A Low-Cost Thermal Imaging Sensor for Military Dismounted Operations

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ABSTRACT

The cost of thermal imaging technology has, up until now, precluded its widespread use in sensor systems which require sensors to be deployed in very large numbers. This paper describes a method of achieving this goal of bringing low-cost 'disposable' thermal imaging into the dismounted military environment. Infrared detectors based on the manufacturing processes used in the production of conventional silicon chips offer a breakthrough in cost compared to other technologies. Despite having modest performance, this technology offers a route toward a very cost-effective thermal imaging sensor for dismounted applications. A flexible detector format which permit the detector to operate as a conventional close-packed 2-d array or as a faster update linear array gives the opportunity for performance optimisation and data reduction at the sensor, important attributes for a remotely deployed sensor with limited power resources. This paper describes a sensor architecture which is well matched to the cost, power consumption, and performance levels suited to short-range dismounted and networked operations, and demonstrates some of the imaging capability achievable with such a simple (and hence potentially extremely low cost) sensor.

1.0 INTRODUCTION

The current thermal imaging technology which is most widely deployed in the dismounted military environment is based around weapon sight and hand-held surveillance applications. In these applications, performance is paramount and much work has gone into increasing the thermal sensitivity and increasing the spatial resolution of such systems. The detector technologies have evolved over the years (ferroelectric, VOx, α-Si), the common factor being that the detectors are built in specialized manufacturing plant which are dedicated to making thermal imaging detector arrays. As a result the costs are carried completely by the thermal imaging products, and the resulting imagers cost typically many thousands of dollars.

In the concept described here, Foundry Uncooled Thermal Imaging (FUNTI) the detector arrays are manufactured on a standard CMOS production process, allowing the detectors to be made at extremely low cost. The resulting imaging systems have performance which is much less than the state-of-the-art in uncooled technology. The low cost, however, enables the deployment of massive numbers of sensors, and allows the sensors to be regarded as disposable. The performance is such that the range of an individual sensor is short (typically up to 100 metres), but the use of many sensors allows large areas of terrain to be monitored whilst providing redundancy. Additionally, the problem of dead ground can be eliminated and use of a high density of sensors in a complex (e.g. urban) environment becomes a possibility. One of the key technology advances which makes dispersed sensors viable is the communications technologies which allow data to be transmitted from the sensors inexpensively over short distances (e.g. Bluetooth™) or long

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distances (e.g. GSM). In almost all cases it is highly desirable to minimise the data which needs to be transmitted over any communications network.

One particular advantage of the use of short-range sensors is that, because the range between sensor and target is short, the system is much less affected by adverse weather (e.g. heavy rain-fall, dense fog) than electro-optic systems with long stand-off ranges. This is illustrated in the graphs (figure 1 and 2) where MODTRAN™ has been used to model the transmission through the atmosphere for 100 m and 1 km ranges in clear weather and heavy rain (25 mm/hour). The transmission loss over 1 km in heavy rain is very severe, whereas over 100m there is still around 75% transmission over the path.

