Vertically Integrated Sensor Array Technology for Unattended Sensor Networks

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ABSTRACT

The increasing need for unattended sensor networks drives individual sensor development, signal processing for network management, and communication technology. The application space is becoming more complex, with requirements for sensor networks in force protection; surveillance of large expanses of rugged terrain; and monitoring complex urban areas. Individual sensors exhibit excellent performance and include a wide variety of sensing modes, such as acoustic, electro-optical imaging, seismic, and radio frequency devices. These sensors continue to shrink with packaging, while applications continue to demand more of the sensor technology. Although single imaging arrays, which are available in spectral bands from the visible through the infrared, can be integrated into packages size as small as a cubic inch, the information from a single sensor is not sufficient to meet requirements for day / night, all-weather operation. This has driven the need for integration of multiple sensors into the compact packages intended for an individual sensor. A major step toward addressing the need for more effective sensor technology for unattended sensor networks is being taken through development of Vertically Integrated Sensor Array (VISA) technology. This technology, currently being developed for imaging sensors, builds multiple layers of signal processing at each pixel in the sensor array. Processing power is dramatically increased, allowing the integration of multiple sensors in small compact packages. This paper reviews the VISA approach to imaging sensors and describes applications for unattended sensors.

1. INTRODUCTION

Unattended sensor networks present technical challenges for individual sensors, signal and image processing, and communication technology. The sensors must survey large areas for extended time periods, while consistently maintaining a high level of performance. The sensor system must collect a large volume of data; convert this data into information; and communicate the information within the sensor network or to a central command. Human intervention is available at a high level, but local decision making at the sensor level may be critical to manage the large volume of data collected in the network.

The capability to operate effectively in difficult environments, such as urban areas and the jungle, will continue to be important. In these environments, sensor communication presents technical challenges, which drives the number of sensors in the network, the physical location of sensors in the network, and design of the sensor interface and data output. These environments also require the use of small, compact sensors with a flexible form factor, compatible with sensor placement in a variety of situations. The need for ultra low power is crucial for extending the operation of the unattended sensor without intervention.

In addition, the need for operation in all weather may require new sensor types, such as millimeter wave and terahertz imaging sensors. These sensors provide an important adjunct to the network, enabling twenty-four hour operation. The methodology for managing this diverse range of sensor assets becomes a major challenge in sensor and network design. Sensor network management must make decisions to optimize the data from each sensor; ensure effective communications and the availability of the appropriate sensor for each situation; and keep power to an absolute minimum. Elemental decision making at the sensor will assist in effectively employing the wide range of sensor types in the network, and optimize the use of available power.

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The VISA technology adds processing power at the individual sensor, providing flexibility to unattended sensor design and an enabling technology for management of network assets. This processing power also enables optimization of individual sensor performance, organization of data output in a configuration necessary for effective communication among different sensor types, and local decision making to assist in management of networks assets.

2. VISA TECHNOLOGY DESCRIPTION AND APPLICATIONS TO UNATTENDED SENSORS

The VISA technology is the integration of multiple levels of signal processing for each detector, with pixel-to-pixel interconnections through each level, forming a three-dimensional read-out integrated circuit (ROIC). It enables increased sensor performance through integration of multiple detector types and on-focal-plane processing functions. A diagram of the VISA approach is given in Figure 1.

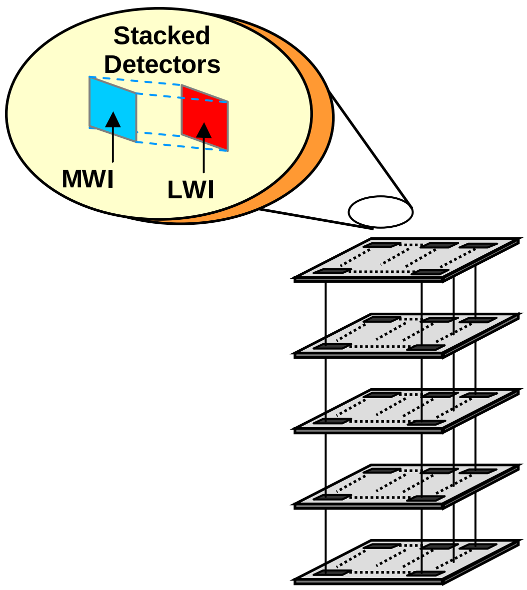

Figure 1 Vertically Integrated Sensor Architecture with multiple levels of signal processing at the detector

The VISA technology, applied to unattended sensors, is relatively new, and applications are only beginning to be explored. The pay-off can be large, extending performance and overall capability, with minor increase in cost. Since VISA is an integrated circuit, the cost benefits of silicon production technology can be directly applicable. A summary of potential benefits of the VISA technology to unattended sensors is shown in Table 1.

