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Review Article

Infrared: A Key Technology for Security Systems

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Infrared science and technology has been, since the first applications, mainly dedicated to security and surveillance especially in military field, besides specialized techniques in thermal imaging for medical diagnostic and building structures and recently in energy savings and aerospace context. Till recently the security applications were mainly based on thermal imaging as surveillance and warning military systems. In all these applications the advent of room temperature, more reliable due to the coolers avoidance, low cost, and, overall, completely integrable with Silicon technology FPAs, especially designed and tailored for specific applications, smart sensors, has really been impacted with revolutionary and new ideas and system concepts in all the infrared fields, especially for security applications. Lastly, the advent of reliable Infrared Solid State Laser Sources, operating up to the Long Infrared Wavelength Band and the new emerging techniques in Far Infrared Submillimeter Terahertz Bands, has opened wide and new areas for developing new, advanced security systems. A review of all the items with evidence of the weak and the strong points of each item, especially considering possible future developments, will be reported and discussed.

1. Historical Introduction

Infrared, as part of e.m. spectrum, was discovered by Sir William Herschel as a form of radiation beyond red light. These "calorific rays" renamed infrared rays or infrared radiation (the prefix infra in latin means "below") were mainly devoted to thermal measurement and for a long time the major advances were due to infrared thermal imaging based on radiometric measurements [1].

The basic laws of IR radiation (Kirchhoff's law, Stefan-Boltzmann's law, Planck's law, and Wien's displacement law) have been developed many years after the discovery of IR radiation.

In 1859, Gustave Kirchhoff found that a material that is a good absorber of radiation is also a good radiator. Kirchhoff's law states that the ratio of radiated power and the absorption coefficient (1) is the same for all radiators at that temperature, (2) is dependent on wavelength and temperature, and (3) is independent of the shape or material of the radiator. If a body absorbs all radiation falling upon it, it is said to be "black." For a blackbody the radiated power is equal to the absorbed power and the emissivity (ratio of emitted power to absorbed power) equals one.

In 1884, L. E. Boltzmann, starting from the physical principles of thermodynamics, derived the theoretical formula of Black Body Radiation Law, stated empirically in 1879 by J. Stefan's, by developing the Stefan-Boltzmann's Law

$$W = \sigma \cdot T^4, \tag{1}$$

where W is the radiation power, T is the absolute temperature, and σ is the Stefan-Boltzmann's constant.

In 1901, Nobel Prize Max Karl Ernst Ludwig Planck developed the Planck's law which stated that the radiation from a blackbody at a specific wavelength can be calculated from

$$I(\nu)d\nu = \frac{2h\nu^3}{c^2}\frac{1}{\exp(h\nu/kT) - 1}d\nu, \tag{2}$$

where $I(\nu)d\nu$ is the radiation power emitted per unit of surface and solid angle unit, in the frequency interval ($\nu \div \nu + d\nu$), T is the Absolute Temperature, c is the speed of light, and h is the Plank's constant.

Soon after Wilhelm Wien (Nobel prize 1911) established the Wien's Displacement Law taking the derivative of the

Plank's law equation to find the wavelength for maximum spectral radiance at any given temperature:

$$\lambda_{\mathrm{Max}} \cdot T = 2897.8\ \mu\mathrm{m} \cdot \mathrm{K}. \tag{3}$$

IR detectors' development, even after the discovery of Infrared Radiation by Sir H. Herschel in 1798, was mainly based on the use of thermometers/bolometers which dominated IR applications till the 1st World War, although in 1821 J. T. Seebeck had already discovered the thermoelectric effect. In the area of bolometer/thermometers L. Nobili had fabricated the first thermocouple in 1829, allowing in 1833 the multielement thermopile development by Macedonio Melloni, who was able to show that a person 10 meters away could be detected by focusing the thermal energy on the thermopile. In 1878 Langley invented the bolometer, a radiant-heat detector that was declared sensitive to differences in temperature of one hundred thousandth of a degree Celsius. Composed of two thin strips of metal, a Wheatstone bridge, a battery, and a galvanometer, this instrument enabled him to study solar irradiance (light rays from the sun) far into its infrared region and to measure the intensity of solar radiation at various wavelengths. Langley's bolometer was a device capable of accurately measuring thermal radiation and was so sensitive that it could detect the thermal radiation from a cow from 400 meter away [2] (Figures 1 and 2).

Between the years 1900 and 1920, the inventors of the world "discovered" the infrared. Many patents were issued for devices for security applications to detect personnel, artillery, aircraft, ships, and even icebergs. The first operating systems, in the modern sense, began to be developed during the 1914–18 War, when both sides had research programs devoted to the military exploitation of the infrared.

First advanced application of IR technology to security in civil area was probably the "Infrared Eye" of Bellingham: a device to detect the presence of icebergs and steamships by using a mirror and an original thermopile, perhaps developed one year before, but proposed for Patent in May 1913 (after the Titanic tragedy in April 1912) [3] (Figure 3).

"The infra-red eye, which in this case is a thermopile, is mounted laterally in tube 2 preferably of stout copper and of a diameter of about 10 inches or example, and near the window end of the same. Window 3 may have a diameter of about 6 inches and consists of a material transparent to infrared radiations. The infrared eye is prevented from directly receiving the radiation in question by being shielded by shield 4 and by being mounted close behind the opaque portion of mount 5 containing said window. At the other end of the tube there is arranged mirror 6 which is preferably of copper, the reflecting surface being gilt. The reflecting surface of mirror 6 is supposed to be toroidal, the toroidal surface being of such curvatures in the vertical and horizontal planes, respectively, as to produce on the sensitive surface of the thermopile sharply localized images in a horizontal plane, the rays in the vertical plane on the other hand being distributed over an angle of several degrees below to several degrees above the horizontal, and the object being to prevent loss of the image by pitching of the ship when the apparatus is in use at sea."

Similarly Parker in the same period of time was patenting an advanced sensor using the high sensitivity of "Delta zero measurement" by means of a Wheatstone Bridge [4] (Figure 4).

"This invention relates to thermic balances or radiometers and has for its object an improved capable of detecting the presence of a body by its sensitiveness to the ethereal radiation produced by that body consists in improvements in radiometers as well as in a novel adaptation thereof to produce an instrument sensitive only to the energy radiated by bodies and also rugged enough to be used as a commercial instrument with particular reference to its use as a detector of the presence of cold bodies, as icebergs. I accomplish this and the other objects by the apparatus herein after described."

So between the years 1900 and 1920, many inventions in the world were based on the infrared with patents issued for devices to detect personnel, artillery, aircraft, ships, and even icebergs. The first operating systems, in the modern sense, began to be developed during the 1914–18 War, when both sides had research programs devoted to the military exploitation of the infrared. These programs included experimental systems for enemy intrusion/detection, remote temperature sensing, secure communications, and "flying torpedo" guidance. An infrared search system tested during this period was able to detect an approaching airplane at a distance of 1.5 km, or a person more than 300 meters away. The most sensitive systems up to this time were all based upon variations of the bolometer idea, but the period between the two World Wars saw the development of two revolutionary new infrared detectors: the image converter and the photon detector. In fact early thermal detectors, mainly thermocouples and bolometers, were sensitive to all infrared wavelengths and operating at room temperature and normally, until few years ago, they were with relatively low sensitivity and slow response time.