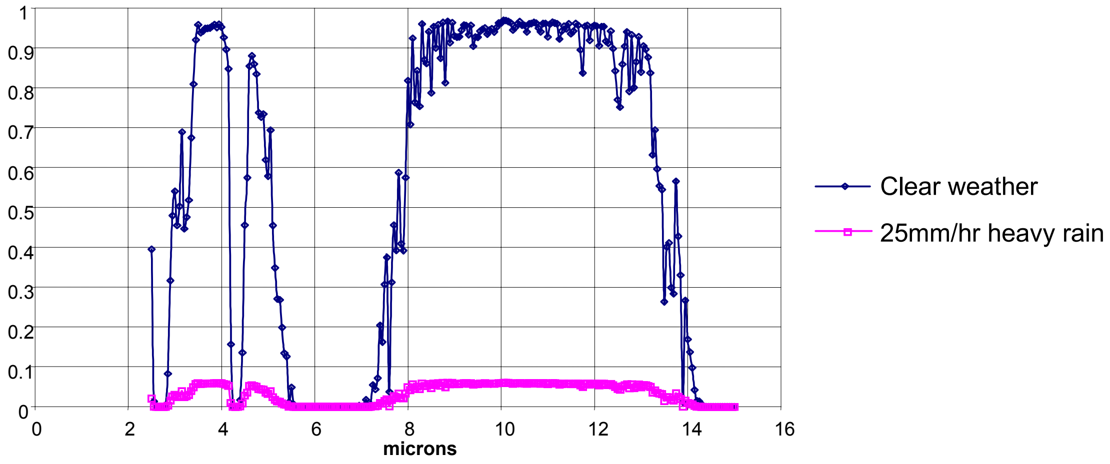

Figure 1: Atmospheric transmission over a 1 km path.

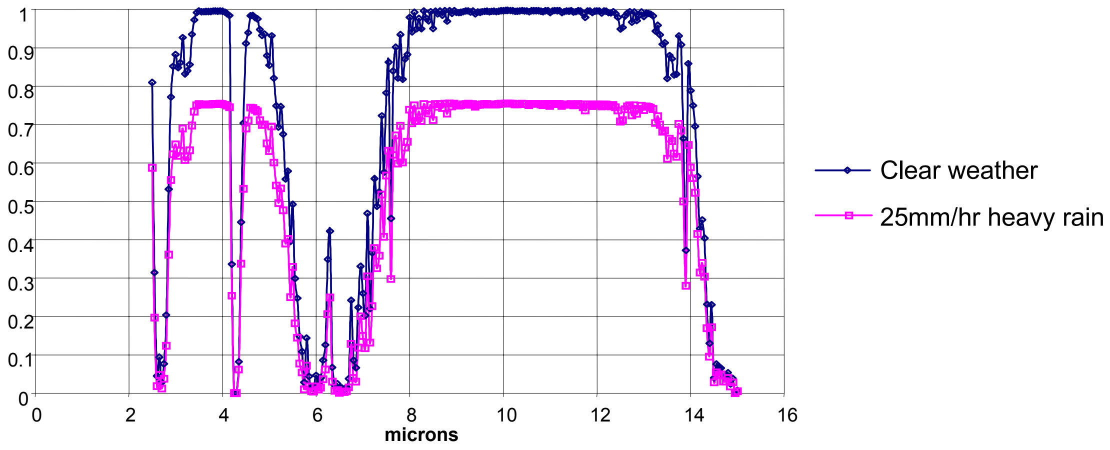

Figure 2: Atmospheric transmission over a 100 m path.

2.0 LOW-COST DETECTOR ARRAYS

The technology used to build low-cost detector arrays is based on the well-known class of thermal infrared detectors known as resistance bolometers. The incident infrared radiation is focused by a lens onto the array of detectors, each of which comprises a resistive titanium track, typically around 0.2 μm thick. This track is formed as a meander shape to maximise the electrical resistance, and is supported by an insulating film, typically around 2 μm thick, which is held away from the silicon chip surface to form a structure known as a microbridge (Figure 3 and 4). The incident radiation is absorbed in the microbridge structure, increasing its temperature, and thereby changing the resistance of the titanium track. This change of resistance is sensed by the electronics in the imaging system, which can thus infer the temperature distribution in the scene. Other materials which have much larger temperature coefficients of resistance are commonly used in thermal imaging, notably vanadium oxide (VOx) and amorphous silicon (α-Si). These materials are able to provide better temperature discrimination but require expensive specialist equipment and processes for their deposition, leading to a much more costly detector technology.

