Low SWaP Video Engine for SWIR Low Light Level Imaging

E. Louzon(1), A. Aharon(1), R. Gazit (1), D. Bar(1), I. Hirsh(1), P. Kondrashov(1), M. Weinstein(1), M. Savchenko(1), M. Regensburger(1), A. Mediouni(1), E. Mor(1), A. Shay(1), K. Rozenshein(1), N. Syrel(1), R. Iosevich(1), A. Giladi(1), E. Berkowicz(1), M. Ben-Ezra(2), A. Tuito(3) and R. Fraenkel(1)

(1) SemiConductor Devices P.O. Box 2250, Haifa 31021, Israel, Email: einatl@scd.co.il
(2) Israeli DF
(3) Israeli MOD

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ABSTRACT:

Imaging in the Short-Wave Infra-Red (SWIR) has some unique advantages over visible or thermal imaging. InGaAs/InP is the leading technology for two-dimensional (2D) SWIR detector arrays, with very high electro-optical performance. For optimal performance, such detectors can be moderately cooled and temperature stabilized using a Thermo-Electric Cooler (TEC). This results in a small package with low power consumption, high reliability, and relatively low production cost.
SCD's SWIR Imager is a low size, weight and power (SWaP) video engine (video core) in which a 640×512/15µm InGaAs Focal Plane Array (FPA) is embedded in a low cost plastic package. The SWIR Imager weights 50 gram, and its size is 31×31×32 mm³. It supports conventional video formats, such as Camera Link and BT.656. The Video Processing Unit (VPU) and algorithms are specifically optimized for Low Light Level (LLL) conditions, utilizing the InGaAs FPA ("Cardinal 640") Low Noise Imaging with Correlated Double Sampling mode to reach a low readout noise of less than $40e^-$. The overall power dissipation of the video engine (not including TEC) is less than 1.4W. Special effort was invested in minimizing the dark current to a level of 1fA at 20°C, thus alleviating the cooling requirements.
In this work we will review in detail the electro-optical characteristics and performance of the SWIR Imager and specifically the embedded image processing capabilities for LLL conditions. The results are based on actual measurements of several prototypes manufactured by SCD over the last year. The SWIR Imager video engine is aimed to replace an Image Intensifier (II) tube in a Driver Vision Enhancement (DVE) system.

1. INTRODUCTION AND BACKGROUND

SCD has been designing and manufacturing SWIR InGaAs detectors since 2011 and in mass production since 2015 [1]. During the last decade SCD has invested substantial resources in order to provide "cutting edge" technology to its customers. This includes proprietary CMOS ROIC, InGaAs based pixel design and production, image processing algorithms and their implementation in hardware and software.
Over the last decade, uncooled detectors have become increasingly embedded in a variety of commercial and military systems and applications [2]. Due to the significant effort required for designing and manufacturing high quality uncooled video cores, system integrators are relying more and more on the video cores or “video engines” instead of a stand-alone detectors, as a basic component of their system [3].
Following the growing need of higher level of product integration SCD widened this investment to the SWIR market. "SWIR Imager" is a multi-purpose, flexible, easy to deploy high-end video core, suited for battery operated military applications and systems such as Image Intensifier tube in a Driver Vision Enhancement (DVE) system, where SWaP (Size, Weight and Power) and a superb image quality in Low Light Level (LLL) conditions is mandatory.
In Fig.1 we demonstrate the capability of the SWIR Imager to function as a driver vision enhancer in complete darkness – moonless night, with less than 5 mLux. Fig.2 demonstrates the capability to detect a person waving and other fine details in a distance of 140 m in a moonless night with approximately 8 mLux.