The first photon detectors (based on photoconductive effect discovered by Smith [5] in 1873 in Selenium and, later on, by Bose in photovoltaic lead sulphide, but not applied for many years) were developed by Case in 1917 [6]. In 1933, Kutzscher developed IR PbS detectors (using natural galena found in Sardinia): these sensors were widely used during the 2nd War. These detectors have been extensively developed since the 1940s. Lead sulfide (PbS) was the first practical IR detector, sensitive to infrared wavelengths up to $\sim 3\,\mu$m. In the mean time Cashman developed TaS, PbSe, and PbTe IR detectors with high performances supporting the developments in England and US.

At first, the image converter received the greatest attention by the military, because it enabled an observer to literally "see in the dark." However, the sensitivity of the image converter was limited to the near infrared wavelengths, and the most interesting military targets (i.e., enemy soldiers) had to be illuminated by infrared search beams. (Since this involved the risk of giving away the observer's position to a similarly-equipped enemy observer, it is understandable that military interest in the image converter eventually faded).

The tactical military disadvantages of so-called "active" thermal imaging systems provided impetus following the 1939–45 War for extensive secret military IR-research

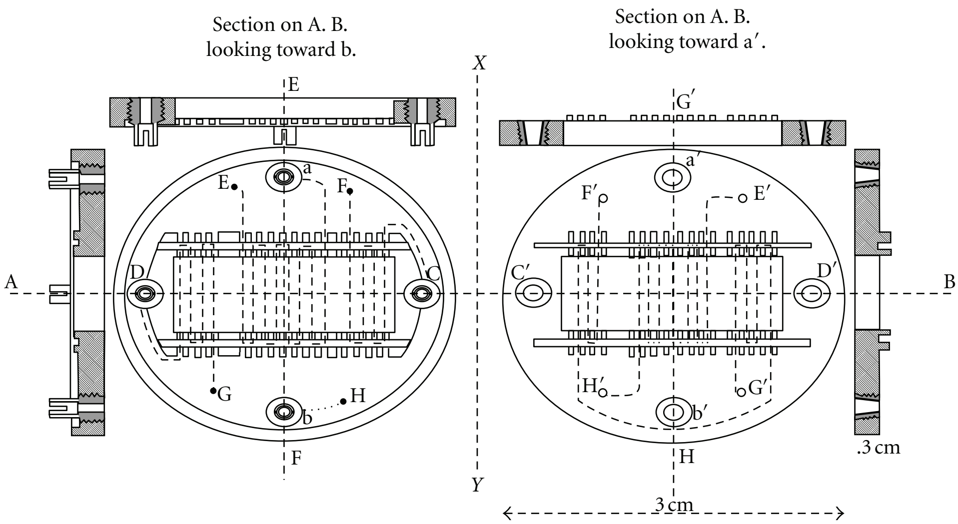

Figure 1: The Langley Bolometer.

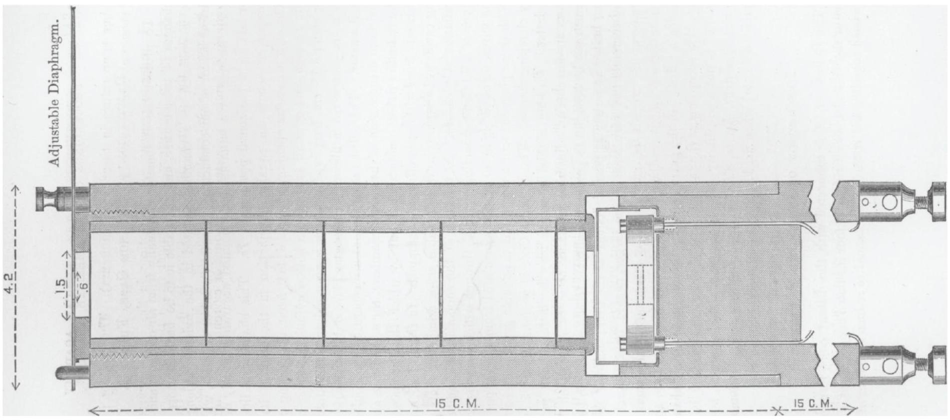

Figure 2: Section of the Bolometer case and Bolometer.

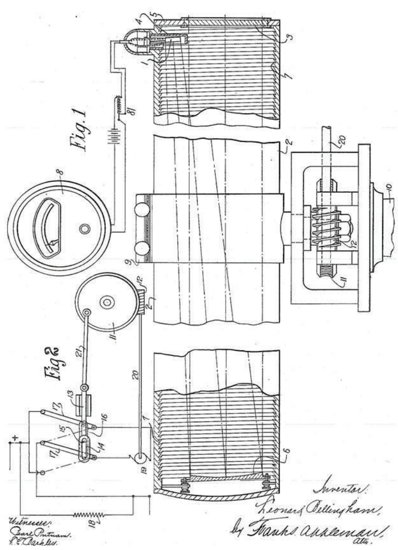

Figure 3: Bellingham. Means for detecting the presence at a distance of icebergs, steamships, and other cool or hot objects. Filed May 1, 1913; patented November 2, 1915.

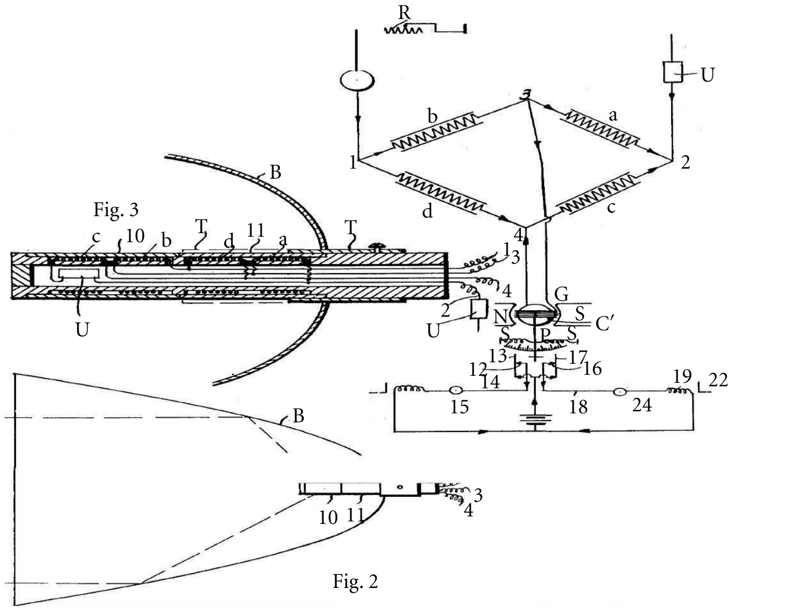

Figure 4: Parker, Thermic balance or radiometer application, filed July 31, 1912; patented June 9, 1914.

Figure 5: Infrared: military applications 2° War.

programs into the possibilities of developing “passive” (no search beam) systems based on the extremely sensitive photon detector. During this period, military secrecy rules completely prevented disclosure of the status of IR-imaging technology. This secrecy only began to be lifted in the middle of the 1950s, and adequate thermal imaging devices began to be available to civilian science and industry (Figure 5).

High level results were achieved in the 1940s, especially in lead salts (PbSe and PbTe good stable cells were developed by OSRD, Office of Scientific Research and Development in co-operation with the MIT, Harvard, and the British TRE Telecommunication Research Establishment, Great Malvern). The history of IR detector developments has been therefore almost coincident with optoelectronics for military applications for many decades, strongly conditioning the cultural behavior of the IR industry and in some way of R&D labs.

