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Infrared Imaging: Sense Out of Chaos

FLIR has a good shot at becoming the Dell of the IR business

Infrared (IR) sensors festoon soldiers' helmets, hang limpet-like on Apache and Pavelow helicopters, and are integral to M1 tanks and their battlefield kin. They equip the latest Gulfstream with aviation's first FAA-approved night vision system for commercial pilots. Cadillac introduced the auto industry's first IR imaging system on its 2000 DeVille sedan—it provides up to five times the range of low-beam headlights. Physicians employ IR gear to track blood flow, tissue structure, or lurking cancer cells. Digital photo buffs get IR sensing in the night-vision mode on Sony's newest F707 silicon camera. New York City firefighters have IR sensors on their headgear to help them see through smoke. In development: The Army-sponsored "fusion goggle," which superimposes an IR image on an optical one, pixel-by-pixel, to provide vision of science-fiction-like acuity, that reveals enemies lurking in any light, and in any camouflage.

Infrared detectors are not new. Sir William Herschel used thermometers in 1800 to sense the components of the spectrum that fell "below" the visible red light when sunlight passed through a prism. A century later, in 1901, the first IR detector could discern a cow a quarter mile away. Today, astronomers use cooled IR detectors to resolve the molecular constituents of the Horsehead Nebula, 1,500 light years away. But while scientists continue to employ ultra-fine IR technologies at the hyperbolic edge of physics, the resolution capabilities of low-cost, mass-produced IR sensors are now beginning to approach those of conventional optical imaging systems.

Make them cheap enough, and IR sensor will land everywhere—in a wide range of automotive and other transportation systems, across the factory floor, in the instrumentation of every engine and motor, in civilian security systems, in medical diagnostic equipment, and in food processing. They will be used to track engine performance and industrial-process efficiency, detect ice on aircraft wings, monitor the conditions of bearings on shafts, detect fungus growing in air ducts, and inspect semiconductor wafers and circuit board wiring faults.

The manufacture of high-resolution infrared detectors and IR cameras already comprises a $1 billion global industry. Until very recently, the market was dominated by military needs, and prices remained commensurately high. But in recent years, IR detector technology has advanced very rapidly—shrinking 100-fold in size, with power requirements dropping by 20-fold or more. The prices of complete IR imagers are falling apace. As a result, IR technology is now poised to become a ubiquitous "eye," first comparable to, and then surpassing, its digital cousin, the optical camera industry. Some forecasters predict a $10 billion market by 2005. It could well be a lot bigger than that.

Building a practical IR camera/imager around the core IR sensor remains a difficult art—roughly comparable to the challenges faced by the early builders of PCs, or cell phones, or digital cameras, or GPS systems, the companies that bought microprocessors and other necessary components, but had to work out where to go from there. For those who master the art, however, there is huge opportunity—because the key semiconductor components are suddenly getting cheap, even as their performance levels rise dramatically.

Over two-thirds of the global market for state-of-the-art IR systems is held by a half dozen companies. The leaders in defense IR are Raytheon (RTN), BAE Systems (BAESY), and DRS

Technologies (DRS). DRS just purchased Boeing's sensor group for $84 million. DRS is a pure defense IR play, with over 80 percent of revenues from government sales. BAE is Britain's aerospace and defense conglomerate. As valuable as IR detectors are in current and future military applications, and as important as defense funding has been in stimulating IR technology progress, it is the commercial (and dual-use military/commercial) markets where we find the greatest untapped potential. Two companies dominate here, with a combined 40 percent market share. Raytheon ranks second in this sector. Behind FLIR Systems (FLIR), which ranks first.

In our October 2001 issue, published in the immediate aftermath of 9/11, we surveyed the military applications of digital power, and Raytheon's leading role in many of these applications, including IR technologies (*Highly Ordered Power, October 2001*). Early last year Raytheon consolidated all its IR capabilities in an Infrared Operations group to become a merchant supplier of "IR engines" and systems, but this division remains focused on defense markets. FLIR has about twice Raytheon's market share in the commercial IR "camera" business. FLIR is squarely focused on the civilian side; it gets less than one-fifth its business from defense applications. In addition to being a high-technology company in its own right, FLIR has a good shot at becoming the Dell of the IR business, picking and choosing among rapidly advancing IR component technologies, and integrating the best into state-of-the-art imaging units.