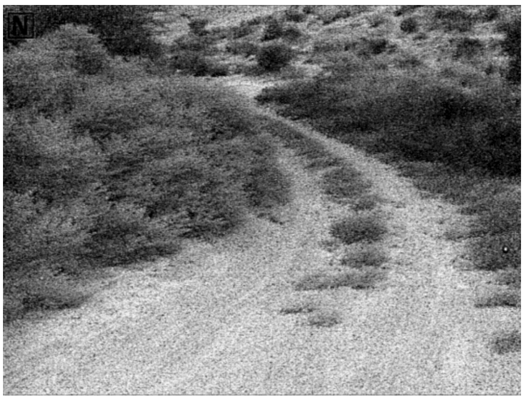


Figure 1: SWIR Imager night mode, during 10 km/h drive at complete darkness, illumination < 5 mLux@ F/1.2 optics.

Figure 2: SWIR Imager night mode at moonless night, illumination < 8 mLux@ F/1.2. Person waving detected at a distance of 140 m.

The first part of this paper is devoted to the 640x512/15 μm pitch detector, with a new plastic package, integrated Thermo Electric Cooler (TEC) and low dark current Focal Plane Array (FPA) of typical 1.5fA (at 20˚ C). In the second part we present the image processing algorithms, designed to achieve a superior image quality in both day and night conditions. The last part is devoted to the video core "SWIR Imager" product and its capabilities.

2. 640x512/15µm InGaAs DETECTOR in a low cost PACKAGE

2.1. PCB-TEC Packaging

Over the last few years significant effort was invested in reducing weight and cost of the packages. Several compact configurations were developed and embedded in new InGaAs products [4].
For the purpose of replacing the Image Intensifier (II) tube, SCD has advanced a step further developing a small Printed Circuit Board (PCB) based detector package.
InGaAs based detectors have no need for vacuum or even dry environment in order to reach superior performance. Hence, we decided to change years of traditional packaging of the IR/SWIR detectors in hermetically sealed packages. The PCB package is a unique design approach to address SWIR detectors packaging concept. However the condition for replacing the Image Intensifier (II) tube was to maintain cooling capability for Low Light Level (LLL) at night mode. To reduce the overall power consumption, the detector can operate TEC less in day mode (high illumination level).
To achieve these demands we invested in minimizing the FPA dark current to a level of 1.5fA at 20°C in addition to selecting TEC devices with minimum sensitivity to the environment conditions. This enabled us to create small-footprint, low production cost, state of the art detectors capable of meeting the specification and cost target of Low SWaP video cores. The reduced weight compared to a metallic package is important for various applications. However, this new concept requires Nitrogen purging at the system level.

2.2. Low Dark Current IR

Reduction of dark current was achieved by implementing new pixel architectures and process modifications. The outcome is the low dark current FPA. The new process was also implemented in SCD "Cardinal 1280" (10µm pitch, available now [5]) and in one of SCD newer products - low noise FPA (coming soon).
Typical specification for the New SWIR InGaAs PCB detector is exhibited in Tab. 1.

Parameter	Typical Value
Format & Pitch	640x512, 15µm
Spectral range	SWIR-VIS: 0.6 – 1.7µm
QE	> 70% @ 1550nm
Dark current	1.5fA @ 20ºC
Inner Environment	Closed-non hermetic- package / Nitrogen purged is required in system level
Frame Rate @ full format	350 F/sec @ 13bit resolution, 80MHz clock rate (Global Shutter)
Windowing	Flexible, 2 row step
ROIC noise	High gain: $40e^-$ (with CDS) Low gain: $210e^-$
FPA power dissipation	< 100mW @ 60 F/sec
Operating temperature range	-40ºC to 71ºC
Storage temperature range	-54ºC to 80ºC
Package footprint	$25x21x8.2mm^3$
Weight	< 10 gr.
Electrical Interface	2 x 20 SAMTEC female connectors
Package	PCB base
Cooling capability (TEC)	ΔT = 40° C @ room temperature

Table 1 – 640x512, 15µ, PCB + TEC detector - Typical performance

Fig. 3 demonstrates typical dark current distribution. The peak of the histogram is at 1.5 fA @20° C. The distribution is Gaussian with very low "high current tail".