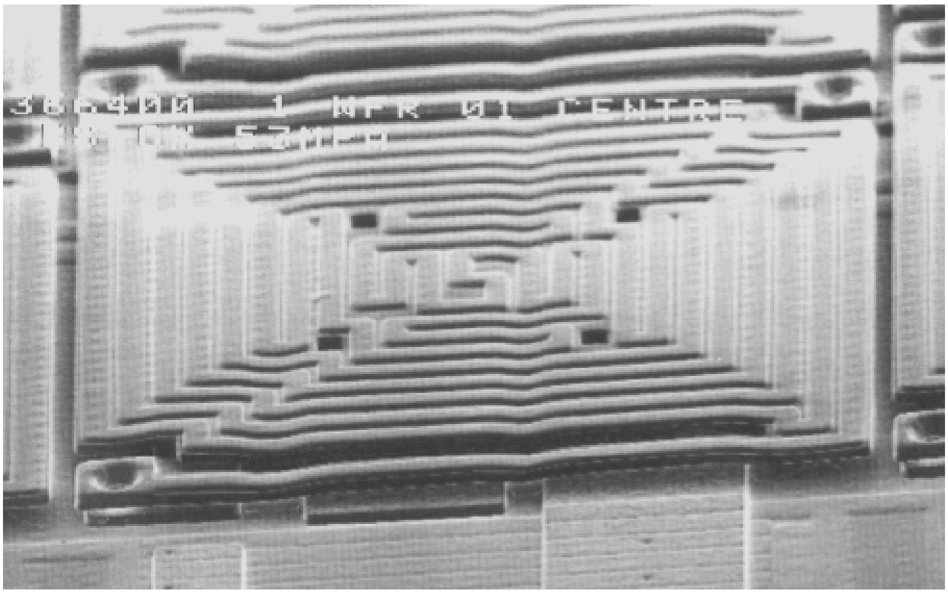

Figure 3: Electron-micrograph of part of bolometer array.

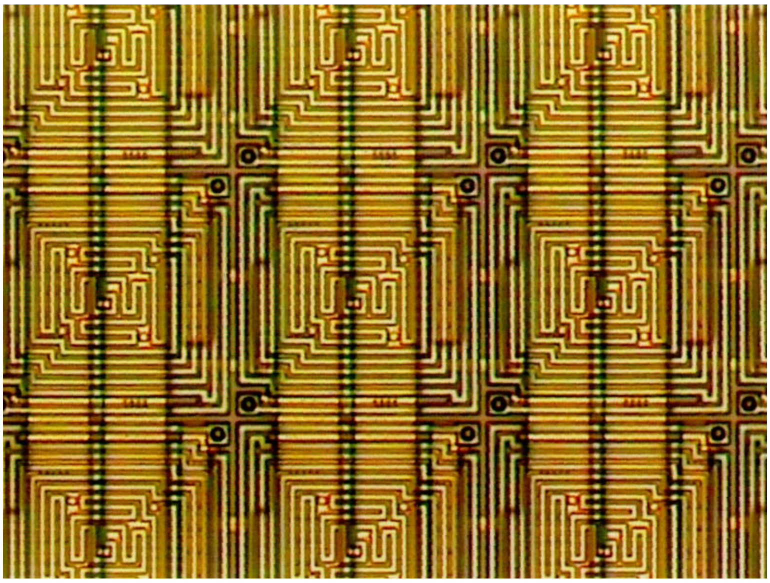

Figure 4: Photo-micrograph of part of bolometer array showing several pixels.

The titanium-film bolometer technology is now being used by QinetiQ for commercial applications, notably for in-car safety in conjunction with First Technology, an automotive component manufacturer. For this application a small two-dimensional array (64x64 pixels) with a wide field of view (≈ 90º) is most appropriate. For a networked sensor a different format which maximizes performance and minimizes the amount of data generated may be more appropriate, as described below. It is important, however, if the low-cost benefit of large-scale production is to be maintained, that a single detector array be used for the maximum number of operational applications, and that flexibility in the use of a single detector type is introduced to optimise the system for particular applications, both civil and military.