The Graveyard

Heat is the graveyard, the final resting place, of every other form of power. The momentum of a cruising SUV ends up as heat. So does electricity from the wall plug. So does laser light, millimeter wave radar, radio waves from a cell phone, bits in a Pentium, or enzymes in a cell. Begin with higher grade energy in any form, begin with electromagnetic waves in any other part of the spectrum, and you end up—always—with electromagnetic waves loaded mainly in the part of the spectrum called the "infra-red."

Or at least that's where things end up here on earth, in the chemical and thermal environment we occupy. In our surroundings, heat is mainly the chaotic motion of atoms and molecules. And this randomized bouncing and shaking, in this particular environment, at surface-of-the-earth temperatures, excites loosely bound electrons, which then emit photons mainly in the infrared bands. If things get really hot, as they do in the filament of a light bulb, a greater part of the emissions move up into the visible light range. Get hotter still, and some significant part of the emissions shift into the ultra-violet or X-ray bands instead. But in the physical-chemical world we occupy in most of our daily life, most "chaos" takes the form of atoms colliding at temperatures that emit a lot more radiation in the infrared bands than in any other.

Thus, animals, soldiers, cars, and tanks emit IR radiation without an external illuminator. They are lit up, instead, by their own biological metabolism, or the combustion of gasoline or diesel fuel in an engine, or the warmth of sunlight, which generally persists long after the sun itself has set—self-illuminated by the mere thermal dynamism of their existence. From sunlight to combustion, every better-ordered source of power leaves a buzz of excited atoms and molecules behind it, and the buzz persists for quite some time, and takes different forms in different materials, depending on what they're made of, and how well they absorb heat, and shed it.

Our eyes don't see any of it, however. Pit vipers, like the rattlesnake, can, but our own eyes work only in the visible spectrum—electromagnetic radiation of wavelengths from 0.4 to 0.75 microns. The IR spectrum, by contrast, spans a broader range, from the "near IR" (0.75 to 1.1 microns) all the way to "long wave" (7 to 15 microns) emissions. The atmosphere is opaque to some of these wavelengths—water vapor and carbon dioxide are the principal sources of absorption. But there are several major windows of transparency (0.7-1.1, 2-2.4, 3-5, 8-14 microns) through which the heat waves propagate easily.

Except insofar as it shines long enough, and intensely enough, to heat things up, visible light has no impact on the brightness of objects viewed in IR bands. IR imagers thus function at night. And they can often discern otherwise hidden features that are washed out by bright light. If you can see in IR bands, you can see power in all the forms most commonly encountered in ordinary life: the power that moves a jet, tank, car, or a human body; the power that gets dissipated as friction in a bearing or valve; or the power that moves electrons through wires, or bits through a silicon chip.

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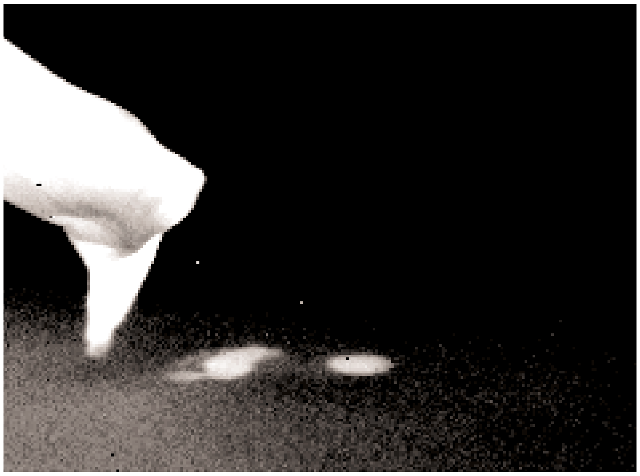
Seeing Chaos

The trouble is, it's very difficult to see chaos. With power, it's order that stands out, against the chaotic background. Chaos doesn't stand out; chaos is the background itself. Something cold can sense something hot—temperature difference is detectable, because it triggers a flow of heat from the hotter side to the colder. But the smaller the temperature difference, the harder it gets to detect. And because there's heat everywhere, and heat is random, the heat in the detector itself can readily obscure any weak thermal "signal" that the detector is trying to pick up. In signal processing terms, the IR spectrum is chock full of noise. So it's very hard indeed, it turns out, to make an IR camera at all, much less one the size of a deck of cards, or—as will soon be possible—one weighing just tens of grams.