2. Focal Plane Array (FPA)

The basic strategic device in infrared technology is the sensor that in its historical evolution has been growing from single detector with an optical-mechanical scan of the acquired scene and then, starting from the middle of

1970s, multipixel sensor Focal Plane staring Arrays (FPA). Infrared technology starting from the 1950s was enjoying a great growth, especially in the development of solid state IR sensors. Almost contemporarily lead selenide (PbSe), lead telluride (PbTe), and indium antimonide (InSb) cooled detectors extended the spectral range beyond that of PbS, providing sensitivity in the 3–5 μm medium wavelengths (MWIR) atmospheric window. (Extrinsic photoconductive germanium detectors were allowing to reach long wavelength spectral region, needing very low temperature with the use of liquid helium). But we had to wait till the 1960s to see the first advanced developments coming out thanks to direct gap photon materials based on ternary semiconductor compounds (HgCdTe and PbSnTe) [7, 8]. This was a real breakthrough, because after the discovery of solid state transistors (1948) and the explosion of solid state electronics, microelectronic was offering new advanced manufacturing technologies like photo-masking and integrated microsoldering and assembly allowing multielements structure (first Linear Arrays and then in the 1970–80s years Bidimensional Focal Plane arrays FPAs) with the highest number of pixels. After the 1980s strong efforts were put to developing integrated electronics for signal readout and elaboration, with working temperature close to room temperature with the main task of achieving high optoelectronic FPA's performances with smaller and lighter structures, with possibilities of applications in civil area thanks to cost reduction and civilization by eliminating optomechanical scanning and cryogenic low-temperature cooling.

The recent development of advanced IR FPA (with $>10^6$ pixels in the 8–12 μm) working at room temperature allows to forecast an incredible growth of uses besides the evident growth of advanced applications of IR based on thermal measurements. The choice, supported by US industries, of concentrating efforts and resources in a specific technology produced the "first generation of linear detector arrays," which allowed to obtain BLIP detectors at liquid nitrogen temperature (this first generation of CMT linear arrays was the basis for the "Common Modules" LWIR FLIR systems with a number of pixels from 60 up to 180, each detector connected with feed-throughs to the room temperature read out electronics). The invention of Charge Coupled Devices (CCDs) in 1969 [9] made it possible to start the developing of the "second generation" FPAs detector arrays coupled with on-focal-plane electronic analogue signal readouts which could multiplex the signal from a very large array of detectors. In the middle 1970s, while the 1st Common Module IR Arrays were produced, the first CCD IR bidimensional arrays [10, 11] were appearing in USA and, the first Smart Sensors based on LTT RF sputtered thin films, using X-Y addressing readout, were developed in Italy [12]. In 1975 the first CCD TV camera was realized and this was allowing to forecast the "2nd generation FPAs" capable of a staring vision, although the necessity of very high spatial resolution and high reliability even in complex structures, with extremely high number of pixels (up to one million pixels), were pushing towards alternative solutions, with materials less difficult than CMT, in the manufacturing process (e.g., extrinsic silicon detectors). The high quantum yield of CMT and the top performances required by the military anyhow allowed to improve the performances of sensor linear arrays by integrating time delay and integration inside the detectors' structure itself (SPRITE detector [13]).

In the late 1970s through the 1980s, CMT technology efforts focused almost exclusively on PV device development because of the need for low power and high impedance for interfacing to readout input circuits in large arrays (photoconductive CMT was not suitable due to its low impedance). This effort has been concretized in the 1990s with the birth of "second generation IR detectors" which provides large 2D arrays with the number of pixels up to many hundred thousands thanks to hybrid integration (indium bumps or loopholes soldering) of CMT bidimensional arrays in silicon substrate with CCD and more recently CMOS readout. At the same time, other significant detector technology developments were taking place. Silicon technology generated novel platinum silicide (PtSi) detector devices which have become standard commercial products for a variety of MWIR high-resolution applications. Monolithic extrinsic silicon detectors were demonstrated first in the mid 1970s [14, 15]. Thanks to PtSi Schottky barrier IR properties, great attention was dedicated to FPA arrays based on integrated silicon Schottky sensors which were showing reliable monolithic silicon CMOS-integrated technology and high uniformity in detectivity, but were operating in the short wavelength region and with the limitation of low working temperatures. Similar considerations can be made for the long wavelength GaAs/GaAlAs Multi-Quantum Well IR FPA arrays [16], which, although if with lower quantum efficiency, are close to CMT performances even showing higher homogeneity and stability in sensitivity thanks to a more reliable manufacturing process, but with the strong limitation of working at lower temperatures (<77 K). This requires the use of Cryogenic structures with high cost of purchasing and maintenance, therefore improving the restriction of the main use to military applications, limiting the market size, and, as consequence, the product growth. In all the latest developments the really driving key technology has been the integration of the IR technology with silicon microelectronics and it was, more and more, emerging the importance to free IR from the constraints of the cooling requirements due to its high cost (almost 1/3 of the total cost) and low reliability and heavy need for maintenance. For the above reasons, work on uncooled infrared detectors has shown an impressive growth since the first developments, allowing the real expectation for a production of low cost, high performance detector arrays which finally should follow the rules of a real global market, opening a real market for civil applications following the winning rules of silicon microelectronics. For these reasons the emerging room temperature detectors in the 1970s by the use of pyroelectric materials [17, 18], which shows the limitations of not being fully monolithic, but the innovative room temperature silicon microbolometers appearing on the IR scene in 1990 [19], seem to be a real breakthrough for future IR sensors.

In Table 1 are reported the highlights of the IR Sensor developments since the Herschel's discovery.

Table 1: History of IR detectors.

1800	IR radiation Sir W. Herschel
1821	Thermoelectric effect Seebeck
1829	Thermocouple G. Nobili
1833	Thermopile Macedonio Melloni
1836	Optical pyrometer Becquerel
1873	Photo-detection (Selenium) Smith
1884	IR radiation law Boltzmann
1902	Photoconductivity effect Bose
1917	Lead sulphide Case
1933	Lead sulphide (galena) Kutzsher
1940	TI2S Cashman
1942	Golay cell Golay—Queen Mary College
1948	Transistor Bardeen-Brattain-Shockley
1950s	PbS, PbSe, PbTe T. Moss RRSE
1959	HgCdTe W. Lawson, J. Putley
1960s	Ge: X, InSb
1969	CCD Boyle-Smith (Bell Labs)
1970s	PbSnTe/HgCdTe, Si: X Lincoln Labs, SBRCHughes, Honeywell, Rockwell, Mullard
1973	Common modules Night vision Lab
1975	IR Fly Eye Smart Sensors: C. Corsi, Elettronica SpA
1978	Si: X/CCD/PtSi/CCDHgCdTe/CCD RCA Princeton Lab W. F. Kosonocky, F. Shepherd D. Barbee-F. Milton-J. Steckel
1980s	HgCdTe SPRITE InGaAs QWIP T. Elliott RSE, F. Capasso L. Esaki, B. FLevine, M. Razeghi, L. J. Kozlowski
1990s	Pyroelectric FPAs/MicroBolometer FPAs/Multi-colour FPAs/Advanced FPAs RRSE-BAE,. R. A. Wood, J. L. Tissot, P. R. Norton, A. Rogalski, H. Zogg S. D. Gunapala, D. Z. Ting
2000	MEMS FPAs—Cantilever IR Nanotubes/Nanowires B. Coole, S. R. Hunter, X. Zhang, J. M. Xu, S. Huang, Y. Zhao, J. Xu, Maurer, G. Jiang, D. J. Zook

