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Before you specify your next machine vision system, check out what SWIR cameras can do for your manufacturing process.

Shortwave IR Imaging in Machine Vision: Principles and Practice

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Shortwave infrared (SWIR) imaging is establishing a place for itself in manufacturing and process control applications that call for machine vision. The technology is also proving useful in military surveillance. SWIR imagers, sometimes also referred to as near-infrared (NIR) imagers, can see objects and events that visible light and thermal cameras cannot, are smaller and lighter than all thermal cameras, and cost far less than many of them. The three technologies are compared in Figure 1.

SWIR imagers work in a manner similar to that of the human eye or visible-light cameras,

Figure 1.

Comparison of Detector Technologies for Machine Vision

	Visible	SWIR			Thermal		
	CCD or CMOS	InGaAs	InSb	HgCdTe	InSb	Cooled HgCdTe	Uncooled Microbolometer
Waveband (µm)	0.38–0.75	0.9–2.5	1–5.3	1.2–2.5	3–5	3–10	8–13
Light sensed	Reflected and emitted	Reflected and emitted	Reflected and emitted	Reflected and emitted	Emitted	Emitted	Emitted
Works through glass windows	Y	Y	Y	Y	N	N	N
Uses standard camera lenses, passive and active filters	Y	Y	to 2.5 µm	to 2.5 µm	N	N	N
Needs cooling	N	No: 0.9–1.7 µm Yes: 1.2–2.5 µm	Cryo	Cryo or TE	Cryo	Cryo	N
Works with low-cost CW or pulsed illumination	Y	Y	to 2.5 µm	to 2.5 µm	N	N	N
Snapshot-mode capable	Y	Y	Y	Y	Y	Y	N
Full-frame LVDS rates fps single output	>500	>100	>100	>100	>100	>100	30, 60
All solid state, no moving parts, no vibration	Y	Y	N	N	N	N	N
Image resolution	1K × 1K 2K × 2K 2K × 3K	320 × 256 640 × 512	320 × 256 640 × 512	320 × 256 640 × 512	320 × 256 640 × 512 1K × 1K	320 × 256 640 × 512 1K × 1K	160 × 120 320 × 240
Digital resolution bits	8, 10, 12	12, 14	14	14	14	12	12, 14
Needs periodic uniformity correction	N	N	Y	N	Y	Y	Y
Simultaneous digital and video outputs standard	varies	Y	Y	Y	Y	Y	N
Performance through humidity and obscurants	F	VG	VG	VG	E	E	E
Relative size and weight for equal performance	1 ×	1 ×	3 ×	3 ×	3 ×	>4 ×	1 ×
Temperature measurement range	>700°C	>150°C	>100°C	>120°C	>0°C	>0°C	<250°C
Camera cost index	0.1	1.0	3	2.5	3	3	0.8

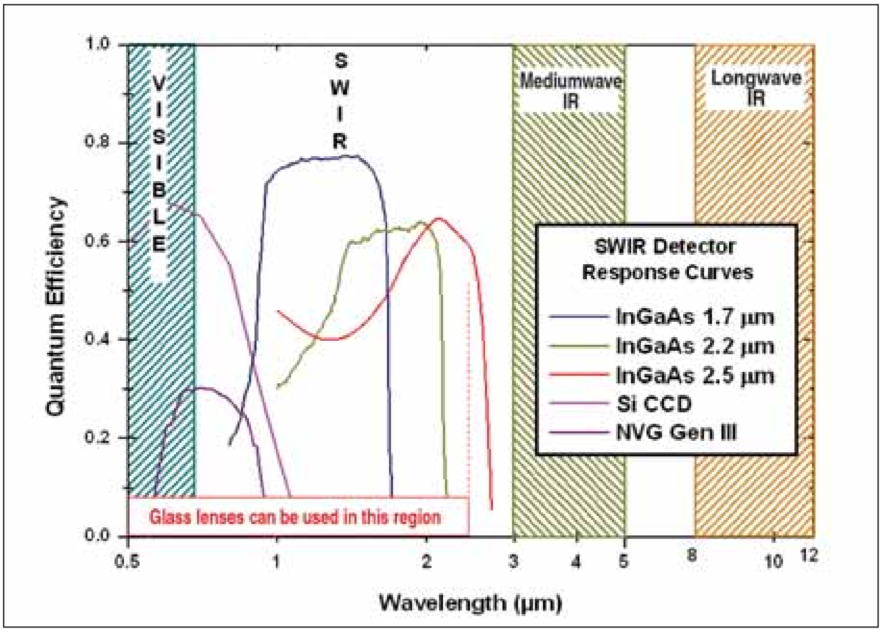

Figure 2. In these wavebands for the three most prominent imaging systems, note that various InGaAs formulations cover the entire SWIR range. The white area indicates those wavelengths that see through glass. Above this range, more expensive silicon and germanium optics are required.