The first key practical issue is the choice between cold and "room-temperature" sensors. The colder your sensor, the more sensitive you can make it—for much the same reason that the darker the night, the better you can see the stars. Thus, the most sensitive IR sensors operate at a temperature of 77°K (or less)—liquid nitrogen temperatures that require vacuum packaging and mechanical refrigeration of some kind at hand. This means bulky, expensive units. Basically, the more ephemeral and chaotic the power you want to sense, the more power and material and order you have to build into the detector itself.

Uncooled IR sensors are vastly more attractive, if you can somehow make them sensitive enough. Which can be done in the mid-IR wavelengths, roughly around 10 microns—the wavelength, as it happens, at which the human body is a strong IR emitter. Only uncooled sensors will find their way into a wide and expanding range of civilian (and some military) applications in which cryogenic cooling of the sensor is simply impractical. As DARPA, the Pentagon's high-tech research arm, puts it: "The ultimate goal of the development is to achieve uncooled sensors operating close to their theoretical limit. If this were achieved, this significantly enhanced sensitivity can be traded for smaller aperture, providing high performance imaging in an extremely small package … at substantially reduced cost, weight, and power." It won't ultimately be an either/or choice, as between cooled and uncooled detectors, however. Cooled detectors will always dominate in the high-end, long-range, most highly sensitive arena. Uncooled detectors will dominate markets—including most commercial markets—where high-volume production, low cost, and continuous operation are required.

There's a third possibility too: Accept the fundamental dark-night advantages of the cold sensor, but find a much more compact way of keeping it cold. The most important possibility here is thermoelectric cooling. This is nothing like the mechanical refrigeration systems that dominate every aspect of cooling today. The flow of electric current across solid-state junctions (between dissimilar metals, for example) can pump heat in the direction of the current flow, creating temperature differences that can be used for cooling (the "Peltier" effect). No thermoelectric cooler is very efficient yet, but there are important technological advances under way, and they are



Infrared images courtesy Indigo Systems Corp.

Our eyes don't see in the broad band of infrared wavelengths. But anything that's alive and metabolically active creates a thermal signature–emits in infrared wavelengths. So too does every wire that carries current, every chemical reaction in a battery or an industrial vat, every point of combustion, every source of propulsion, or source of digital bits. If it grows, moves, or actively changes state, it's hot enough for state-of-the-art IR technology to see. Thus the hidden cancer cell becomes visible to physicians, as do hidden 'guests' at night (top left photo, where the residual heat from the car's engine also glows brightly). An IR camera can see the subtle heat signature left behind a person walking on a wood floor (top right photo). Temperature variations in the milli-degrees are visible in IR, revealing tiny footprints of bacterial growth on food or pharmaceutical products as well.

opening up significant new possibilities in IR detection. Thermoelectrically cooled IR sensors are now being packaged in flat-pack assemblies, similar to integrated circuits. And detector technology continues to advance. A new generation of functional, uncooled sensors is now emerging.

Building the sensors themselves presents extraordinary challenges. A digital thermal picture has to be painted pixel by pixel, just as an optical picture is at the front end of a digital camera or videocam. Night driving sights, hand-held imaging and rifle sights currently use arrays of pixel elements, a 240x320 array for example; more advanced Defense Department applications require much higher pixel density (640x480 arrays). And there are four key front-end layers required to create a single pixel: sensing material, support/transmit structure, read-out electronics, and signal processing.

…. much of the rest of the IR-imaging art now lies in the execution

Each pixel requires a front-end detector—a tiny area of surface of sensing material that converts inbound infrared radiation into a tiny flow of current. This can be done in one of two ways.

First with the right materials, a photocell can directly convert IR photons into an electrical signal, much as a solar cell converts optical photons into electricity. Until recently, photoelectric IR detectors were based primarily on a mercury-cadmium- telluride (HgCdTe) compound, which is most strongly responsive to IR wavelengths 3-5 and 8-12 microns, and indium antimonide (InSb). This approach offers enormously rapid time responses (a microsecond or less). Both materials require cooling, however. HgCdTe must be cooled down to liquid nitrogen temperatures. InSb can operate at -78ºC, a temperature achievable with a cascade of thermoelectric (Peltier) coolers (as can another IR-sensitive compound, lead sulfide and lead selenide).