3. Smart Sensors

The most important applications for security systems have been developed in military fields evidencing a consistent growth in the system concepts especially for the capabilities of intelligent evaluation of the signal detection and warning for threats' presence. So starting from the late 1970s [20–23] and the beginning of 1980s under the pushing of USA Strategic Defence Initiative for achieving outstanding performances in sensors systems a new class of infrared sensors systems called "Smart Sensors" were appearing on the infrared stage. "Smart Sensors" integrate the sensing function with the signal extraction, processing, and "understanding" particularly in application fields such as remote sensing where minimum size and high level multifunction performances were considered as the main achievements to be reached. So the term "Smart Sensors" has been originated to indicate sensing structures capable of gathering in an "intelligent" way and of preprocessing the acquired signal to give aimed and selected information [24].

In a broad sense, they include any sensor systems covering the whole electromagnetic spectrum: this paper deals specifically with a new class of smart sensors in infrared spectral bands whose developments started some years ago [20, 21] when the integrated processing capabilities based on advanced readout integrated with signal processing were still far from the complexity needed in advanced IR surveillance and warning systems because of the enormous amount of unwanted signals emitted by operating scenario especially in military applications [23].

Later on, thanks to the CCD readout technology, it was recognized that the rapid advances of "very large scale integration" (VLSI) processor technology and mosaic infrared detector array technology could be combined to develop new generations of Smart Sensor systems with much improved performances. Therefore, sophisticated signal processing operations have been developed in these new systems by integrating microcomputers and other VLSI signal processors within or next to the sensor arrays on the same focal plane avoiding complex computing located far away from the sensors. These developments were later widespread on too many applications and the term "Smart Sensors" was used and "abused" to identify and define sensors with some integrated type of processing and even to erroneously define "Smart Sensors" that are supplying aimed information.

In conclusion there are two main classes of IR Smart Sensors: the first one supported by the impressive growth of integrated microcircuitry which, thanks to the CCD/CMOS integrated readout, can allow sophisticated preprocessing using the Smart Sensing techniques (these devices known as "vision chips" in the visible range have been recently strongly investigated and successfully developed) [25], and the other one, more oriented to specific applications, in which most of the intelligence of preprocessing is inside the design and structure of the sensor itself [23, 25].

The Smart Sensor technology in fact should allow integrating technical design and development from optics, detector materials, electronics, and algorithms into the sensor's structure and function rather than trying to get the required performance by relying on massive improvements in just the aspect of the number of pixels and related electronics readout and processing technology. Therefore, the performance of the Smart Sensor can be achieved with lower technological risk and with integrated structure which allows smaller size and higher reliability and often higher performances for specific applications like, for example, warning and alarm systems. The "Smart Sensor" design concept is based on the processing capabilities, at least at some stage of threshold, inside the sensors structure itself. Such new family of sensor, defined in a broad sense, intelligent sensors, or Smart Sensors are the result of an optoelectronics analogue processing which in some way are simulating some functions of signal pattern extraction information selection for pattern recognitions, as it happens in the dynamic link between the human eye and brain or, more truly, in the primitive visual structures of some insects (fly-eye) [26].

The main task is to satisfy better or even to substitute the highly complex elaboration of signal output deriving from the enormous mass of data coming from the high number of sensing pixels by implementing an elaboration prefiltering capability in the sensor structure itself. This prefiltering capability associated to an integrated electronic processing can allow implementing correlations in the spectral, temporal, and spatial domains, so that it is possible to contain the flux of acquired data extracting only those with higher information content. Examples of such correlations can be exemplified by some well-defined signal extractions (Point Source Detection, Edge Enhancement, and Morphological Structure Recognition).

These correlations associated to appropriate temporal signatures can allow to discriminate and identify the targets, like that performed by an insect eye thanks to a spatial-temporal correlation. (Figure 6). One of the simplest feature extraction and in the same time most appealing for the numerous applications is the discrimination of point sources from extended background emissions and/or of fast events (moving targets or changeable emissions) for static or slow moving scenario. In this case a reticule structured detector, which is electronically modulated to obtain a spatial-temporal correlation of the focused spot target, buried within the diffused background emission, can allow the detection of point source or a well-defined-shaped target improving the signal to clutter ratio. This dynamic spatial filtering can be implemented with special feature structure which is capable of preferable detection for selectable forms (e.g., point sources, linearly structured objects, etc.). These correlations associated to appropriate temporal signatures can allow discriminating and identifying the targets, like that performed by an insect eye thanks to a spatial-temporal correlation. One of the simplest feature extraction applications is the discrimination of point sources from extended background emission and/or of fast events (moving targets or changeable emissions) from static or slow moving scenarios. Normally this is obtained by an external chopper (mechanical or optical) which modulates the incoming signal depending from its collimated spot size. This signal processing can be done by emulating the fly-eye structure that is a sensor with a finger-type electrodes structure which, thanks to an electronic modulation in a differential way between two adjacent subpixels, can detect spot size almost cancelling the signal due to a diffused irradiation source (e.g., clouds and diffused sun irradiation) which are widespread in more than one single sub-pixel (a third electrode structure can be inserted for avoiding the missing of the detection of point target in case that the focused spot is falling just in the middle of two adjacent electrodes [23]).

Associated with the pushing towards highest number of pixels ($>10^6$) and the highest working temperatures (close to room temperature), the general trends of future detectors will show more and more increasing of the "intelligence" of the sensors which will integrate the sensing function with the signal extraction, processing/"understanding" (Smart

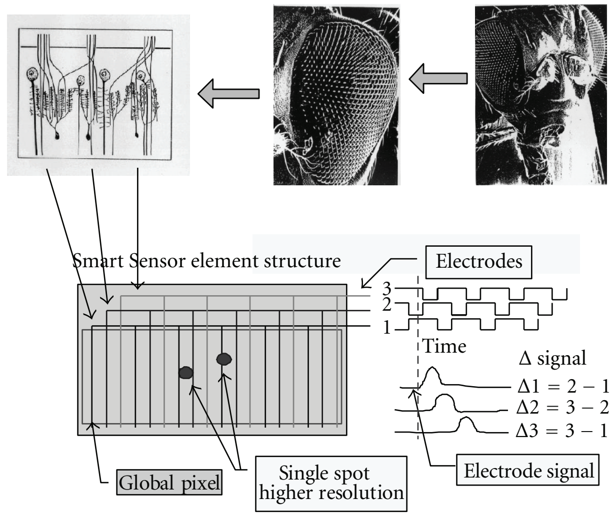

Figure 6: Smart Sensor emulating fly-eye recognition structure with an integrated 3 electrodes modulation.

