SMART SENSORS

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The term "Smart Sensors" refers to sensors which contain both sensing and signal processing capabilities with objectives ranging from simple viewing to sophisticated remote sensing, surveillance, search/track, weapon guidance, robotics, perceptronics and intelligence applications.

Recently this approach is achieving higher goals by a new and revolutionary sensors concept which introduce inside the sensor some of the basic function of living eyes, such as dynamic stare, non-uniformity compensation, spatial and temporal filtering.

New objectives and requirements are presented for this type of new infrared smart sensor systems.

This paper is concerned with the front end of FPA microbolometers processing, namely, the enhancement of target-to-noise ratio by background clutter suppression and the improvement in target detection by "smart" and pattern correlation thresholding .

Introduction

One of the "Key" technology and know-how in FPA is the developing of "Smart Sensors" which integrate the sensing function with the signal extraction, processing and "understanding".

This outstanding goal has been pursued with particular effort 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 pre-processing the acquired signal to give aimed and selected information.

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 [1] when the integrated processing capabilities based on advanced read-out integrated with signal processing was 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. [2].

Later on, thanks to the CCD read-out 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

New objectives and requirements for new focal plane processing have been developed in these new smart sensor systems by introducing inside the sensor itself some of the basic function of living eyes, such as dynamic stare, non uniformity compensation, spatial and temporal filtering.

In conclusion there are two main classes of IR Smart Sensors : the first one supported by the impressive growth of integrated micro-circuitry which, thanks to the CCD/CMOS integrated readout, can allow sophisticated pre-processing using the Smart Sensing techniques (these devices known as “vision chips” in the visible range have been recently strongly investigated and successfully developed) [3], and the other one, more oriented to specific ,low cost smart applications , in which most of the intelligence of pre-processing is inside the design and structure of the Sensor itself [4].

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 read-out and processing technology. As a result, the general complexity of the overall should be much smaller than the one achievable pushing just, for instance, the number of sensor pixels. 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 e.g. warning and alarm systems.

IR Smart Detection Systems

One of the most complex and challenging application area for “Smart Sensors” is the Infrared field where the information to be extracted is based on the detection of very small signals buried in electronic noise loaded by a highly diffused background noise and by a flood of intensive “ unwanted signals” .

The nature of infrared scene with low contrast and high background flux implies that unlike their visible counterparts, infrared imaging devices require some processing of detector output signal to correct non uniformity and remove the background pedestal [5].

Without this on-focal-plane processing, most of the data from the focal plane is useless clutter or unwanted data, because of the whole acquired pattern only a few pixels contain targets information

Yet conventional approaches process this great amount of data through the read out electronics, the analogue to digital converters, and the digital signal processor before finally separating and rejecting the clutter. In contrast, the Smart Sensor rejects this clutter before it is read out of the focal plane so that most of the useless data are avoided to be processed.

In summary, focal plane processing in new infrared smart sensors will be end-to-end image and patterns processing which is completely integrated in the sense that decisions for detection will be made at several steps in the sensor structure and eventually finalized at a later stage, anyway after the tracking, recognition and other operations have been performed in the early stage.

Fairly sophisticated signal processing techniques have to be developed to accomplish these objectives. The major signal processing steps consist of the suppression of background clutter and the enhancement of the target-to-noise ratio to a level adequate for threshold. In the classical threshold stage approach, a decision is made for target acquisition by setting a threshold level which accepts a small number of false alarms. Target tracking and recognition are performed in the post-threshold stage in particular, smart sensor have often to perform the target recognition during the acquiring stage or, better, are using feature and shape pattern recognition as threshold activation.

Especially in the pre-threshold stage, target signals are expected to be deeply buried in background clutter noise and unwanted signals which can be hundreds of times 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.

This paper is concerned with the processing techniques limited to the front end of the focal plane processing, namely, the enhancement of target-to-noise ratio by background clutter suppression and the improvement in target detection by "smart" and pattern correlation threshold.

Smart Sensors Realisation

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) [1] [4].

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 pre-filtering capability in the sensor structure itself.

This pre-filtering 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 discriminating and identifying the targets, like it is performed by an insect eye thanks to a spatial-temporal correlation.

