Some perimeter security systems rely on optical cameras to identify potential threats from a safe distance. Blending images formed by IR and visible-light sensors into a single composite view provides a promising approach for day and night surveillance. A camouflaged intruder might escape notice on a visible-light camera but will show up clearly on a thermal imager. A small boat entering an illuminated harbor will be visible on a CCD camera before it is picked up on an IR imager. Blended CCD/IR images provide enhanced capabilities: Security officers, for example, could scan the heat coming off a car to see if it was driven recently while using the CCD camera to scan for occupants (see figure 1).

**Performance Metrics**

IR sensors hold the key to detailed blended images. Most commercial uncooled IR sensors operate in the 8- to 12-µm range, within which source energy remains high and atmospheric absorption low. These sensors perform best on objects that have small temperature deltas from ambient, such as human bodies,
animals, plants, cars, trucks, and buildings.

IR sensor performance is a function of sensitivity, resolution, and range. Sensitivity, the ability to resolve two objects of nearly equal apparent temperature, is measured by noise-equivalent temperature difference (NEdT) and minimum-resolvable temperature difference (MRTD). NEdT, measured in millikelvins, consists of the amount of IR radiation needed to produce a signal equal to the heat (noise) created by the detector itself. The lower the noise floor of the system, the lower the NEdT and the smaller the detectible signal. MRTD, measured in degrees centigrade, describes how well a detector distinguishes between objects at similar temperatures. Low-MRTD sensors can, for example, differentiate temperature differences in the eyes, ears, and mouth, and produce a highly detailed facial image.

In a digital camera, the image resolution is defined by both the optical system and by the number of pixels on the IR detector. By reducing the pitch between sensor elements to 25 µm, from 37.5 µm or 50 µm, designers have developed IR sensors consisting of 320 × 240 pixels. They are capable of four times the resolution of the previous industry standard 160 × 120 array. Resolution is essential in producing IR images with enough detail to help security personnel identify and assess potential threats.

Range is a function of resolution and sensitivity. It is often measured by the Johnson Criteria—the number of pixels required for users to detect the presence of an object (two); recognize it well enough to classify it as, for example, a human or a car (eight); and identify it as a specific member of a class, such as a sedan or a van (13). The detection range of a thermal imager, then, is the distance at which users can determine reliably that changes in two pixels represent motion. Commercial dual IR/CCD thermal imagers typically have a detection range of 450 to 500 m.

Many security systems leverage the Johnson Criteria to identify potential intruders using automated video-motion-detection (VMD) software. VMD analyzes any changes in pixels for indications of motion by potential intruders. This requires cameras with focus-free (large depth-of-field) lenses, which keep the entire perimeter sharply in focus to ensure any motion is easily detected.

Uncooled and Cool

Thermal camera performance metrics vary with the choice of focal plane array (FPA) sensor. Barium strontium titanate (BST) FPAs, the most widely used type of sensor, show good sensitivity, with NEdT below 145 mK and MRTD below 0.1 °C. BST is a ferroelectric material that works much like a capacitor. IR radiation impinging on a BST pixel creates a localized electrical charge. The hotter the source, the greater the charge. This change in pixel capacitance registers as a change in voltage whose magnitude determines the brightness of the pixel during the image readout cycle.

BST sensors operate on a two-phase cycle governed by a chopper wheel, a rotating (approximately 1800 rpm) wheel with one or more apertures. In the first phase, the aperture allows IR radiation to pass through the lens and charge the BST. In the second phase, the chopper blocks the lens and the BST reads the temperature of the wheel. This produces a base-state charge in the sensor. When the sensor takes the next reading of its environment, system electronics subtract the base state (wheel) charge from the new charge to produce an accurate image.

Unfortunately, the chopper wheel fails to fully block IR radiation. A hot source will heat the back of the wheel, just as a magnifying glass heats the back, as well as the front, of a piece of paper. The heat that leaks through the wheel is not tightly focused; it heats up a larger area than the IR radiation that comes through the aperture. When system electronics subtract this area from the actual image, it creates a halo around the hot spot in the image.

Figure 1 Visible light images show the person behind the wheel (top left), whereas images with mixed visible/IR (middle left) and pure IR (bottom left) show heat signatures that may also provide data about the recent or current presence of a driver. In the visible light image of the rear of the car, you can read the license plate, whereas the mixed visible/IR (middle right) and pure IR (bottom right) images show a heat signature indicating the car’s engine recently ran.
A fiber-optic sensor technology originally developed to detect enemy submarines also offers the ability to detect and locate intruders penetrating secured areas. Leveraging Rayleigh optical scattering changes in singlemode telecom fiber, the system essentially acts as a very long sensor array with no expensive gratings or mirrors. The fiber is buried in the ground to a depth of 9 in., yet is able to detect pressure waves originating from people and vehicles moving near or over the buried fiber. Engineers at the Naval Undersea Warfare Center (NUWC; Newport, RI) developed the technology.

After launching an encoded laser signal in the optical fiber, the system detects changes in the phase of the backscattered light through phase interferometry. These changes contain the acoustic signal information about the intrusion sound, i.e., the time-of-flight (location) and phase (sound pressure) changes. Essentially, the system is a long-baseline optical interferometer that incorporates a long-coherence-length laser source operating around 1300 nm and with a spectral width of better than 5 kHz. The long coherence length ensures frequency and phase stability of the optical signal during the round-trip path through the fiber. It is estimated that a single 150-mW laser can provide sufficient power for a sensor array as long as 15 km.