Sensors). The basic objectives of new IR smart sensors are much more demanding because significant improvements in the performance of VLSI processors and infrared mosaic detector arrays are being achieved. Especially in the prethreshold stage, target signals are expected to be deeply buried in background clutter noise which can be much higher than the target intensity. Therefore, imaginative pattern recognition processing techniques using all spatial, temporal, and/or spectral information of both targets and background clutter should be developed for suppressing background clutter and unwanted signal, but maintaining or ever enhancing the target signal. At last, it is important to underline that the important recent developments of neural networks for advanced computing allow foreseeing an impressive growth of the "Smart Sensor" concept especially for those detector technologies which will take advantage of the possibility of integrating processing devices [27].

4. Infrared Technology System Applications

For a long time infrared was confined to military applications especially based on thermovision, technology that is "infrared: to see the invisible" (Figures 7, 8, and 9).

In the end of 1990s the crisis originated by the solving of Soviet Union and the consequent the end of "Cold War" was pushing the use of infrared towards civil applications (the famous slogan "from military to civil" and "the dual-use mode" with the explosion of thermovision technology applied to environmental control, building/art masterpieces analysis, medical functional diagnostics*, and recently car guidance/collision avoidance systems)* [26, 28–35].

The developments were so great that, thanks to simultaneous lowering of costs due to mass production of advanced room temperature FPAs sensors, there was emerging a dual way use from civil to military markets [36, 37].

Figure 7: High-resolution visible and infrared aerial photos.

Figure 8: Visible and infrared photos of a wood. Both photos (FLIR System Inc.) are evidencing targets in the infrared photos not detectable in the visible.

4.1. Smart Sensors for Collision Avoidance in the Fog. An important application of the IR Smart Sensors for civil security is an IR system for driving assistance in low visibility due to fog/smokes as "collision avoidance in low visibility."

In fact thanks to the better visibility trough fog in IR field in respect to visible many systems proposals have been done by car producers for the use of thermal viewers to be installed on board. These IR systems up to now have shown heavy limits for the sensible cost also if using the IR room temperature microbolometers and for maintenance and reliability and over all for "man interface" (it is evident that few car drivers can use an helmet-type display or can have enough skillfulness to look at a display while driving in very low visibility).

For these reasons a new generation of simple, reliable, Smart Sensors operating at room temperature with no costly

Figure 9: Aerial infrared photo of "Kennedy Aircraft Carrier": aircrafts parked or just landed can be recognized.

thermocontrol, which supply a sound and light alarm in case of presence of an obstacle on the road, could be a winning solution. In the presence of fog, air is more transparent to IR radiation than to VIS light. CREO developed a low-cost smart sensor, based on a 32×2 bilinear microbolometer array, to be fixed close to the car headlamps, and capable to perform radiometric identification of hot objects and deliver an audible alarm to the driver.

In Figure 10 is shown a high-resolution thermal image of two possible obstacles in a winter environment: a car parked for more than 10 minutes and a running car. In Figure 11 is shown the signal detected by the IR Smart Sensor structure supplying automatic alarm in both cases.

4.2. Toxic Gas Sensing. Owing to the increasing demand for security in civilian crowded areas, both for the risk of accidents in dangerous materials transportation and in industrial toxic substances processing and recently of terrorist threat, the development of novel large-scale applicable technologies and methodologies for quick detection and identification of extremely toxic compounds is strongly advised. Particularly, in military battlefield operations or in case of terrorist attacks, high detection capability coupled to low false alarm rate and identification capability, at least for classes, are required. The alarm systems should be compact and small size, even expendable in case of military battlefield operations. In fact due to the presence of dense smokes and powders besides toxic gases, the environment of a battlefield is normally turbid; therefore, it needed a stand-off point detection system which should operate in the dangerous selected areas and delivered by special launcher systems or put on board of URPV (Unmanned Remote Pilot Vehicle).

Moreover, most of the CWAs (Chemical Warfare Agents) are heavier than air and are spreading in the atmosphere when there is ground movement: therefore, it needed a point stand-off detection system to detect the presence of toxic gases. Last but not least the system should be unattended without the need of any intervention by human operators.

Existing technologies are based on two main classes of sensors: one based on simple physical-chemical sensors which are modifying their electronic properties in presence of some gases and the other based on complex sensor subsystems which are correlating the physical-chemical properties detected by specific measurements. Both may be high sensitive although the first class type is confined to be used only for specific gases and with performances changing with time and up to now is unable to supply gas identification. The second class type (e.g., surface acoustic

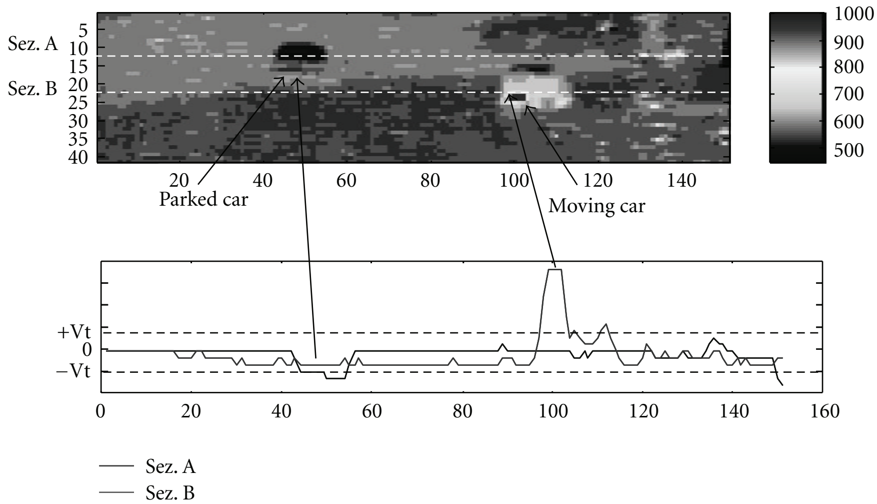

Figure 10: Thermal imaging—Smart Sensors signals.

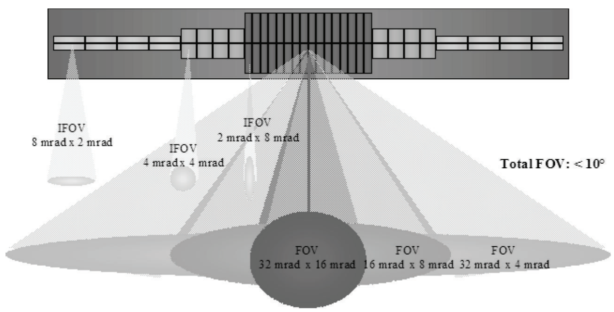

Figure 11: Smart Sensor structure for collision avoidance.

wave, ion mobility spectrometry, and mass spectrometry), can achieve high sensitivity and selectivity, but most of these technologies cannot give both at the same time and not in unattended way needing human intervention in their use 1-3. Best performing systems usually require costly and sophisticated laboratory equipments (e.g., FTIR spectrometry, gas chromatography, and mass spectrometry [38–40]). Furthermore, they often require ancillary operations, such as sample preparation and preconcentration, thus requiring long time for analysis, not operationally acceptable.

4.2.1. Toxic Gas Sensing Based on NDIR Multichannel Absorption Spectroscopy. Best performing systems are costly and sophisticated laboratory equipments (e.g., FTIR spectrometry, gas chromatography, and mass spectrometry) and are recently substituted by innovative system, based on consolidated technique of nondispersive infrared spectroscopy (NDIR) with Bidimensional Multipath Multi-Spectral Staring Smart Sensors in the IR (3 ÷ 5 and 8 ÷ 12 micron) using a MEMS Multielement Blackbody Source optically coupled to a Multipass Cell/Spectrally Linear Variable Filter. A new Sensor Staring Array Structure, designed to perform multispectral measurements for Gas Detection, Identification, and Alarm, has been developed. (Resolution of 0.3 microns spectral resolution allows not only to detect but even to identify, at least for classes, even a small amount (down to few parts per million) of toxic gases operating at room temperature and pressure, even if unattended).