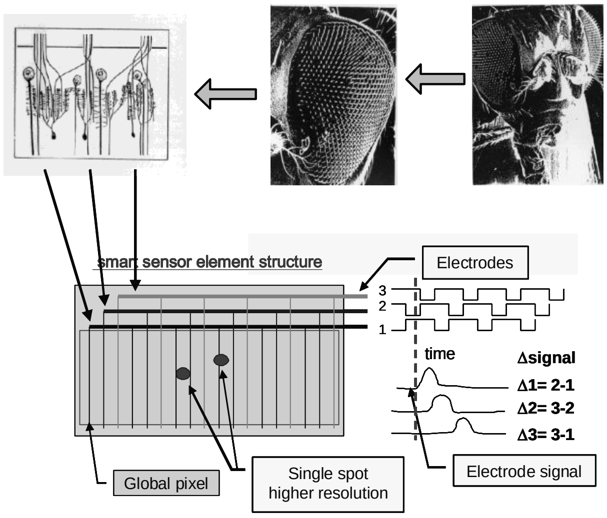

Fig.1 Smart Sensor emulating Fly-Eye recognition structure with an integrated 3 electrodes modulation [6]

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 sub-pixels, 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 [6].

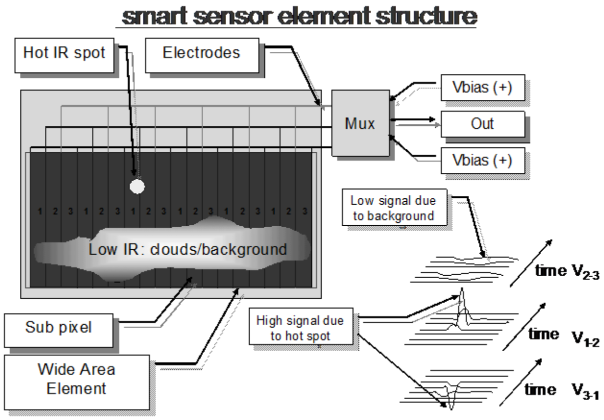

Fig.2 Smart Sensor: Hot Spot Detection. Higher spatial resolution and movement information is achieved by 3 electrode differential measurements: hot spot is detected 100% while diffused background signal is strongly reduced

The “smart sensor” is based on a reticule structured detector, which is electronically modulated to obtain a spatial-temporal correlation of the focused target spot 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. “[6]

This electronic integrated modulation is based on the “Insect Eye Structure which allows to extract automatically signal due to a point source from a more intense unwanted signal due to an extended source.

The driving idea is that a much higher optical resolution than the single large area sensor pixel can be obtained by introducing a reticule of multiple fingers electrodes which can be electronically modulated in such a way to eliminate by a zero measurements the same quantity of signal quantity detectable by the sensor area within two adjacent finger electrodes.

In Fig. 3 is described the Block diagram of the Smart Sensor electronically modulated.

The Block A has the two fundamental functions:

1- the Control of Bock C (by the Bias-Set) and the Output (V-Out)

2- the Command Signals(V-Control) to Block B for generating the voltage biasing

The Block B has the function to generate the biasing voltages (V-Bias(t)) with the desired form and frequency. These Voltages are supplied by Block C which is connecting physically also the Signal Output (V-Out) with the electrodes ($e_{1,}$ $e_{2\ldots}$ e_{n}).

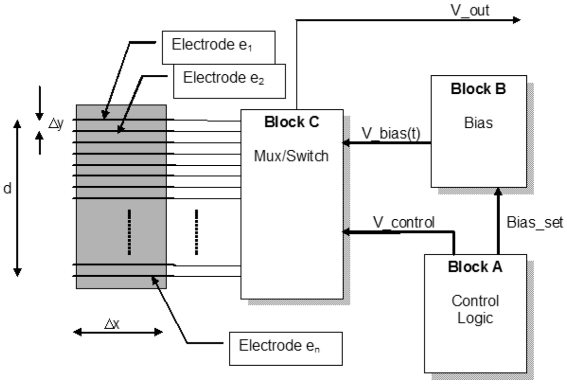

Fig 3:.Block Scheme for improving single pixel large area element resolution.

We can observe that the form of electrodes can be any and is defined only by the desired spatial frequency and that the electrodes configuration of the bias $V_1(t)$ e $V_2(t.)$ and of the output V_out, should be alternate.

Moreover the electrodes configuration and the Bias $V_1(t)$, $V_2(t)$should be related by:

$$n_2.V_1(t) = n_1.V_2(t) \qquad (1)$$

$$m = (n_1 + n_2).k \qquad (2)$$

where

$$m = d / \Delta y \qquad (3)$$

and m is the number of elementary cells defined by single electrodes, n_1 the number of elementary cells is the sensor area defined between the electrode $V_1(t)$ and the output, n_2 the number of elementary cells is the sensor area defined between the electrode $V_2(t)$ and the output, d is the distance between the first and the last one, k is an integer number.

This dynamic spatial filtering can be implemented with a special feature structure which is capable of preferable detection for selectable forms (e.g. point sources, linearly structured objects, etc.)