A digital signal processor in the system defines individual detection zones, which can be programmed by the operator. These zones can be pre-set to a specific length initially (for instance, to 100 ft); when an intrusion occurs and a zone becomes “active,” the system software can be programmed to automatically adapt the number of zones and the length of the zones (for instance, to 20-ft lengths) to determine location more precisely.

The genesis of the technique lies in adaptive beamforming techniques used in Navy sonar systems. Sounds of intrusion can be extracted from the zone data, then monitored or displayed to a system operator, along with the location of the array zone from which the sound originated. For perimeter security situations, threshold detectors can be created within the signal processor and set by the operator to provide an audible alarm when a threshold is exceeded within a zone. This provides an automatic detection, or tripwire, feature within the system.

To test the approach, engineers buried a 4000-ft. fiber-optic array approximately 9 in. deep around a portion of the perimeter of the NUWC property. The perimeter security system electronics sat in a temporary electronics van at one end of the array. During approximately two years of experiments and testing, the perimeter security system successfully demonstrated the ability to detect and locate typical intrusion-type sounds such as those caused by walking and running individuals, motorized vehicular traffic, and noises by individuals climbing a chain link fence adjacent to the array. Detection zone size and number were operator set and controlled as described.

Looking forward, border security installations will require much longer array lengths, but the use of a singlemode optical fiber as the sensor will keep overall system cost low. Current plans call for the installation of a 10-mi.-long fiber-optic sensor array at a remote test site. Testing a 10-mi. section of sensor array while it is still on a spool will not provide accurate results—the fiber will not display the same Rayleigh scattering properties and loss characteristics as a relatively straight array section because of the bending.

Classification of the intrusion returns is another area of development that will greatly reduce the false alarm rate of the perimeter security system. NUWC engineers have a wealth of experience in developing techniques to classify distant noises in the ocean. Development of automatic classifiers for the perimeter security system is in the planning stages at NUWC. The perimeter security technology is available for licensing by companies seeking to adapt the technology for commercial products.
In many applications, this halo effect is not a serious problem. In security applications, however, the halo can disguise the low-intensity emissions of someone moving behind it. This is why intruders often try to evade thermal imaging security cameras by entering an area near electrical transformers and other hot spots.

Vanadium oxide (VO\textsubscript{x}) microbolometer-based systems do not produce halos, nor do they contain moving parts. Bolometers are devices whose electrical resistance changes with temperature. Microbolometers are bolometers micro-machined onto semiconductor chips. They consist of an array of cantilevers coated with a thin film of VO\textsubscript{x}. Incident IR radiation heats the cantilevers, which alters the resistance of the VO\textsubscript{x} coating. The amount of voltage that passes over the cantilevers determines the intensity of its pixel.

Unlike BST FPAs, which must be refreshed between readouts, VO\textsubscript{x} arrays are analog devices that provide continuous feedback on thermal conditions. VO\textsubscript{x} arrays are inherently sensitive and the elimination of the chopper wheel further reduces the thermal background noise of the system. This gives VO\textsubscript{x} devices significantly lower sensitivity (NE\textsubscript{d}T below 85 mK, M\textsubscript{R}\textsubscript{T}D below 0.1\textdegree) than BST sensors.

**Practical Systems**

Our group has developed a pair of pan-and-tilt cameras (the DI-7000 and the DI-5000) that combine CCD and VO\textsubscript{x} detectors, allowing users to adjust operation from all IR to all visible, or any point in between. Equipped with a 50-mm germanium lens and a 51-\textmu-m-pitch sensor, the DI-5000 can detect human movement at 450 m. The DI-7000 uses dual lenses: When outfitted with a 25-\textmu-m-pitch sensor, its 30-mm lens can detect human motion at 500 m, and its 90-mm lens can zoom in for recognition and identification.

The cameras use focus-free lenses to ensure sharply focused, unchanging perimeter images. VMD software analyzes the image stream and automatically detects any pixel changes that might indicate motion by potential intruders.

VO\textsubscript{x} FPAs generate a continuous output signal that varies infinitely over 3 V. The DI-5000 and DI-7000 digitize the output into a 14-bit signal equivalent to 16,384 shades of gray per pixel. They then convert the digitized signal into an 8-bit format compatible with 8-bit (256 gray scale) black-and-white security monitors by normalizing the full signal range to accentuate the slight differences in temperature found in the midrange of the image. This approach improves both contrast and image quality.

The dynamic process re-normalizes around the temperature midpoint as it changes with each new readout. A similar dynamic histogram is used to process the image created by the CCD visual light camera. The two images are then overlaid. Users can adjust the output to display the desired proportion of IR sensor or CCD image, providing the best possible view for security purposes.

The cameras incorporate software-configurable electronics capable of reading a variety of FPA sensors, dynamically equalizing their output into 8-bit histograms, and controlling camera pan-and-tilt. The use of software-configurable electronics speeds the development of new surveillance products and permits rapid, cost-effective customization. It also ensures rapid incorporation of new technologies, such as the next-generation 640 × 480 VO\textsubscript{x} FPAs now under development. 

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