Characteristic / Need for Unattended Sensor	**Benefit of VISA Technology**
Need for wide area surveillance	Large format arrays with **parallel processing at the sensor** for ID
Identification with low false alarm	Three-dimensional imaging camera with **high resolution, small pixels**
All-weather	**Integration of multiple technologies**, e.g., IR with MMW micro-antennas
Extremely low power	**On-FPA decision making**; read-out of selected windows
Small / compact design	**System-on-a-chip** with processing at the detector

Table 1 Unattended sensor requirements and benefits of the VISA technology

The development underway addresses materials and processes for high aspect ratio vias and wafer interconnection, as well as circuit architecture for integration of multiple functions into the three dimensional focal plane array. These functions will add capability to unattended sensor networks for many applications.

Target detection in difficult environments may require the assimilation of information generated from multiple sensors of different types. However, transmitting all the information generated at each sensor to a central processor for decision making can overload the data communication network, creating processing bottlenecks. Processing at the sensor can alleviate these burdens, increasing efficiency of the network and reducing overhead, and power consumption. The VISA technology enables parallel processing and data reduction at the detector, resulting in transmission only of significant information. Decisions that can be at the focal plane include: 1) Frame-to-frame changes; 2) Moving target indication; 3) Target cues based upon shape or spectral signature.

In addition to target detection, the sensor network must provide a means to identify potential targets with a low false alarm rate. Target identification reduces the need for operator intervention, which can be a severe burden in remote locations and over large areas. Laser illuminated imaging, although not generally used in an unattended sensor, offers considerable benefit in target identification. The laser imaging focal plane can be integrated with a wide field of view passive sensor, and the laser beam steered to selected areas for target identification. VISA provides an enabling technology for the integration of passive and active sensors, registered pixel-to-pixel, into a single three-dimensional focal plane.

The unattended sensor must also function continuously regardless of the environment or weather conditions, where traditional sensors lose functionality. For these conditions, antenna coupled sensors are being developed for imaging in the millimeter and sub-millimeter spectral regions. VISA provides an enabling technology for integration of these antenna coupled sensors with high performance infrared, near-infrared or visible sensors. The power of the three-dimensional electronics in the integrated detector allows the pixel level read-out to be optimized for each of the sensors in the integrated sensor package.

The VISA technology is developing focal plane processing architecture for a variety of applications requiring a compact, low power sensor package and on-focal plane decision making. This development begins with the capability for high dynamic range digital processing on the focal plane array.

3. VISA DEVELOPMENT HIERARCHY

The VISA technology addresses the development of a new sensor architecture, with far-reaching implications for all sensor types, and a unique capability for unattended sensors. The initial VISA technology demonstration will show feasibility for:

1) Digital focal plane array
2) Two or three layers of signal processing at the detector
3) High speed imaging

Further development can extend this architecture to:

1) Additional signal processing layers at the detector
2) Integration of diverse material types
3) Power / thermal management

The development of the VISA focal plane architecture starts with a high dynamic range, digital focal plane array. Digital architecture leads directly to an improved imaging capability and has growth potential to advanced focal plane processing. This technology provides the base to directly convert analog image information into a digital format on the focal plane through the integration of an analog-to-digital converter at each pixel. Direct read-out of digital information from the focal plane provides the advantages of high speed read-out with noise immunity and wide dynamic range.

As more layers are integrated into the VISA stack, the additional focal plane processing power can accommodate the outputs of multiple sensors. The VISA technology enables the integration of multi-spectral and potentially hyper-spectral imaging into an unattended sensor suite. Via technology must be developed to access multiple sensor layers, and connect the sensor output to the appropriate layer in the focal plane processing stack. An important aspect of the technology is that different circuit architectures, and heterogeneous material types, can be integrated into the three-dimensional stack.

The VISA technology also provides the capability for high speed image capture and on-focal plane storage to correlate information between frames. This capability can be applied to multi-spectral imaging, with simultaneous imaging of multiple detector layers. With the VISA technology, the initial processing of multi-spectral information can be performed directly on the focal plane. This reduces the need for high speed read-out of multiple sub-frames and wide bandwidth, high power off-focal-plane digitization.

4. THE DIGITAL FOCAL PLANE ARRAY

The digital focal plane array is being implemented in configurations compatible with the VISA architecture. A thin layer of silicon integrated with the read-out circuit to form a two dimensional stack is sufficient for high performance digitization at the focal plane. Typical parameters for the digital focal plane are given in Table 2. The VISA program goals of 18 bits at 1 KHz and 12 bits at 10 KHz have been achieved or exceeded by each of the VISA focal plane developers.

<u>Digital Focal Plane Array Goals</u>
– 8 Bits at 10 KHz conversion rate
– 16 Bits at 1 KHz conversion rate
– Less than 500 mw (scaled to 256x256 array operating at 1KHz)

Table 2: Typical parameters for digital focal planes

In the VISA architecture, an A/D converter at each pixel in the focal plane consists of an analog interface to the detector, typically a capacitive trans-impedance amplifier with charge storage. The storage site on the analog focal plane layer is filled and emptied multiple times, and the count is maintained on the digital layer. At the completion of an integration time, the analog residual and digital count are read-off the focal plane, and combined into a single digital word. Test circuits verifying the conversion rate, number of bits and linearity of the design are consistent with the VISA Program goals.