Microbolometer Smart Sensors

Successful developments achieved in most of IR FPA technologies were showing the importance of monolithic approach unfortunately strongly limited by spectral range and cooling requirements in the case of Silicon Schottky diodes, but the recent successful results obtained in silicon microbolometers is overcoming both limitations.. Especially thanks the complete integrability with electronics readout microbolometers array appear to be a good choice due to its high spatial uniformity and, being a silicon based technology, can allow large, high yield focal plane arrays, economically fabricated.

Particularly interesting is the case of Large Area Microbolometers for applications where high sensitivity coupled to simplicity and low cost of the IR arrays are required (e.g. automotive, large scale distributed alarm systems).In this case the integrated modulation above reported is even more cost/effective ,but important physical phenomena conditioning the signal detection have to be taken in account.

The most important phenomenon is the signal crosstalk due to thermal diffusion of the absorbed IR radiation which is interacting with the signal modulation according to the following considerations and equations.

When considering Infrared Smart Sensors based on microbolometers technology some further physical phenomena coupled to complex thermodynamic problems are to be considered and evaluated.

The main one is the signal crosstalk between closely adjacent sensor pixels which moreover is strongly dependent on the size and shape of incoming radiation. Various incident forms of IR radiation have been evaluated by theoretical modelling and experimental test measurements with interesting results.

Three cases of IR incident radiation have been studied:

- radiation extended all over the sensing area, almost constant in all the sensing large area pixels
- radiation with an irradiated area just close to the area of a single sensing pixel
- radiation confined to a spot incident in the centre of a large area sensing pixel

It is clear that for using the smart concept previously described it is necessary to operate the signal extraction by introducing adequate corrections formula like reported:

Simulation and experimental studies are anyway showing that the smart elaboration based on differential amplifying of any sensor pixel and is close adjacent one is discriminating well point source target from extensively and diffusely irradiated sensors area although in presence of a sensible thermal crosstalk.

In Fig. 6 and 7 are shown thermal images of an 8 pixel linear array obtained by computerized simulations based on FEM method for various types of focused and diffused irradiance.

The equation used is the classical PDE’s equation of the heat propagation in solid bodies

$$\rho.C.(\delta T/\delta t)-\nabla.(k.\nabla T) = Q + h.(T_{ext}-T)-\sigma.(T_{ext}-T)^4 \qquad (4)$$

where ρ is the mass density, *k*, the conductivity, *C* the specific heat, *Q* the incident power per volume, *h* the convection coefficient, *k* the Boltzmann constant, T_{ext} the external temperature, ∇ the operator $(\delta/\delta x,\delta/\delta y,\delta/\delta z)$.

Fig.4 and 5 show the distribution of the normalized ΔT respect to the room temperature in the 8 pixel linear array, as a result of 3-D thermal simulations. The simulation has been done for an array in vacuum (Fig.4) and in air (Fig.5) with three different types of irradiation: all the array (a), the central pixel (b), a focused spot in the central pixel (c).

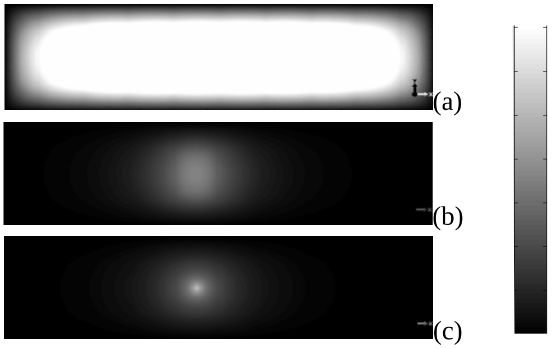

Fig.4 Normalized results of a 3-D thermal simulation for a 8 pixels linear array in vacuum

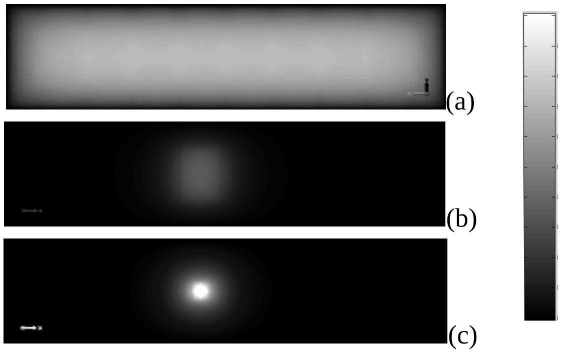

Fig.5 Normalized results of a 3-D thermal simulation for a 8 pixels linear array in air

Average temperature gradients distribution for the array in air are shown in Fig.6.