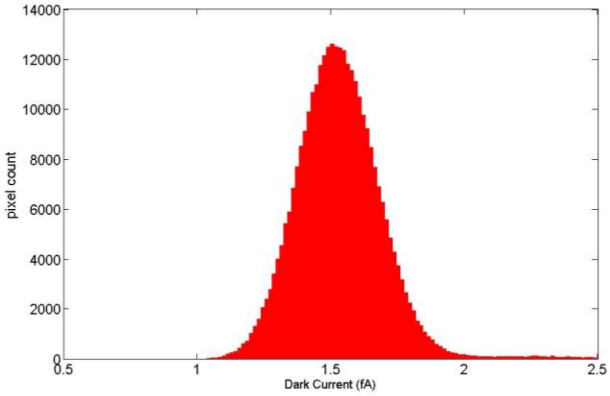


Figure 3: Dark current distribution @ 20° C

Calculation of the overall Signal to Noise Ratio (SNR) of the detector vs. illumination condition demonstrates the potential to use SCD InGaAs high gain mode for night vision, as shown in Fig. 4. Low gain mode (dot blue line) shows high SNR for high illumination levels enabling operation at low power mode at day light. Switching to high gain mode (dashed red line), with appropriate cooling supports SNR > 10 under moonless and starlight conditions. The new low dark current SWIR FPA (solid green line) will further improve the SNR down to starlight overcast scenario (~10^{-15} A photo current).

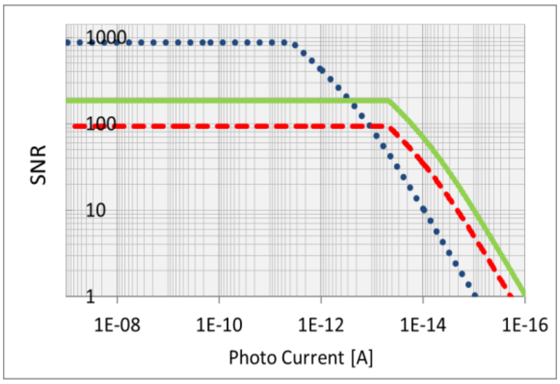
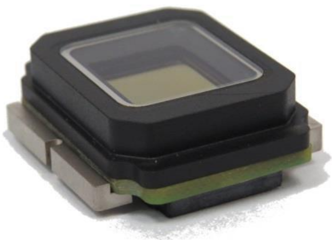
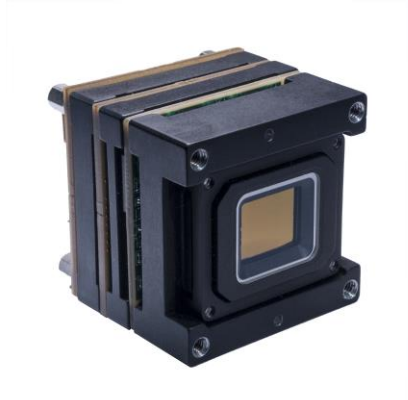


Figure 4: Calculated SNR (at 25Hz) vs. Photo current [A] with F/1.2 optics. Low Gain (dot blue line), High Gain (dashed red line) and High Gain Low Noise (solid green line).

Fig. 5 exhibits the PCB-TEC packaged detector (Fig.5a), and the entire video core (Fig.5b).



(a)



(b)

Figure 5: (a) PCB-TEC detector, (b) SWIR Imager video core

3. IMAGE PROCESSING

The SWIR Imager video core implements two basic operation modes: high-gain (for Low Light Level) and low-gain (for high dynamic range) imaging at 25/30Hz, and high frame rate mode at 50/60Hz.

The image processing pipe is divided into Image correction and image enhancement subsystems as shown in Fig. 6.