3.0 SENSOR PERFORMANCE

There are two main elements to modelling the performance of the arrays described here, the thermal and the electrical modelling. The modelling of the performance of metal film bolometers is made relatively easy by the very low 1/f noise that is measured with thin metal films. The low TCR of the metal film reduces the electro-thermal coupling and so makes the use of linear approximations more valid than for high TCR materials. We have developed a full linear model of the detector and its supporting electronics to help us understand the performance trade-offs with this detector technology, together with a simplified finite difference model to analyse the electro-thermal coupling. As part of the initial feasibility and trade off study, in which we have balanced cost of production and performance, we have arrived at a detector format of 64x64 pixels with 75 micron pitch. This gives a nominal detector resistance of 2.3 kΩ. at room temperature.

The FUNTI microbridge structures have a typical thermal mass of around 5×10^{-9} JK^{-1}, with a thermal time constant of around 5-10 msec. With our nominal design we have carried out a complete signal and noise analysis, including an analysis of noise contributions from the other system components (amplifiers, bias sources, ADC etc). The results of this analysis show that the design NETD is approximately 2.5x the theoretical best NETD (i.e. the NETD in the ideal case where the only noise source is detector Johnson noise). As with all resistance bolometers, the performance increases as the bias temperature is allowed to increase. The bias temperature is chosen as a compromise between sensitivity and dynamic range, and is typically in the region 10°C to 20°C. At 20°C bias temperature the measured NETD is typically 0.3K to 0.35K at f/1, which agrees well with our theoretical analysis.

The relatively poor thermal structure and low TCR of the metal films make severe demands on the dynamic range of the signal processing. Even with well matched bolometers (say 1% standard deviation) assuming we want 99% of detectors to be within range of the ADC we need to be able to accommodate a ± 3% range of resistance values. Using bolometers made from titanium (TCR 0.0038/°C) subjected to a temperature rise of 20°C due to the bias current, an additional dynamic change of resistance of 7.5% needs to be allowed for. A total allowable variation of 15% therefore gives a reasonable margin for other errors (e.g. mismatch of offset voltage in the column amplifiers). The signal from 1°C change in the scene would typically give rise to a temperature rise on the bolometer of ≈ 1 mK which in turn gives a fractional change in resistance of 4×10^{-6}, so for a reasonable quantisation level we must resolve better than 1 in 10^{6} fractional change in resistance. In order to achieve this high dynamic range it has been necessary to apply over-sampling techniques with a state-of-the-art ADC in order to maintain the combination of low noise and high dynamic range.

4.0 SENSOR DESIGN

Our current state of development in this technology has led to the development of a readout chip (ROIC) and processing electronics to act as a demonstrator and to validate our modelling of detector performance. In the prototype sensor the ROIC has been kept as simple as possible. It comprises only the multiplexing function and 9 simultaneous outputs. In its normal operating mode each pixel is addressed for 40 microseconds, giving a frame rate of 30 Hz. This is flexible in our system as all the system parameters such as bias voltage and pixel read time are externally controllable. This flexibility is of particular significance for this technology since the base performance of the sensor is low, so optimising the performance for each particular application without loss of performance is crucial, preferably without making modifications to the hardware.

The processing electronics amplifies and digitises the signals from the array. A global offset is applied adaptively to skim off the bulk of the read current, and optimise the signal dynamic range for the analogue-to-digital converter (ADC). As described above, dynamic range is a particular problem with this technology due to the low signal levels. A novel over-sampling technique has been devised which enables a very high dynamic range to be achieved, approaching 20 bits. The electronics is able to carry out the usual 2-point gain and offset correction, with the offset value being updated periodically by means of a uniform reference flag. In practice, gain correction is not needed for many applications because the CMOS manufacturing processes are so well characterised that the response uniformity is typically better than 1% over an array.