Gallium compounds now offer a second photoelectric option. The gallium-based quantum-well infrared photodetector (QWIP) was developed by Lucent about a decade ago. GaAs/AlGaAs QWIPs require cooling too, down to liquid nitrogen temperatures. But QWIPs can be manufactured using semiconductor fab processes, and precise band gap engineering allows the devices to be built to detect particular IR wavelengths. Very large arrays can be built, with very high uniformity and yields, and they can be stacked to simultaneously detect two or three discrete IR wavelengths.

The second approach, the main alternative to a photoelectric process, is to use materials that react predictably to subtle heating from IR radiation. The silicon microbolometer, for example, looks for changes in electrical resistance caused by tiny changes in temperature, and is rapidly emerging as the architecture of choice for many lower cost, commercial systems. Pioneered under DARPA sponsorship by Honeywell, Inframetrics, and Raytheon, the microbolometer employs a silicon "bridge" with a film of vanadium oxide that changes resistance as the thin slice of silicon undergoes microscopic heating from incident IR photons. Honeywell's technology, only declassified in 1992, rapidly became a major non-exclusive license to a half dozen companies. (Honeywell has retained the exclusive use of the technology for its building controls and commercial avionics applications.) Microbolometer arrays today are available with 50-micron pixels; the industry is chasing the next goal of 25-micron pixels, following a Moore's law-like trajectory, which will boost performance commensurately. An older approach to the thermal-electric architecture uses a thin film of a pyroelectric ceramic that changes its electric charge with temperature (barium strontium titanate is commonly used, as it is by Raytheon for the Cadillac's night vision option).

The main advantage of microbolometers and pyroelectric IR detectors is that they operate at room temperature. Their main disadvantage is that they respond much more slowly, with response speeds of 100 microseconds to 10 milliseconds. This isn't fast enough if you're trying to track a missile, but it's fine for many civilian applications.

Whatever the technology used to convert IR photons into electrons, each pixel in a Focal Plane Array (the IR detector) requires its own highly linear amplifier directly behind it. This amplifier must pick up the tiny electrical signal, filter out noise, and dispatch it down the line—and it must do all this within microns of the imaging pixel, otherwise other sources of thermal and electrical noise will drown out everything. In some cases, a monolithic structure—putting the IR pixel detector on the same substrate, immediately beside the silicon-amplifier—is feasible. For higher sensitivity, however—more pixels per unit area, and/or exotic detection materials—the amplifier must be located behind the pixel-generating surface, rather than alongside it.

The pixel-sensors and the amplifiers must of course be linked, one way or another. The supporting/connecting structures have to do two things simultaneously that very few materials can in fact do. The arms must conduct electricity, to transmit the signal from the sensor back to a tiny amplifier, and hence into the digital circuitry that will make sense of it. But the arm must not transmit heat to the sensor itself—the sensor must remain thermally isolated, or it won't see anything beyond the thermal noise of its own surroundings. All techniques leave plenty of thermal 'noise' in the system. The most common approach is a Read Out Integrated Circuit (ROIC) located extremely close (within 10 microns or so) to each pixel, or co-fabricated on the same monolithic surface. The use of detector materials such as InSb, or HgCdTe is not compatible with a silicon ROIC, so a hybrid package is needed and tiny indium "bump bonds" join the individual amplifier elements on the ROIC to the detector pixel. But hybrid processes are expensive—chips must be processed one by one, rather than wafer by wafer. That's tolerable when extreme performance is needed, as is the case in scientific and industrial test equipment, avionic systems, and medicine. But the monolithic option provides the clearest path to semiconductor economies.