Figure 3. A thermal camera could see only the top surface of this wine glass, still in the "hot end" stage of production. SWIR provides a false-color temperature profile on all surfaces. (Photo by Martin Ettenberg.)

but detect energy in the shortwave range of the spectrum (~900–1600 nm, also known as the NIR waveband). Virtually all objects emit or reflect energy in that waveband, even under starlight. And when no natural light is present, SWIR emitters can illuminate the object to permit detection by an SWIR camera. The technology's other major advantage is that plain glass is transparent to SWIR energy but opaque to IR or thermal energy. Detector arrays in SWIR cameras work much as do silicon detector arrays in visible (CMOS or CCD) or IR cameras, but they are based on wafers made of $In_xGa_{1-x}As$, InSb, or HgCdTe. Of these three materials, only InGaAs needs no cooling and offers uniform response over the entire SWIR waveband.

Most InGaAs SWIR cameras are solid state—no shutters, cooling systems, or other moving parts. Some come factory set and need no tweaking for their entire service lives. The imagers work with plain glass optics (see Figure 2), whereas thermal cameras require silicon or germanium lenses that cost ten times as much. Furthermore, these imagers are characterized by low noise, minimal cooling and electronic overhead, and simplicity of operation, making them similar to silicon CCDs and CMOS devices. A look at some typical applications will illustrate the versatility of SWIR technology.

SWIR at Work

Molten Metal. Emissivity differences between hot metal and slag show up more clearly in the 900–1700 nm bandwidth than in the visible or IR range. An analog image of the two materials tells operators when to end the process, maximizing yield of metals uncontaminated with slag. SWIR imagers' ability to work through glass allows them to monitor the 1899ºF–3000ºF process from protective enclosures

Glassmaking. Manufacturers of glass hollowware have long sought a way to pick out defective product at the "hot end" of their process, while the pieces are still at 200ºC–700ºC (see Figure 3). At that stage, rejects can be shunted aside and reprocessed efficiently, greatly reducing scrap. It turns out that the peak performance range of lattice-matched InGaAs SWIR cameras falls right within this temperature band. Because the imagers work through glass, the camera can inspect the bottles from one side. They can also be calibrated to accurately measure emmisivity vs. temperature and thus monitor the object's temperature uniformity and cooling rate. These data allow glassmakers to prevent shattering due to uneven cooling. Sometimes a manuracturing defect creates a web of hair-like glass filaments that crisscross the inside of the bottle. When cooled and hardened, these filaments fracture into shards that fall to the bottom of the container, where they can remain through the end of the fill process. When SWIR imagers detect a temperature differential between filaments and bottle wall, they activate an error signal that pulls the bad bottle off the line and flags a

Figure 4. Linescan SWIR imagers are at work classifing polymers for sortation on a recycling line in Europe. Some types of plastic can be given a new life as other products, including coats and outdoor furniture.

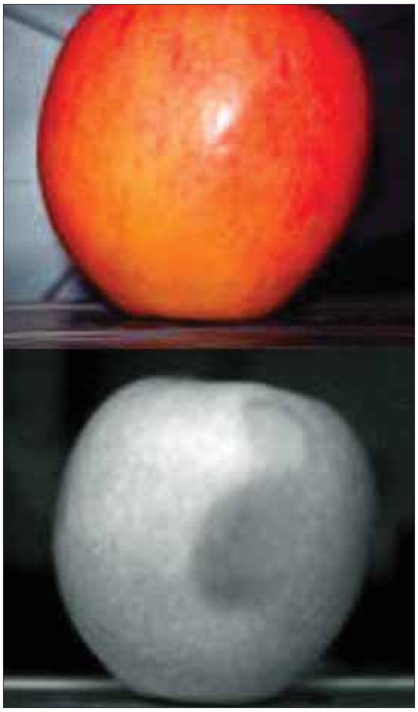

Figure 5. Bruises under the skin of an apple that human sorters would miss are revealed by SWIR machine vision systems. These cameras detect differences in moisture inside the fruit more cost-effectively than thermal cameras.

need to modify the production equipment appropriately.