Innovative systems, although based on the consolidated technique of nondispersive infrared spectroscopy (NDIR), performing a fast multispectral measurement of the radiation emitted from a thermal blackbody source in the IR spectral range, particularly between 8 and 12 micron wavelength region, have been recently developed [41].

The detection and identification of absorbing species is achieved by analyzing the spectroscopic signal variation. The novel technical approach consists in the implementing of a low cost source and a microbolometer room temperature sensor array with smart 6 architecture coupled to a spectrally linear variable filter by using a high throughput efficiency optical system 7 to increase the path length and make simultaneous acquisition of several spectral bands within a reasonably compact size. The linear variable filter is a narrow band pass filter in which the wavelength of peak transmittance changes linearly along one direction of the filter surface.

The optical resolution of each detection channel is optimized in width to be matched at the best between resolving power and integrating absorption signal in the widest band as possible, so it has to be not too narrow and not too large. Also, considering technological constrains associated to the filter feasibility, a good tradeoff is around 0.1 micron bandwidth. The system is working at room temperature, small, portable, low cost, and low power consumption device, in order to allow easy operation and large scale distribution both for environmental and security applications.

A new Sensor Staring Array Structure has been developed and designed to perform multispectral measurements for gas detection, identification, and alarm. Resolution of 0.1 microns spectral resolution allows not only to detect but even to identify, at least for classes, even a small amount

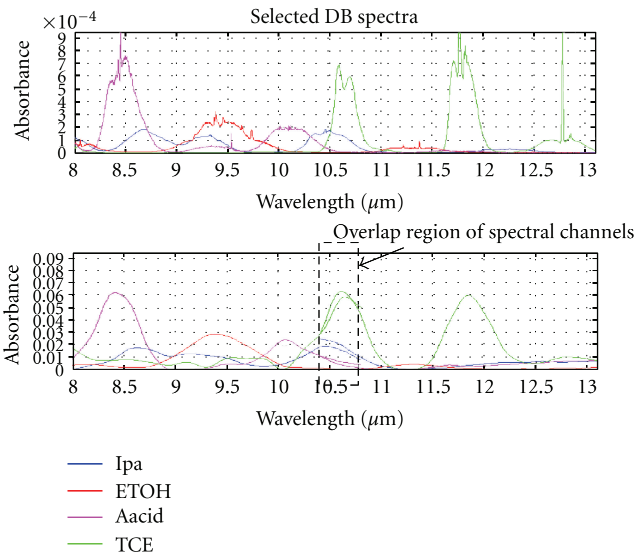

Figure 12: Spectra of 4 vapour organic compounds: from high-resolution database (top); as measured by the NDIR-CANARIO sensor (bottom). CANARIO-EDA Italy-Spain Project. Similar results available for CWAs [41].

(down to few parts per million) of toxic gases operating at room temperature and pressure, even if unattended [41] (Figure 12).

Application security: detection of toxic gases by IR spectroscopy: the vast majority of TICs and CWAs show strong absorption bands in the MID-IR.

This system aimed at developing a compact point sensor for providing early warning in the presence of chemical agents in the air. Battlefields and urban areas at risk of terroristic attack were the foreseen application scenarios. Wide chemical range and effective identification of targets and rejection of other vapours were given as the key performance objectives.

The sensor is based on Active Multispectral InfraRed Absorption Spectroscopy in the gas phase and uses 42 spectral channels to represent molecular fingerprints across the Medium and Long Wave IR spectrum (MWIR and LWIR). The heart of the sensor is an advanced detector device operability (self-calibration capability); the system is showing sensitivity for most Toxic Industrial Compounds and Chemical Warfare Agents with a limit of detection to Nerve Agents around 500 ppb.

The NDIR system matches very well the requirements of an early warning system for toxic gases, that could be implemented both as an autonomous unit and as the node of a sensor network; key assets are its ability to detect and correctly identify a huge number chemicals of different nature and class of risk (CWAs, TICs, solvents, and perfumes.), with minimal false alarm rate; other crucial assets are its compact and simple design, cost-effectiveness, unattended, and continuous operability (self-calibration capability).

Moreover, it shows identification capacity and high rejection of interferents and it is suitable for surveillance and warning in the presence of toxic gases intentionally or accidentally released in the air.

4.2.2. Standoff Detection. Infrared/microwaves techniques and Imaging Hyperspectral Sensors are mostly developed for their selectivity and specificity to detect differences in the spectra of two or more species of chemical warfare agents (CWA) allowing detection of explosives with high sensitivity and very low false alarm rate. Infrared transmission spectroscopy is an analytical tool to detect and identify chemicals in the gas phase.

Open-path Fourier transform infrared (FTIR) spectroscopy is an established method to monitor environmental pollutants (1), for example, aircraft exhaust gases (2), detect toxic gas emissions at industrial plants (3), and even detect chemical warfare agents (CWA). Thus, open-path FTIR is a potential method for explosive detection too. A major drawback of open-path FTIR is the long integration time needed to collect a spectrum because of the low power of the thermal radiation sources usually employed. This is especially the case if trace compounds have to be detected, which only show up in tiny spectral features in the spectra.

The sensitivity of infrared spectroscopy is linked to the measurement of small relative transmission changes of for example, less than 10-3. Selectivity and specificity are linked to the ability to detect differences in the spectra of two or more.

A major drawback of open-path FTIR is the long integration time needed to collect a spectrum because of the low power of the thermal radiation sources usually employed. This is especially the case if trace compounds have to be detected, which only show up in tiny spectral features in the spectra.

The sensitivity of infrared spectroscopy is linked to the measurement of small relative transmission changes of for example, less than 10^{-3} at one or more spectral positions. Selectivity and specificity are linked to the ability to detect differences in the spectra of two or more species. If spectral features of two compounds overlap at one wavelength, at another wavelength a difference may occur which could be used to discern between the two species. As is the case with chemical warfare agents (CWA) for detection of explosives very good sensitivity and a very low false alarm rate, that is, specificity, are a must.

Recently integration of multispectral IR spectroscopy with quantum cascade lasers and hollow-waveguides is promising improved sensitivity and area coverage allowing fast and effective detection at public places like airports, railway, or coach stations [42].

In fact infrared laser spectroscopy, an established method to measure gas concentrations, due to the high power of the laser and its higher optical collimation compared to the thermal emitters used in FTIR equipment sensitive, allows to make long distance measurements. Especially for small molecules with singe rotational-vibrational lines in the infrared laser spectroscopy methods are extremely sensitive and relative transmission changes of 10^{-4} and below have been measured even in industrial in situ applications.

4.2.3. QC-Laser Spectroscopy. The stronger and more specific infrared absorptions of most chemicals/toxic gases are in the mid/far infrared range between 3 μm and 20 μm wavelength, making this region interesting for infrared spectroscopy, for this reason, although most work on laser spectroscopy is performed in the near infrared, where suitable laser sources thanks to wide use in telecommunications wavelength bands, the quantum cascade lasers (QCL) in the middle/far IR are the ideal source for IR laser spectroscopy. After the first QCL spectroscopic applications made with pulsed QCL operation, most of the developments are using CW sources at room temperature, nowadays available for many wavelengths in the mid/far infrared [43–46].