The silicon-based microbolometers developed by Honeywell (with non-exclusive licenses granted to all the major producers of these devices—BAE, Raytheon, Indigo) can be co-fabricated on the same substrate as the silicon ROIC. These Honeywell microbolometers are now likely to emerge in various forms as ubiquitous IR equivalents to Intel microprocessors for IR engines (where Honeywell is collecting royalties instead of serving as the fab). It is indeed the advent of this room-temperature silicon microbolometer that accounts for the plummeting costs and steadily rising performance of complete IR imaging systems. The monolithic semiconductor-film bolometer (SFB) detector array can be integrated on the same silicon chip with a CMOS signal-conditioning and multiplexing circuit (ROIC), co-packaged with analog-to-digital conversion, and signal processing functions. These combined on-chip characteristics essentially define the "smart IR sensor."

Focusing the incoming IR photons is a separate challenge. Every camera needs a focusing lens, but conventional optics are opaque to IR wavelengths (as is the lens in the human eye). Silicon and germanium lenses are used instead (for 3-5 micron and 8-12 micron IR respectively), but they're expensive—a large germanium lens can cost thousands of dollars. Raytheon, and independent suppliers such as Amorphous Materials, have developed a lower cost alternative, chalcogenide glass (GeSbSe).

With the advent of low-cost IR detector units and suitable optics, much of the rest of the IR-imaging art now lies in the execution, in putting the pieces together in the most compact, stable, and sensitive way. IR imagers are inherently more challenging than optical ones. Two classes of commercial IR companies are emerging: those that will serve primarily as suppliers or components (like AMD or Intel) and those serving more like the Dell Computer or Canon camera companies, buying up key optics, IR engines, ROICs, and A-to-D displays, (and other components now at hand), to create an entirely new industry. Raytheon will likely continue as a major component supplier, Intel-like, and as a dominant defense systems supplier—indeed, Raytheon's IR group would form a formidable independent IR company if it were spun out. FLIR has a good chance of emerging as the Dell.

FLIR

Ordinarily, our search for digital power leaders leads us toward a single, fairly specific technology or material. We look for technologies that break existing molds, that are poised to jump well ahead of the current state of the art. We can't do that with IR at this point—we don't think anybody can. IR technologies are indeed advancing very fast—but on too many fronts. Which makes it too early to anoint just one technology as the likely winner. There won't be a discrete "winner" in any event—the IR frequencies span such a broad range, detector designs and sensitivities vary so much, and the potential applications of IR technology are so varied that quite a number of different IR technologies are certain to emerge as important. So we have been led, inevitably, to one company that not only develops IR technologies, but also picks and chooses across the field, putting the pieces together as functioning, state-of-the-art units.

FLIR now builds complete imagers around both cooled and uncooled infrared detectors. While the company manufactures many of the components for its products, including gimbals, optics, certain detectors, and high-speed motors, it also purchases many critical subcomponents pre-assembled, including detectors, coolers, circuit boards, cables, and wiring harnesses. FLIR buys its state-of-the-art IR engines from a number of suppliers, including uncooled microbolometers from Boeing (now part of DRS), and from Sanders (acquired by BAE at the end of 2000), and the more sensitive cooled IR engines from Rockwell Scientific as well as the new exotic QWIP arrays from ACREO AB (Sweden). (FLIR has an exclusive deal with Sanders to use that company's uncooled microbolometer in commercial thermography.)

Headquartered in Portland, Oregon, FLIR Systems was founded in 1978, acquired the IR group from within Hughes in 1990 and went public in 1993. A series of acquisitions followed: in 1993, a UK-based developer of dual sensor airborne camera systems; in 1996, a developer of image analysis software; in 1997, a Swedish company (AGEMA Infrared Systems) that had developed the first infrared sight for military applications, the first IR unit for electrical power line detection and the first battery-powered portable scanner for industrial inspection; in 1999, a Massachusetts-based provider of "complementary" imaging products (Inframetrics) and one of the players (along with Honeywell and Raytheon), in the important DARPA development of uncooled IR microbolometers). In 2001, FLIR acquired Saab's Optronics Division, a supplier of thermal imaging subsystems for missile and other weapons systems to defense electronic firms throughout Europe.

FLIR is divided into two divisions. Accounting for about half of FLIR's revenues, the company's Thermography division provides infrared cameras for non-contact temperature measurement. These units don't build high-resolution "pictures;" they focus in and locate hot spots, higher-temperatures zones—thermal differences and anomalies of any kind, often minute ones, located at specific points, or spread over larger areas. The Imaging division (the other half of revenues) provides stabilized infrared and visual imaging systems.

