is used almost exclusively for viewing objects close at hand. In this application, the additional pixels in a mid-format array do not translate to added capability. In fact, for the same size optics, a smaller array will often produce a *better* image because of improved sensitivity.[*] From a performance standpoint, a 160x120 array is more than adequate, particularly since Omega™ uses bilinear smoothing to create a more cosmetically pleasing 320x240 image. When cost is added to the trade space, small-format is an obvious winner. Approximately 4 times as many arrays can be fabricated from each silicon wafer, which translates to substantially lower cost per FPA. And since the FPA is the single most expensive component in a thermal imaging camera, a system with a mid-format array cannot compete.

In addition to being the costliest element in a thermal imaging system, the FPA also has a direct influence on the cost of another high-dollar item, the optical assembly. Because lenses used in infrared optics are made from germanium and/or other expensive materials, reducing the size of optics is tantamount to reducing cost. On the other hand, the area of the optical aperture determines the amount of signal received at the focal plane. A detector array with poor inherent sensitivity demands large, expensive optics to compensate for inadequate performance. Conversely, an array with excellent sensitivity supports a compact optical design with higher f/number. The FPA used in the Omega™ camera was designed in-house by Indigo Systems for optimum signal-to-noise ratio (SNR), resulting in < 50 mK NEdT using a low-cost f/1.2 lens assembly. The Omega™ therefore represents a cost-effective solution that does not sacrifice performance.

3. FUTURE CHALLENGES

Considering the substantial progress accomplished in the past few years, it is logical to wonder what will be the next major improvement in equipping firefighters with thermal imaging capability. One distinct possibility is a hands-free approach in which the camera is mounted on a helmet. The concept of helmet-mounted systems has been met previously with skepticism, and based on previously available technology, there was certainly reason to doubt an effective solution was possible. But recent improvements in commercial infrared systems warrant another look at hands-free operation. The most important requirement is reducing size and weight to the point that a system can be worn comfortably and unobtrusively. As demonstrated by the Omega™ core, current technology is now capable of overcoming this obstacle. Furthermore, low power consumption of state-of-the-art uncooled sensors (Omega™ power $\leq$ 1.5W) makes it possible to use a small, lightweight battery. One of the primary disadvantages of a helmet-mounted system is that it cannot be easily shared by multiple firefighters. However, as the cost of infrared technology comes down, this drawback becomes less of a concern because it is more feasible to equip every firefighter with thermal imaging capability. One last technical hurdle to hands-free imaging which is somewhat outside of the domain of the infrared community is the issue of displaying the imagery to the firefighter. Miniature flip-down displays with adequate optical specifications are commercially available, but the optimal solution is to integrate a display into the firefighter's face-shield.

[*] Assuming the same field-of-view and aperture size, the total signal power is identical whether the FPA format is mid or small. Since a small-format array has a quarter of the pixels, the signal per pixel is 4 times greater.

4. SUMMARY

The challenges of firefighting are like no other application of thermal imaging. Only recently has infrared technology advanced to the point that a single design can simultaneously satisfy competing environmental, ergonomic, performance, and cost requirements. The E5000, summarized in Table 3, serves as a prime example. It is the result of integrating a state-of-the-art low-cost camera core into an exceptional package designed to withstand the demanding environment of the firefighter.

Table 3: Summary of E5000 engineering solutions to the challenges of firefighting

Firefighting Challenge	E5000 Solution
Extreme ambient temperature	• TEC-less operation • Effective thermal management (insulation and heat-sinking)
Extreme dynamic range	• Effective use of dual gain states • Excellent non-uniformity correction • Advanced AGC
Temperature gauging	• Color heat-seeker feature • On-screen spot-meter with graphic display
Portability	• Less than 2.8 lbs (with battery) • Excellent ergonomics – appropriately sized handle, CG above the grip • Easily attached to turnout gear via carabiner
Easy to use	• Single button operation (on/off), no need for manual focus • Large, bright display with optimized view angle • Simple, intuitive indicators and on-screen graphics • Fully automatic gain-state / NUC table selection
Harsh environment	• Exceptional packaging, rugged construction • Advanced, flame-resistant materials • Verified against shock, vibration, immersion (IP67 rating), and flame
Low cost	• Small-format array (160 x 120) • Compact, f/1.2 optics