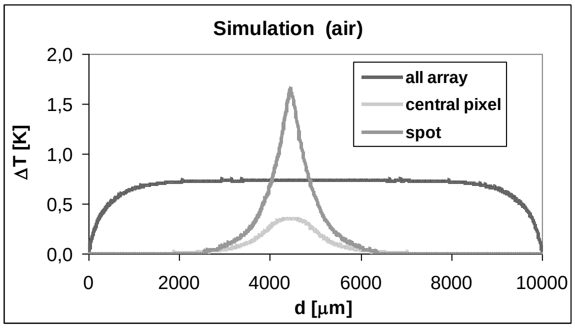

Fig.6 Simulation data for the array in air

It is evident that the cross talk between each elementary sensing pixel and its adjacent that is about 30% in the case of an irradiated signal diffused all over the pixel and order of magnitude less in the case of a focused point target irradiation thanks to the differential signal extraction obtained by the smart sensing structure is possible to obtain a consistent lowering the false alarm rate enhancing the signal-to-noise ratio.

Applications

An important application of the IR Smart Sensors above described is a car system for
” 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 microbolobeters 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 skillness 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 thermo-stabilisation, which supply a sound and light alarm in case of presence of an obstacle on the road could be a winning solution.
A schematic view of the system for collision avoidance is shown in Fig.7.

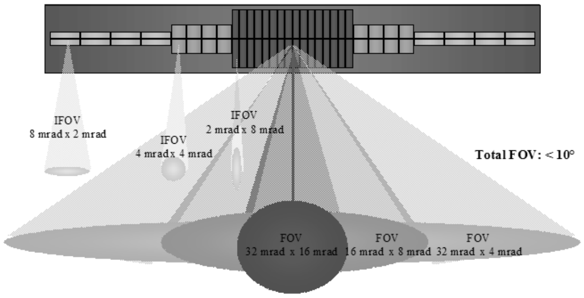

Fig.7: Smart sensor structure for collision avoidance

In Fig.8 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 Fig.9 is shown the signal detected by the IR Smart Sensor structure supplying automatic alarm in both cases.

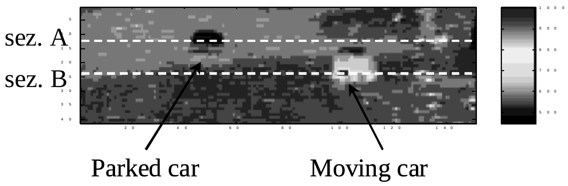

Fig.8 Thermal imaging

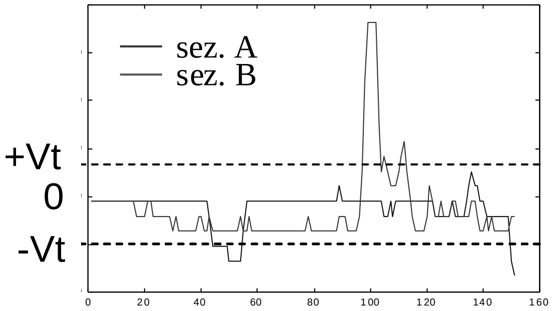

Fig.9 Smart Sensors Signal

Conclusions

The new approach of the Smart Sensors with filtering and processing capabilities integrated in the sensor structure can revolutionise future trends of IR sensors.

Considering that in future IR technology, the leading application will be thermography and more specifically bidimensional imaging: this could allow us to develop the following considerations:

The number of pixels of the FPA, which should be the maximum as possible, will be limited ,more than by the integrated processing technology by the size of each sensor pixel (in case of optical diffraction limits, that is e.g. it cannot be less than 10 μm)..Therefore considering the optical resolving power and size of collimating lens, should be around 10 million pixels.

Future front-end processors shall be more dedicated to the development of integrated electronics and in medium-long term to advanced processing (Smart Sensors). Therefore the most important aspect for future IR sensors shall be the real compatibility and integration with silicon microelectronics.

Quantum yield or IR photon efficiency will be less strategic if the imaging frame rate will allow enough integration time compatible with a staring FPA. Integration time in the range of a ten of milliseconds can be accepted.

Front end processors don't foresee specific limitations ,but surely great attention will be given to Microsystems technology, especially three dimensional structures for layers underetching at different levels .This is particularly true for microbolometers which will be more and more three dimensional Microsystems devices (fulfil factor should be close to 1).

The technology actually with major market possibility are the new silicon microbolometers which, thanks to their high number of pixels and uniformity in sensivity, might reach in the near future the level of performances already achieved in the visible (e.g. a completely integrable with CCD devices). Moreover microbolometers can be structured with complex form completely integrated with silicon microcircuits and working at room temperature.

The most evident result of all the above considerations will be the market growth of silicon microbolometers, especially in civil applications, while an increasing strategic value will be assumed by the integration of signal enhancement and processing within the sensors (Smart Sensors).

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