Recently QCL system for gas detection operating in the pulse mode, driven by a short pulse in the 10–100 ns range with pulse repetition rates in the low 10–100 kHz range, are allowing enough time to get consistent absorption features of the sample gas within the pulse duration.

Advanced QCL laser system has detection capability of hidden explosives and other items on personnel. As is the case with chemical warfare agents (CWA) for detection of explosives, very good sensitivity and a very low false alarm rate, that is, specificity, are a must. Fast and effective detection of explosives is a key security issue against possible terrorist attacks. Especially at public places like airports, railway, or coach stations efficient detection systems are needed. Usual methods at airport security checks are wiping carry-on baggage/laptop computers, and so forth to collect samples which are analyzed subsequently by, for example, gas chromatography mass spectroscopy (GC-MS); gas chromatography chemo luminescence (GC-CL) ion mobility spectrometers (IMS) (Figure 13).

5. Terahertz THz Systems

Recent events have led to dramatic changes to the methods employed in security screening. For example, following the failed shoe bombing, it is now common for shoes to be removed and X-rayed at airport checkpoints. There is therefore an increasing focus on new technologies that can be applied to security screening, either to simplify or speed up the checking process, or to provide additional functionality. Terahertz (THz) technology is a promising, emerging candidate.

5.1. Terahertz Radiation and Its Properties. The "terahertz gap" due to the fact that until recently there was a lack of high power sources and high sensitivity detectors can be allocated between 100 GHz (3 mm) and 10 THz (30 μm)that is between the millimeter-microwave part of the e.m. spectrum and the far infrared. Concerning microwave sources till now few sources (recently solid state) are capable of generating enough power radiation efficiently produced at frequencies above hundred gigahertz, whereas solid state laser sources have been limited by thermal effects in their performances in the far infrared region. However, in recent years, several approaches have been developed that enable the efficient generation and detection of terahertz radiation truly commercially viable. The most mature technology uses ultrafast pulsed laser technology and produces very short terahertz pulses. As a pulsed technique, with picosecond timescales, the method is intrinsically broadband.

Radiation at terahertz frequencies has unique properties that may be advantageous for security applications. It penetrates many nonconducting materials, but unlike X-rays is nonionizing. The short pulses produced by laser techniques also allow radar-like imaging in three dimensions, as well as the simultaneous collection of spectroscopic information as in magnetic resonance imaging (MRI) or optical spectroscopy. This is important because many substances have characteristic intermolecular vibrations at far infrared/terahertz frequencies that can be used to characterize them as molecules.

Terahertz technology, which is a nonionizing radiation, is really a powerful technique in security screening applications thanks to the following properties [48–50].

(i) Spectroscopy allows detecting and identifying different chemicals, thanks to their characteristic spectral signatures, even when hidden inside dress clothing.

(ii) 2D terahertz imaging capable of making visible metals and even plastics and ceramic, materials that are hard to be detected using backscatter X-ray.

(iii) High-resolution 3D imaging thanks to the extremely short pulses used in pulsed terahertz techniques like in the radar technology. (e.g., layers of powder can be detected and resolved inside a mail envelope).

In synthesis Multispectral (IR-Thz) Systems for security applications will have high growth especially coupled to new solid state tunable laser sources with innovative, new technologies for Multispectral Pluridomain Smart Sensors:

(i) to IR/Thz Imaging/Pattern Security Applications,

(ii) to IR/THz Spectroscopy for Security Applications,

(iii) to Stand-Off Laser Detection IR/THz Spectroscopy.

5.2. Security Applications of THz Technology. Recently terroristic events, based on new types of threats and explosives, have pushed towards the developments of new techniques of detection and alarm employing different parts of the electromagnetic spectrum, particularly extending from infrared to terahertz radiation, that is, the e.m. band between infrared and microwave. Also in these new developments there is a priority to the developing of imaging systems, at least for the know-how originated in infrared technologies, while spectroscopic detection is mostly developed by microwaves techniques.

Radiation at terahertz frequencies has unique properties that may be advantageous for security applications; in fact, it can penetrate many nonconducting materials, but unlike X-rays is nonionizing, and can allow radar-like imaging in three dimensions thanks to the extremely short pulses used in pulsed terahertz techniques, as well as the simultaneous collection of spectroscopic information like infrared. This is important because many substances have characteristic

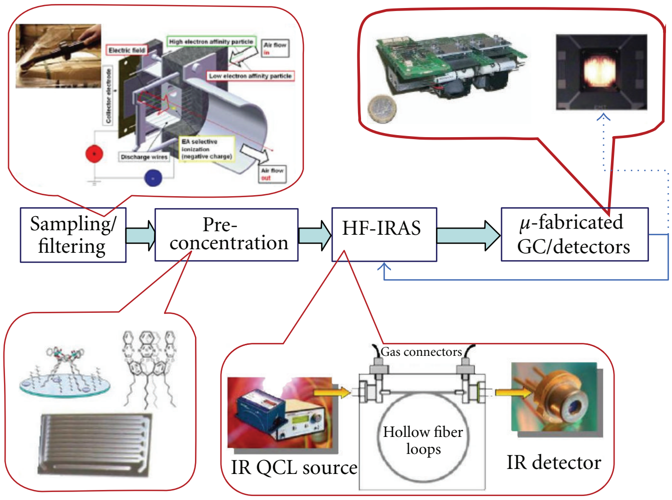

Figure 13: DIRAC system architecture: EC-FP7 Project [47].

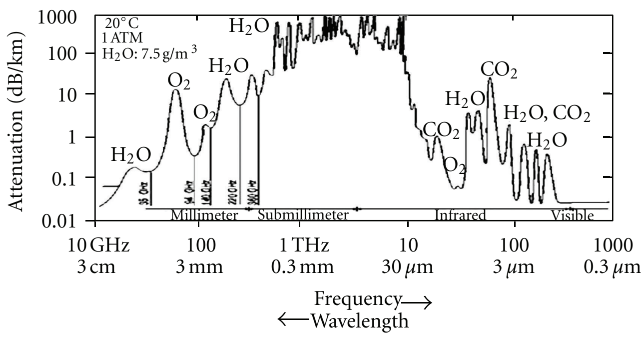

Figure 14: Absorption bands in atmospheric transmission.

intermolecular vibrations at Far IR-THz frequencies that can be used to characterize them as molecules like IR spectroscopy that can detect bond vibrations of single molecules (Figure 14).

5.3. Surveillance; Detection and Warning Systems: Past, Present, and Future Trends. Standoff detection is showing hidden explosives and other items on personnel.

(i) Selectivity and specificity are linked to the ability to detect differences in the spectra of two or more species. If spectral features of two compounds overlap at one wavelength, at another wavelength a difference may occur which could be used to discern between the two species. As is the case with chemical warfare agents (CWA) for detection of explosives very good sensitivity and a very low false alarm rate, that is, specificity, are a must.