The thermography units are handheld and fixed-installation cameras. Most are built around proprietary, uncooled sensor technology. The fixed units are wired to connect with common factory automation systems (see September 2001 DPR). FLIR units are used for condition monitoring—detecting hot spots on equipment that indicate faults, locating defective power transmission components or electrical connections, predicting the end of life of bearings in rotating machinery, evaluating the integrity or amount of insulation in a building or container, or locating roof leaks and related damage. FLIR units are likewise used to inspect and monitor commercial vehicle's brakes, bearings, and tires. They are also used in a wide variety of research and development applications—the development of cell phones, laptop computers, telecommunications equipment, consumer appliances, automotive components, and aircraft engines, for example. They are used in manufacturing control, to monitor the flow of heat, identify moisture and contaminants, assess material thickness, and evaluate the bonding of composite materials. And they are used in a wide variety of other, often unexpected applications, such as animal care, food preparation, storage and handling, and leak detection.

…. one must grasp just how sensitive IR detectors have become

To appreciate the potential range of applications, one must grasp just how sensitive IR detectors have become. One FLIR system, for example, detects temperature variations of as little as five thousandths of a degree Centigrade. That's the kind of temperature elevation that can be caused by a tiny spot of bacterial growth or fungus growing on food or pharmaceutical products, for example. Just about anything that's alive and metabolically active will create a thermal spot that state-of-the-art IR technology can now see. So too, of course, will every ordinary wire that carries current, every chemical reaction in a battery or an industrial vat, every point of combustion, and every source of propulsion. If it grows, or moves, or actively changes state, it's hot enough for IR technology to discern against the thermal background.

FLIR's imaging units are more complex, expensive, and gee-whiz remarkable—they take what we think of as "pictures" but do so without light, or through fog and clutter that light cannot penetrate. They provide vision enhancement—though increasingly, the "enhancement" eclipses the optical alternative completely.

For airborne and marine applications, FLIR has developed highly stabilized turrets that typically contain an IR imaging system, an optical camera, a laser range finder, a laser illuminator, and a spotter scope, along with sophisticated embedded software to provide tracking and related data. For ground applications, FLIR manufactures both handheld products and platform-mounted products. These units begin with a high-performance infrared camera, together with an infrared lens system; some also include optical cameras and integrated pan and tilt capabilities.

FLIR's imaging systems are used in airborne and marine surveillance and reconnaissance, by military, civil defense, and rescue units—the Coast Guard, Customs Service, FBI, Marines, Air Force Reserve, and Air National Guard, among others. They are being incorporated in advanced navigation safety systems, to enable pilots or car drivers to see terrain and objects through smoke, haze, and fog. They monitor borders, coastal waters, and fishing boundaries, forest fires, oil spills, and wildlife. They provide perimeter security at government and military installations, at home and abroad. TV broadcasters use FLIR's infrared cameras to shoot at night. Law enforcement agencies use them to track suspects, locate lost people, and provide situational awareness to officers on the ground. FLIR's recently introduced Ultra 7500, for example, is an airborne imager for law enforcement organizations, designed to provide continuous, high altitude, long-range search and surveillance capabilities from rotary and fixed wing aircraft.

FLIR got to where it is today by design, not by happenstance—the company's market direction and revenues have progressed apace as it has implemented a plan to push IR technology into commercial markets. (Its stock price has marched steadily upward too, ever since an accounting controversy and management shake-up in early 2000.) The company builds products out of the most advanced IR technology—but its focus is always on the product, the commercialization of the technology, in civilian rather than military markets. This has led to an emphasis on the fast-emerging capabilities of uncooled systems.

FLIR has purchased, or allied itself with, suppliers of state-of-the-art IR components from around the globe—with the likes of National Instruments (integrated hardware-software machine-vision systems), and GlaxoSmithKline (drug-screening technology).

Reflecting its focus on integration, FLIR is committed to building the IR market. IR technology is new, and still largely unfamiliar; and prices have only recently dropped to the point where IR systems make economic sense in many new commercial applications. Thus FLIR has established the Infrared Training Center (in Boston and Stockholm, Sweden) to provide IR training and certification across sectors, and also co-sponsors the world's largest industrial thermography conference.