Pharmaceuticals. SWIR-based machine vision and hyperspectral spectroscopy systems monitor liquid fill levels in opaque containers and deliver real-time chemical analyses on products moving on belts or through pipes. For example, many liquid drugs are dispensed in white plastic bottles that make visual camera inspection of fill level impossible. Since water in the liquid absorbs light strongly in the 1440 and 1940 nm bands, a SWIR camera in combination with incandescent backlighting of the vial easily reveals fill levels. SWIR or NIR spectroscopy is also used for real-time or continuous measurement of the presence of water, proteins, carbohydrates, fats and oils, and various hydrocarbon molecules. SWIR arrays also enable NIR-Raman spectroscopy of coatings and tablet ingredients. SWIR line cameras work well for Raman applications due to their linearity, high dynamic range, sensitivity, and anti-blooming design. Furthermore, they can monitor the placement and readability of NIR fluorescing authenticity marks online.

Recycling. First in Europe and now in the U.S., recyclers are coming to depend on SWIR-based spectroscopy for sorting plastics in the waste stream (see Figure 4). Inexpensive SWIR 1024 × 1 or 512 × 1 linescan cameras with wavelength sensitivities ranging from 1100 to 2200 nm are mounted on spectrographs. They quickly identify the type of polymer in a container passing down a sortation conveyer, and the output triggers a dam or paddle that diverts each container into its proper bin.

Agriculture, Textiles, and Forest Products. Moisture is a key indicator of process control and quality in agriculture, textile processing, and the forest-product industry. Because water is opaque to SWIR illumination, detecting its presence or absence can be useful in gauging crop health and product ripeness or dryness. For instance, the technology can detect flaws, such as bruises under the skin of fruits passing by on an inspection line, that are invisible to the eye (see Figure 5). Though perfectly suitable for many processed foods, bruises are not acceptable in fresh produce. Moisture content is also an indicator of when a dyed fabric is dry enough for the next step, and of whether dye coverage in a particular area is correct. In particleboard manufacture, online SWIR-based machine vision systems measure moisture in chips and the data are used to regulate heating and drying operations downstream.

Wafers, Lasers, and Fiber Optics. Standard alloy $In_{.53}Ga_{.47}As$ imagers are confirming alignment in fiber-optic interconnects and performing post-production defect analysis on semiconductor wafers. This alloy is the simplest and thus the least expensive to make, and has the best SNR of the various InGaAs alloys. Its ability to see

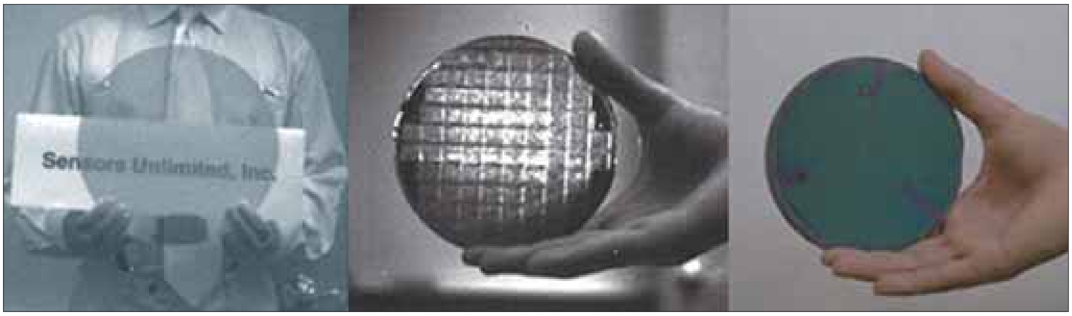

Figure 6. Silicon's transparency to SWIR cameras is illustrated here by a sign viewed through a 12-in. silicon wafer and by the visibility of the wafer's circuitry. A color visible-light camera would see only the wafer's surface.

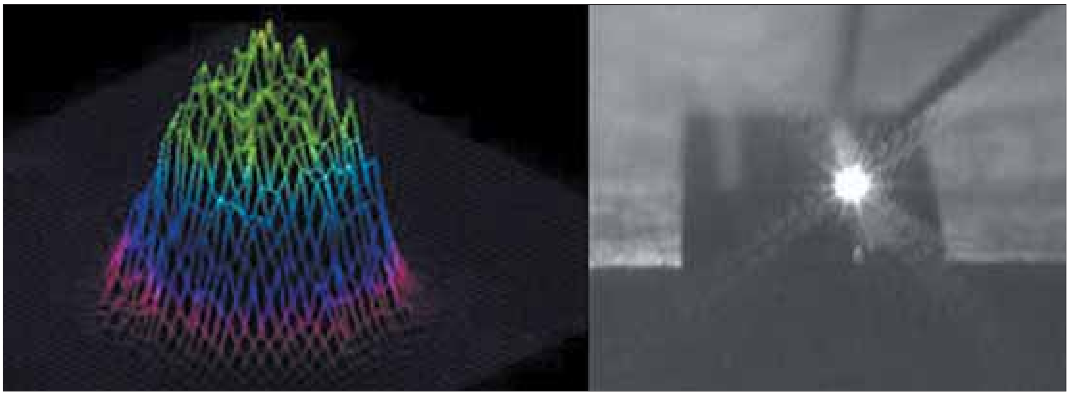

Figure 7. False color 3D mapping of laser beam intensity vs. position, along with a direct image of a laser beam, show the absence of blooming in SWIR InGaAs focal plane arrays.