(ii) Fast and effective detection of explosives is a key security issue against possible terrorist attacks. Especially at public places like airports, railway, or coach stations efficient detection systems are needed. Usual methods at airport security checks are wiping carry-on baggage/laptop computers, and so forth to collect samples which are analyzed subsequently [51] by; for example

(a) gas chromatography mass spectroscopy (GC-MS);

(b) gas chromatography chemo luminescence (GC-CL);

(c) ion mobility spectrometers (IMS).

Multispectral (IR-THz) Systems for security applications will have high growth especially coupled to new solid state tuneable laser sources with innovative, new technologies for Multispectral Pluridomain Smart Sensors.

Thermography, associated to functional diagnostics with high filtering correlation in time and spectral domain, will stay as the main market and system application associated to an impressive development of high number, fast, multispectral, room temperature sensors (microbolometers).

6. Synthesis Historical Technology Evolution

The main application for IR technology was in the past and will be in the future surveillance and warning and more specifically for military applications that conditioned for a long time the development of IR devices and systems. The highlights of this application field are quite well known and have allowed to develop an impressive know-how either in the systems' performances.

The first historical lesson, missed for lack of knowledge of the users, was the underestimation of the strategic value of IR surveillance systems (at that time the RADAR was not yet operating although in 1904 Christian Hülsmeyer [50] had used radio waves for detecting "the presence of metallic distant objects," only in 1922 Guglielmo Marconi [52] proposed the idea of a Radio Telemeter for localizing metallic objects at distance and therefore the remote sensing was mainly just optical). In fact Bellingham, probably in 1910, had developed a method to detect the presence of icebergs and steamships by using a mirror and the original thermopile: he patented this device later in 1913 [3]. His infrared radiometer's primary advantage over the disappearing-filament optical pyrometer was that it was able to detect temperatures substantially lower than ambient. If this device was installed on the Titanic ship avoiding that grave tragedy, probably the efforts in developing IR surveillance systems would have been much greater. During World War 2 great efforts have been dedicated to the development of IR surveillance systems especially in the Army with both parties capable of IR detection of enemy's tanks and support to night moving.

After the 1970s R&D developments of IR surveillance systems, especially for navy applications, were done in advanced Countries (especially US, UK, France, and Italy, where the first Modular FPAs Staring Omni-Directional Surveillance System prototype was designed and realized) [20]. In the 1980s the SDI Program for Ballistic Missile Defense by US was originating highly advanced E. O. Surveillance System with performances close at BLIP limits. Nowadays the main efforts are dedicated to the multispectral detection capability. Lastly, wide application of IR warning is expected in automotive for Smart Collision Avoidance Systems in poor visibility conditions: room temperature. Smart IR Receivers could be installed with high reliability and simple, immediate man-machine interface in any type of motor vehicles [53].

Future trends of infrared detectors are linked to the development of new emerging technologies of sensor fabrication for mass production especially for civil applications, with a strong two-way synergy between civil and military. New markets (automotive, intelligent building, and environmental control) and consolidated markets (biomedical and medical, energy control, and surveillance and warning) will get strong benefits from Microsystem Technologies (sensors, control and actuators) especially in automotive applications, with a real possibility of high level products at contained cost feeding a double-way of technology transfer between civil and military in the future more and more towards new military market applications (especially portable equipments). The competition among various technologies and "technical schools" has been strong with unforeseeable emerging new actors in the last years (overall, room temperature microbolometers for future, and extremely valid applications in the civil field). Operational requirements (mainly of maintenance and reliability) were pushing IR science to look for new advanced sensors which could avoid the cryogenic needs. The new microbolometers technology, because of the micro size of thin films bolometers, completely integrable with silicon technology and therefore often named silicon microbolometers, have been emerging in the last years with a very high promising for future IR sensors market growth. For extremely high sensitivity sensors especially for military and space applications the technologies actually with major possibility of future development are mainly based on photon sensors (Intrinsic and Quantum Well). Multispectral and hyperspectral capabilities with spatial-temporal filtering capabilities are also emerging especially in military and space applications for target identification. The key emerging factor for future IR FPAs technologies is the room working temperature for uncooled imaging systems and the complete integrability with silicon microcircuits technology especially because integrated signal processing (Smart Sensors) will play a fundamental role in future applications where mass production could allow consisting cost reduction (huge markets are expected especially for automotive applications for unit cost of few hundreds Euros). So, for the first time, thanks also to the elimination of cryogenic cooling, wide use of I.R., Smart Sensors are emerging on the international market, becoming strategic components for the most important areas, like transports, (especially cars, aircrafts, and helicopters), security, environment and territory control, biomedicine.

6.1. Infrared Systems Evolution

(i) From Thermography to Digital Functional Imaging.

(ii) From Imaging to Pattern Analysis and Detection.

(iii) From Detection to Smart Sensors Alarm Systems.

(iv) Computational Methods in Gas Fluidodinamics.

(v) Energy/Structure Building Control, Electricity-Mechanics Control, Medical-Veterinary Diagnostics, and Art Restoration.

(vi) To Multispectral/Hyperspectral Patterns Systems.

(vii) To IR/Thz Imaging/Pattern Security Applications.

(viii) To IR/THz Spectroscopy for Security Applications.

(ix) To Stand-Off Laser Detection IR/THz Spectroscopy.

7. Conclusions

Terroristic events, based on new types of threats and explosives, have pushed towards the developments of new techniques of detection and alarm employing different parts of the electromagnetic spectrum, particularly extending from infrared to terahertz radiation, that is, the E.M. band between infrared and microwave. Also in these new developments there is a priority to the developing of imaging systems, at least for the know-how originated in infrared technologies, while spectroscopic detection is mostly developed by microwave techniques. Recently the emerging terahertz technologies [11], thanks to their nonionizing radiation and their detection capability of hidden objects in clothing and in packaging containers and luggage, coupled to the spectroscopic detection of plastic explosives and other chemical and biological agents, are the most promising technologies for integrated, efficient systems for security screening and counterterrorism. Radiation at terahertz frequencies has unique properties that may be advantageous for security applications; in fact, it can penetrate many nonconducting materials, but unlike X-rays is nonionizing, and can allow radar-like imaging in three dimensions thanks to the extremely short pulses used in pulsed terahertz techniques as well as the simultaneous collection of spectroscopic information like infrared. This is important because many substances have characteristic intermolecular vibrations at

Far IR-THz frequencies that can be used to characterize them as molecules like IR spectroscopy that can detect bond vibrations of single molecules. Terahertz technologies, thanks to their nonionizing radiation and their detection capability of hidden objects in clothing and in packaging containers and luggage, coupled to the spectroscopic detection of plastic explosives and other chemical and biological agents, are very promising technologies for integrated, efficient systems for security screening and counterterrorism attacks. Far-infrared/microwaves techniques and Imaging Hyperspectral Sensors will be mostly developed for their selectivity and specificity to detect differences in the spectra of two or more species of chemical warfare agents (CWA) allowing detection of explosives with high sensitivity and very low false alarm rate. Recently integration of multispectral IR spectroscopy with quantum cascade lasers and hollow waveguides is improving sensitivity and area coverage allowing fast and effective detection at public places like airports, railway, or coach stations. In future, an evolution from Infrared Thermography to Digital Functional Imaging and from Imaging to Pattern Analysis and from Detection to Smart Sensors Alarm Systems is expected. Multispectral (IR-Thz) Systems for security applications will have high growth especially coupled to new solid state tunable IR laser sources with innovative, new technologies for Multi-Spectral Multi-Domain Smart Sensors.

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