A number of sensor configurations have been developed. For short range applications (90º field of view), provided that the best image quality is not needed, a single element lens can be built into the detector package instead of the normal widow (Figure 5). Such a simple lens, operating at around f/1.0, is possible only because of the large pixel size, so the resolution of the system is detector-limited on axis, but lens-limited toward the field edge by the off-axis lens aberrations. With the wide angle lens used in our prototype the flag is situated in object space, giving good radiometry for the offset correction process. Once again the driver for the lens design has been low production cost. This is the sensor configuration which is likely to be used for very high volume applications such as in-car occupant sensing [1].

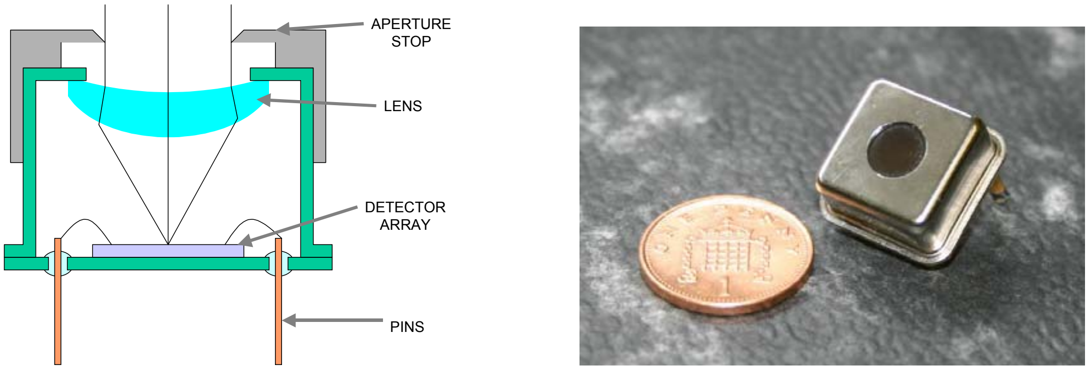

Figure 5: Detector array packaging.

For use at longer range the detectors are fitted with plane windows and external lenses are fitted to the sensor unit. The simple ROIC currently being used requires external amplifiers and multiplexing before the signals are digitised, together with power and a low-noise reference for the bolometer bias. The data processing and interfaces are implemented in a single FPGA chip.

Our prototype imager is equipped with a video scan converter to provide any video format, normally programmed to give 50 Hz monochrome CCIR video. It also provides 16-bit digital data via a serial interface (USB 1) which enables image data to be streamed directly to hard disk or to real-time image processing running on a PC, and an uncommitted serial output. The current design (Figure 6) consumes approximately 1 watt from a 5 to 9 volt supply in normal operating mode and occupies 40 mm x 150 mm of PCB area. It should be possible to reduce the size and power consumption very significantly in the future, by integrating more functionality on the ROIC, by reducing the number of interface options, and by optimising the choice of FPGA.

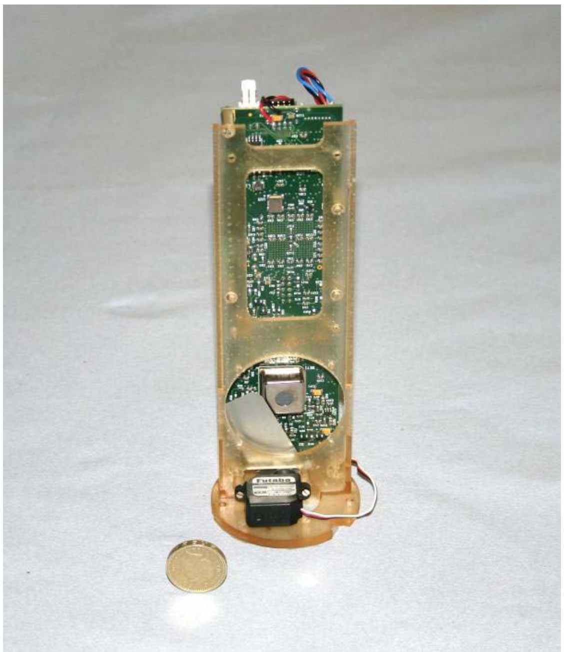

Figure 6: Photograph of prototype sensor unit.