through silicon (see Figure 6) gives it significant advantages in semiconductor production:

- The wafer's surface, internal structure, mask alignment, and voids all can be imaged through the backside of the wafer as it moves through the processing line.
- Alignment of optical elements such as lenses or fibers to devices, or certain sandwiches of ICs, can be accomplished by imaging photomask registration marks though the substrate.
- Postproduction wafer defect monitoring with photo-emission microscopy is enhanced by the fact that many internal defects in ICs emit photons up to 1300 nm in wavelength, while the silicon substrate is transparent beyond 1100 nm.

Offline laser beam profiling (see Figure 7) provides valuable information about laser efficiency, wavelength, and optical dispersion, and maps the energy lost outside the beam. The telecom and datacom sectors use lasers with wavelengths of 980, 1310, 1480, and 1550 nm—right in the heart of the lattice-matched InGaAs detector range.

Monitoring lasers in the bands outside 900–1700 nm requires extended-range detectors. In response to growing military demands, the technology is scaling up to production volumes, lowering the cost to ROI-justifiable levels. Soon a single SWIR detector will add the datacom laser wavelengths of 780 and 850 nm to those previously noted, and new detectors will be available to profile the longer wavelength lasers being developed in the 1800–2200 nm wavelengths for LIDAR.

Alternatives

Most industrial machine vision systems still incorporate CCD or CMOS imagers operating in the visible wavelengths. Thermal cameras are generally used for remote temperature measurement in industrial settings. These are complementary sensing ranges, as each can detect contrast between objects that the others cannot. And there has been progress in all three classes of camera. To varying degrees, they have grown smaller, lighter, more sensitive, more rugged, more feature rich, and lower in price. Microbolometers, for instance, cost less than SWIR cameras and can perform imaging in the thermal range without needing cooling. They are emerging from military applications into automotive night vision and may have a place in some machine vision systems. They are slow, however, which disqualifies them from high-speed, flash, or pulsed-illumination machine vision applications. Bolometers also require mechanical shutters and silicon or germanium lenses.

CCDs and CMOS visible-range imagers have evolved too, now coming in smaller pixel sizes with greater sensitivity and at far lower cost. If the

Figure 8. This InGaAs microcamera makes machine vision imagers fit where they couldn't before. It was developed for military applications such as covert surveillance from unmanned vehicles.

object or event of interest is visible to the eye, CCDs and CMOS visible-range imagers remain the choice for high field-of-view, high-speed machine vision applications.

Still, SWIR InGaAs cameras offer a combination of benefits that thermal and visible-spectrum cameras don't. In gritty industrial applications, for instance, lenses will inevitably be damaged and need replacement. It is far more economical to use glass than germanium or sapphire. As do visible-light CCD and CMOS detectors, SWIR devices respond to reflected light, which yields high-resolution images. IR cameras sense only heat or thermal differentials, and so have lower resolution. InGaAs cameras and arrays are as simple to operate as a silicon CMOS imager, but they can image different wavelengths, critical in many applications. With no mechanical shutters or large cooling systems on board, they are also relatively immune to vibrational error.

Bigger Arrays, Smaller Packages

Some of the greatest imaging progress of late has been in InGaAs SWIR cameras. Linear arrays up to 1024 pixels on a 25 mm pitch provide higher resolution for a wider field of vision, so fewer cameras cover more area. These cameras offer selectable analog and digital output as a standard feature. And they are being made smaller, lighter, and much more economical than IR or other SWIR imagers.

Recently for the military, we demonstrated a solid-state microcamera (see Figure 8) measuring only 5.9 × 2.8 × 1.7 cm, weighing only 70 g, and featuring factory-set nonuniformity corrections. The camera outputs both 12-bit digital and RS-170 analog video. Such compact devices should be of interest for machine vision applications that require squeezing multiple cameras into small, hard-to-reach places. One example is a machine tool manufacturer who needs to fit a camera to monitor the X, Y, and Z axes during a cutting operation. In addition to monitoring the dimensions of the workpiece, they also need to sense overheating, making this an ideal application for the microcamera.

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