Check FLIR's web site (www.flir.com), and for each major application segment, the company puts up a gallery of IR photos. Cute PR or necessary education? Mostly the latter. For most engineers—from the D.O.T. safety inspectors interested in on-the-fly ways to check truck and bus brakes (and bearings and tires), to those in food processing, electrical utilities, building maintenance—the information-revealing capabilities of high-resolution IR images are entirely new territory. Such images, largely scientific curiosities until recently, have been kept out of general commerce until now because of the price and unwieldy nature of IR systems. But the high-resolution IR cameras that have recently emerged look a lot like the home video digital cameras, and integrated IR systems look just like another motherboard plug-in. For action movie cognoscenti, FLIR cameras were used to generate the infrared vision perspective of the alien in the movie Predator—PR again, but this technology is very much at the stage when good PR helps good engineers.

FLIR has a distribution organization covering more than 60 countries, and in 2000, the company earned a little more than $185 million in revenues (a doubling since 1997), 48 percent of which came from international sales. (Revenues are expected to reach $215 million in 2001.) Sales to the U.S. government accounted for some 18 percent of the company's revenue stream.

In addition to Raytheon, DRS, and BAE, FLIR's competitors include Wescam, several Japanese players (NEC, Nippon Avionics, Mitsubishi), Frances' SOFRADIR, and a couple of dozen smaller, private companies—such as Infrared Components, Infrared Solutions, and Kollsman. An impressive private "comer" in IR is Indigo Systems. The company has announced plans to set up InSb and microbolometer fabs, and is an acknowledged leader in the art of ROICs.

[Austin Richards, one of Indigo's scientists, just published an excellent book on imaging in general, including an IR chapter. It's an excellent layman's tour of what we've called digital power vision; *Alien Vision: Exploring the Electromagnetic Spectrum with Imaging Technology*, (SPIE Press, 2001). For those interested specifically in following the rapid advances in IR technologies and the tumult of industry activity in this sector, there is *Infrared Imaging News*, a first-rate, if arcane, newsletter dedicated to this space.]

But if any single company is likely to emerge as the dominant pure play in civilian IR markets, it is likely to be FLIR. In the last couple of years, FLIR has made all the right technology and market calls, focusing particularly on uncooled IR technologies for civilian markets. Once an expensive military and research tool, IR technology is now poised to push rapidly into many new civilian markets. FLIR is buying the best components from the best vendors. It is building IR markets where none existed before. It is assembling, packaging, and marketing a wide range of IR technology—the best possible approach, as it happens, for an arena in which such a wide range of technologies continues to evolve so quickly.

Out of Chaos

Low-grade heat—chaos—is where highly ordered power goes to die. But it doesn't go gentle into the night. As it expires, ordered power always leaves a thermal trail behind it—the drift toward chaos can be tracked and recorded. Which means, paradoxically, that the decay of order can itself be used to maintain or enhance order itself. A ball bearing that is headed toward catastrophic failure sends out a thermal cry of distress—and if an IR sensor picks that up, the bearing will be replaced before the whole motor is destroyed. Small leaks of fluid, or of electric current, likewise emit thermal warnings that can be picked up and acted upon before the small problem turns into a big one. Hostile bacteria growing in ducts or on food, hostile soldiers concealed in camouflage, and the engines on hostile jets all emit heat that warns of worse to come—and if the warning is heard, the worst can be evaded. The more sensitive the chaos detector, the earlier it can detect signs of greater chaos to come.

FLIR develops chaos-sensing technology. It pulls together complete chaos detectors and imagers. FLIR watches the aftermath of power, and thus reveals where power is coming from, and where it's headed. FLIR is a "see" company. Building its products out of fast-emerging solid-state IR technologies, it is perfectly positioned to join the pantheon of leading digital power companies in the 21st century.