5.0 SENSOR ARRAYS FOR DISMOUNTED APPLICATIONS

It is important to put the performance, and hence the potential applications, of the FUNTI technology into context. The performance available from the FUNTI technology means that it is unlikely to be used for 'direct view' applications such as weapon or surveillance sights. The fact that the detector is entirely manufacturable on a standard CMOS process means that it would be possible in principle to build an imager on a single chip in very high volume. In practice, yield considerations, and the difficulty of building high-resolution ADCs on standard CMOS processes, mean that a 3-chip imager occupying no more than 20 mm x 20 mm of PCB area is a more feasible, lower risk, approach. With a wide-angle lens (say 30°) a complete imager within a 25 mm (1") cube (excluding batteries) should be feasible.

With the possibility of such an inexpensive small imager there are a number of possible applications. Mounted on individual soldiers this technology offers the possibility of rear- and side-facing sensors to alert against short-range ambush. Similarly, sensors mounted around armoured vehicles would be able to sense activity close by, providing close-in situational awareness when operating 'hatch-down'. The main application of this technology lies in the employment of very large numbers of sensors as part of a sensor network [2,3]. There are a number of requirements for a networked sensor which place severe constraints on any imaging sensor, but which match well to the capabilities of the FUNTI technology. Most of these arise from the need to minimise the power consumption and data rate of each sensor node, which may need to operate for long periods on a small battery pack. The impact of sensor type on the data rate is illustrated below (Table 1). Not only must the sensor itself have low power consumption, it should produce the least data commensurate with the task to be performed so that the lowest power signal processing can be used, and the bandwidth of any communication link is minimised. Previously it has been proposed [3, 4] that linear arrays based on this technology provide an effective means of reducing the data rate whist retaining good imaging quality. The use of several, e.g. four, linear arrays on the same focal plane can significantly enhance the information gathered by the sensor (Figure 7), i.e. direction and speed of travel. The operation of the 64x64 pixel prototype system in both linear and 2-d modes has been demonstrated, proving that a single sensor can be optimised by software changes alone for both modes of operation.

Table 1: Comparison of sensor data rate

Sensor format	Pixel count	Frame rate	Sensor data rate
Full TV resolution	640x480	30 Hz	9200 k pixels/sec
¼ TV 30 Hz	160x120	30 Hz	576 k pixels/sec
FUNTI 2-d format	64x64	30 Hz	122 k pixels/sec
Single linear sensor	64x1	20 Hz	1.28 k pixels/sec
Quad linear sensor	64x4	20 Hz	5.12 k pixels/sec