The digital processing at the detector provides pay-off in many application and especially unattended sensors. The digital focal plane is directly compatible with algorithms developed for contrast enhancement, edge extraction and filter functions. The digital pre-processing on the focal plane adds flexibility to the unattended sensor and facilitates integration of multiple sensors through pre-processing.

5. HIGH OPERATING TEMPERATURE DETECTORS

There are two basic approaches to high operating temperature detectors, the thermal detector and the quantum or photon detector. The photon detector integrates charge, with sensitivity proportional to the amount of charge integrated. The VISA read-out circuit expands the area available for charge integration, leading to increased sensitivity and potentially higher operating temperature.

In the thermally sensitive detector, small temperature differences must be extracted from a large background, requiring precise control of the focal plane temperature and uniformity across the focal plane. The thermal surroundings of the focal plane, system housing and optics, also change with the ambient temperature, requiring recalibration to maintain the high sensitivity inherent in the focal plane. The overall thermal sensitivity is a combination of both temporal and spatial components, with spatial noise the dominant factor in many designs.

With the VISA technology there is an opportunity to expand the processing at the sensor to maintain the precise uniformity required for high thermal sensitivity. The non-uniformity terms consist of an offset and a gain correction term. The thermal offset correction, essential to high dynamic range, can be applied to each pixel through the VISA stack. The increased processing area on the focal plane allows application of a precise off-set correction, even as the pixel size is reduced.

As the ambient temperature changes, uniformity correction terms for the appropriate temperature must be applied to the focal plane output. The VISA technology can be used to store the array of correction terms for each temperature in the expected operating temperature range of the sensor and to correct the sensor output. Integration of the non-uniformity correction onto the focal plane, and parallel processing at each pixel to achieve precise temperature uniformity contribute toward development of small, compact unattended sensors.

6. MULTIPLE SENSOR INTEGRATION

Unattended sensors must also operate in a wide range of environments, where information from multiple sensor types can ensure continuous operation of the network. Each sensor produces a different type of information. For example, imaging in the near infrared provides a reflective signature; while longer wavelength infrared presents emissive signatures. These two sensors modes can ensure that the network operates continuously even in situations where thermal contrast is poor and when the ambient illumination is low. In addition to these different types of signatures, multiple sensors can add redundancy in situations when the atmosphere obscures information from a particular sensor.

The information from the various sensors can be transmitted to a central network processor where target information is assimilated. However, integration of multiple detectors into a common sensor format reduces the data communication burden and simplifies network management.

For imaging arrays, multiple detectors must be registered pixel-to-pixel, and signal processing must be integrated with the detector to read-out the information. The VISA technology provides the three-dimensional processing at the detector, with a separate signal processing layer for each detector.
The current VISA demonstration of a multi-color detector is a mid / long wavelength design being pursed at Rockwell Scientific. The demonstration will show the integration of the A / D conversion and digital processing at each pixel of the two color focal plane. However, since this focal plane is designed for operation at cryogenic temperature, the detector technology must be extended to a higher temperature to be completely compatible with unattended sensor power requirements.

7. HIGH RESOLUTION ACTIVE IMAGING

The sensor network must also have the capability to distinguish targets from false alarms and identify partially hidden or camouflaged targets. Local processing at the sensor can be used to direct unique sensor assets at potential targets, increasing the probability of identification in difficult situations.

One of these unique sensor assets is laser illuminated imaging, where the return from the target is sampled and a three-dimensional image is generated. The electronics for laser illuminated imaging must be integrated into the pixel unit cell, and processed in real time to achieve the high range resolution required for target identification. Integration of this processing into the unit cell is limited by current electronics technology, especially as the cell size is reduced to achieve small compact sensors.

The VISA technology for this application is under development at Lincoln Laboratory, with a goal of showing a 64x64 array with thirty micrometer (30 µm) detector unit cell and a range resolution of less than one inch. This array can be integrated with a larger passive array, which detects potential targets and passes the target detections to an active array for identification. Intelligent processing at the sensor, and the capability to integrate multiple sensor types are the key technologies in this advanced unattended sensor concept

8. SUMMARY

The VISA technology presents the potential for new capability in unattended sensors. VISA is currently being applied to imaging sensors with planned demonstrations showing increased detector operating temperature, multi-color operation, and high resolution range imaging. The digital processing being integrated into each pixel lays a foundation for decision making on the focal plane. This leads to more efficient network management and the ability to integrate a wider range of sensor types into the network. Processing power at the sensor is an enabling technology leading to twenty-four hour network operation even under difficult atmospheric conditions. Extensions of the VISA technology will include stacks with a larger number of layers, integration of new semiconductor materials, and techniques for focal plane power management and thermal control.