Peter Huber and Mark Mills
January 9, 2002

The Power Panel

Ascendant Technology	Company (Symbol)	Reference Date	Reference Price	1/9/02 Price	52wk Range	Market Cap
Project, Sense, and Control	FLIR Systems (FLIR)	1/9/02	41.64	41.64	4.13 - 49.55	689.2m
	Analogic (ALOG)	11/30/01	36.88	38.50	33.40 - 50.00	508.5m
	TRW Inc. (TRW)	10/24/01	33.21	37.18	27.43 - 45.45	4.7b
	Raytheon Co. (RTN)	9/16/01***	24.85	32.20	23.95 - 37.44	11.7b
	Rockwell Automation (ROK)	8/29/01	16.22	19.16	11.78 - 49.45	3.5b
	Analog Devices (ADI)	7/27/01	47.00	47.35	29.00 - 64.00	17.1b
	Coherent (COHR)	5/31/01	35.50	35.39	25.05 - 53.75	1.0b
Electron Storage & Ride-Through	C&D Technologies (CHP)	6/29/01	31.00	23.60	16.35 - 55.65	615.9m
	Maxwell Technologies (MXWL)	2/23/01	16.72	9.80	5.81 - 22.56	99.6m
	Beacon Power (BCON)	11/16/00	6.00*	1.20	0.75 - 10.75	51.3m
	Proton Energy Systems (PRTN)	9/29/00	17.00*	9.02	4.00 - 16.50	299.6m
	Active Power (ACPW)	8/8/00	17.00*	6.56	3.56 - 31.50	265.9m
Powerchips	Cree Inc. (CREE)	4/30/01	21.53	31.22	12.21 - 37.75	2.3b
	Microsemi (MSCC)	3/30/01	14.00	30.69	9.47 - 40.10	871.3m
	Fairchild Semiconductor (FCS)	1/22/01	17.69	29.95	11.86 - 30.33	3.0b
	Infineon (IFX)	11/27/00	43.75	22.35	10.71 - 45.81	15.5b
	Advanced Power (APTI)	8/7/00	15.00	12.09	6.50 - 21.00	105.4m
	IXYS (SYXI)	3/31/00	6.78	9.35	4.27 - 27.75	250.4m
	International Rectifier (IRF)	3/31/00	38.13	40.20	24.05 - 69.50	2.5b
Network Transmission	ABB (ABB)	9/29/00	24.24**	10.70	6.10 - 18.95	12.7b
	American Superconductor (AMSC)	9/30/99	15.38	12.17	8.35 - 34.88	249.0m
Power: Heavy-Iron-Lite	General Electric (GE)	9/29/00	57.81	38.55	28.50 - 53.55	382.9b
	Catalytica Energy Systems (CESI)	9/29/00	12.38	5.04	4.00 - 24.00	87.4m
Distributed Power Generation	FuelCell Energy (FCEL)	8/25/00	24.94	19.25	10.48 - 46.72	750.5m
	Capstone Turbine Corp. (CPST)	6/29/00	16.00*	5.54	3.20 - 47.38	426.8m
Silicon Power Plants	Emerson (EMR)	5/31/00	59.00	58.49	44.04 - 78.00	24.6b
	Power-One (PWER)	(see below)				
Motherboard Power	Power-One (PWER)	4/28/00	22.75	12.46	5.32 - 52.50	982.5m

Note: This table lists technologies in the Powercosm Paradigm, and representative companies that possess the ascendant technologies. But by no means are the technologies exclusive to these companies. In keeping with our objective of providing a technology strategy report, companies appear on this list only for the core competencies, without any judgment of market price or timing. Reference Price is a company's closing stock price on the Reference Date, the date on which the Power Panel was generated for the Digital Power Report in which the company was added to the Table. All "current" stock prices and new Reference Prices/Dates are based on the closing price for the last trading day prior to publication. IPO reference dates, however, are the day of the IPO. Though the Reference Price/Date is of necessity prior to final editorial, printing and distribution of the Digital Power Report, no notice of company changes is given prior to publication. Huber and Mills may hold positions in companies discussed in this newsletter or listed on the panel, and may provide technology assessment services for firms that have interests in the companies.

** Offering price at the time of IPO.*

*** Effective April 6, 2001, ABB was listed on the NYSE. The reference price has been adjusted to reflect this change. The 52-week range covers the period from April 6, 2001 only.*

**** The October 2001 issue closed on September 16, 2001 and was posted at 8 a.m. on September 17, 2001. Due to the markets' close in the week after September 11, our reference price reflects Raytheon's closing price on September 10, 2001.*

More information about the Powercosm and its technologies
is available on www.digitalpowerreport.com