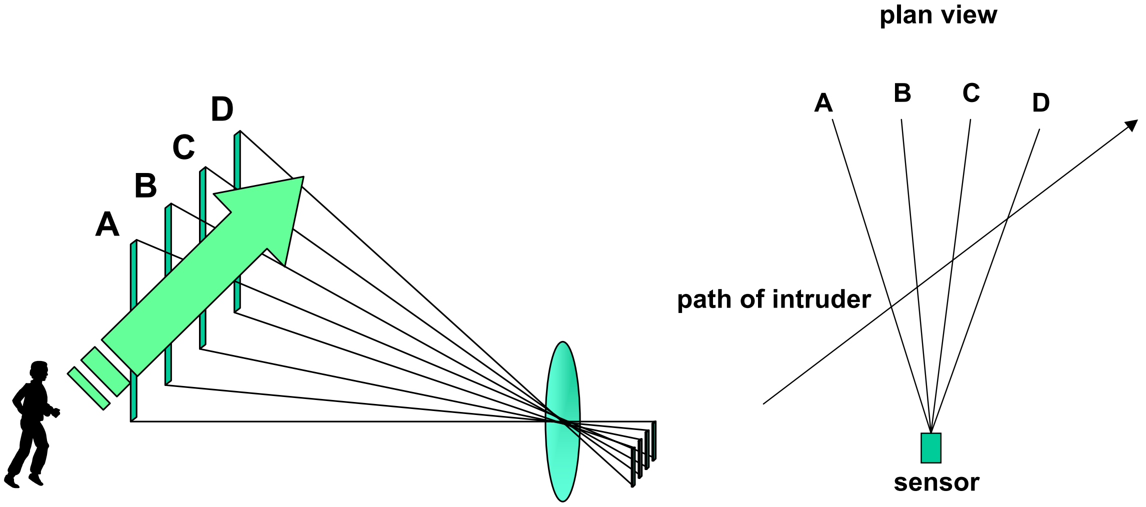

Figure 7: Schematic showing concept of multiple linear array system.

6.0 IMAGERY

Imagery is shown here which has been obtained using the prototype sensor, fitted with a 25 mm f/0.8 lens. The sensor is operated at 30 Hz frame rate in 2-d mode and has a line rate of 120 Hz when operated in linear mode. The imagery was taken early in the morning (before first light) under cold conditions. Data was streamed to a lap-top PC and the imagery shown is single frames extracted from the data stream with no additional processing. Figure 8 and Figure 9 show results from the sensor used in its conventional 2-d imaging mode of operation, Figure 10 shows images from the same sensor reconfigured for linear array operation. It should be noted that the higher sampling rate for the linear array results in over-sampling of the image in the horizontal direction, which in turn results in a significant improvement in the image quality. This effect is reduced as the crossing rate of the target vehicle increases.

Figure 8: Example imagery of a walking man using 10° field of view (1” focal length) lens.

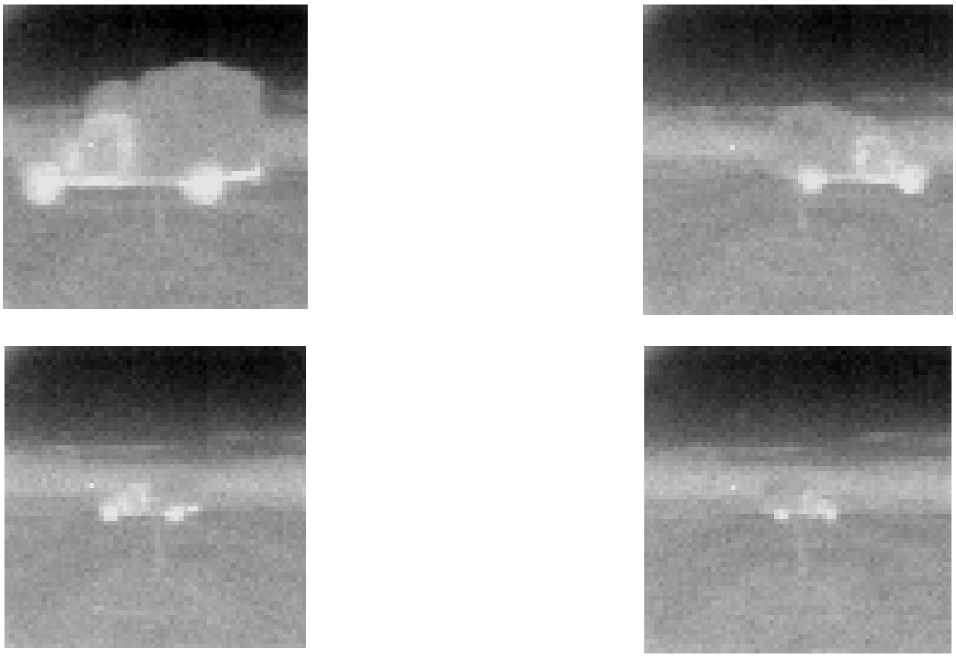

Figure 9: Example imagery of box-body truck using 10° field of view (1” focal length) lens.

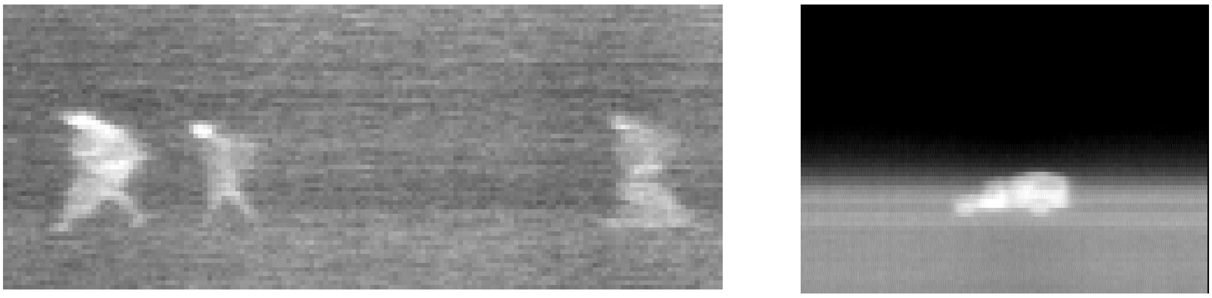

Figure 10: Example imagery in linear array mode of operation using 10° field of view (1” focal length) lens.

7.0 WAY AHEAD

The current status of the metal film bolometer technology is that a demonstrator system is operating in a trials environment with a 64x64 multiplexed format. The sensor can operate in 2-d and linear operating mode and is currently undergoing a series of field trials in a range of conditions to help to establish the performance limits of such a sensor, and to identify the roles for which it is most suited. The line array mode provides greatly reduced data rate and, because of the higher sample rate than the 2-d mode, is able to produce better quality imagery on moving targets.

The current sensor has a NETD which requires a high-aperture lens (f/0.8) for satisfactory performance. Modelling has shown that it should be possible to improve the detector NETD by up to a factor of 2 without using any process steps which are not compatible with the CMOS foundry processes, which is the key to low cost. This would significantly reduce the cost and weight of the sensor units by permitting the use of smaller lenses, or permit longer range operation using the same size optical aperture.

There is currently interest from military programmes in taking this technology forward to a more advanced level of implementation. In particular combining such thermal imaging sensors with acoustic sensors in the long-range detection and recognition of artillery, which requires large numbers of sensors to be sited remotely, and probably air dropped or launched from rockets or artillery This places high demands on the survivability of the sensor and the networking technology. In addition the urban warfare environment can benefit from inexpensive deployable sensors which have a relatively short range, but which are deployed in large numbers, both inside and outside buildings.

The arrays in a two-dimensional format with lenses integrated into the package are currently being developed for commercial automotive and security applications. A key feature of the sensor we have developed is the use of COTS technology and adapting the way the way the detector is operated to achieve additional functionality. In order to maintain low cost it is important to maintain this compatibility with commercial devices made in large volumes. To provide the lowest cost sensor a revised focal plane ROIC with a much higher level of integrated functionality would be highly desirable.

8.0 CONCLUSION

It is highly desirable to have available a low-cost 24-hour imaging capability to provide situational awareness for the dismounted soldier, at a sufficiently low cost that the sensors can be regarded as disposable. This capability is now becoming available with the advent of thermal imaging technologies which enable the infrared detector array to be made in a silicon chip foundry, rather than having to set up a special manufacturing facility. It is believed that the high-volume commercial applications will drive the cost for this technology down to below $100 for an imaging module. By optimising the detector format for the particular sensor application it can be made to have the desirable attributes of low power consumption and low output data rate. The basic titanium film bolometer detector technology has been demonstrated, in both a 2-d and a linear array configuration. The sensor configuration has been designed to be flexible and can be software selected to suit the application and operational scenario. This technology is approaching the level of maturity where is could be integrated into a military sensor for dismounted or networked applications.

9.0 REFERENCES

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ACKNOWLEDGMENTS

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