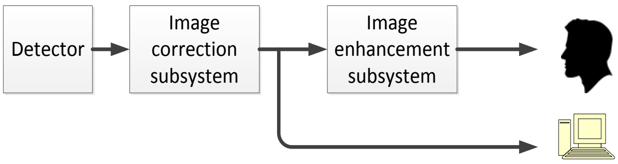


Figure 6: Image enhancement and correction sub-systems In the SWIR Imager

The Image correction subsystem deals with raw detector data processing as well as image artifacts, and includes algorithms:

- High Dynamic Range (HDR) day time vision
- Low Noise Imaging Correlated Double Sampling (LNIM-CDS) for low light level conditions
- Temperature Based Non Uniformity Correction (TBNUC)
- Bad Pixels Correction (BPR)
- Noise Reduction in the spatial and temporal domains (NR)

The video generated by the Image correction subsystem is suitable for automated video analysis (Machine vision).

The Image enhancement subsystem is an optional block that improves the perceived image for a human observer.

3.1. Image correction subsystem

The Image correction subsystems implements video pipeline that applies a series of algorithms to reduce residual non-uniformity (RNU), reduce image noise and increase dynamic range.
Increasing the dynamic range is performed in Standard Imaging Mode (SIM) were two consecutive frames with different integration times are captured and combined to a single image with high dynamic range (HDR). Noise reduction is applied when low light conditions are detected and the SWIR Imager automatically switches to low noise imaging (LNIM) mode where correlated double sampling (CDS) procedure is implemented to enable extremely low noise readout.

3.2. LNIM-CDS

At low light conditions the SWIR Imager switches to high gain operation mode of the ROIC. A low noise image (LNIM) is captured with a reference "noise image". The algorithm implements correlated double sampling (CDS) processing. Typical low light, performance (~ 2 mLux) is demonstrated in Fig. 7**.**

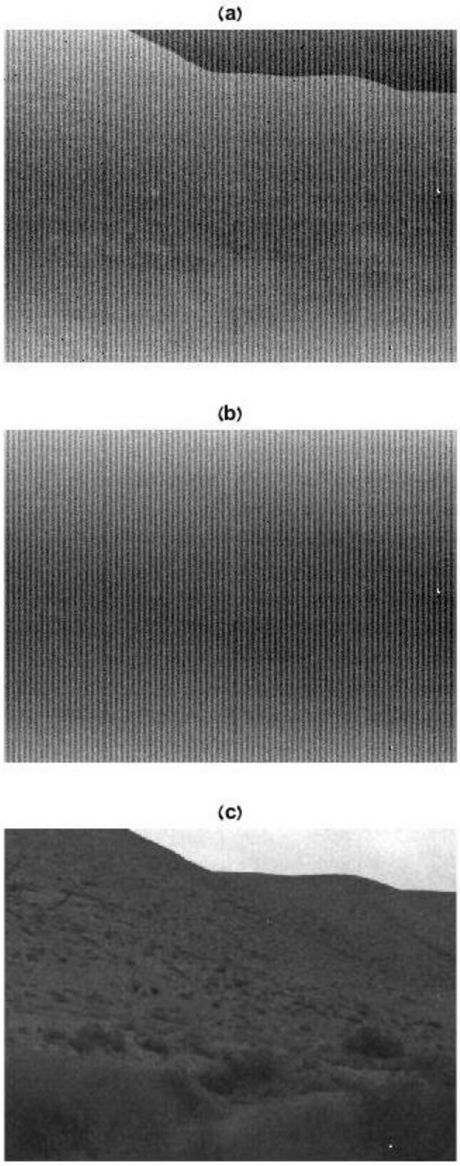


Figure 7: LNIM operation mode process in moonless night at a very low light condition (about 2 mLux): (a) scene imaging at high gain mode; (b) CDS offset; (c) the resulting corrected image.

3.3. HDR

At high dynamic range scene, typically imaging with high illumination condition, SWIR Imager automatically switches to low gain mode (of the ROIC) and High Dynamic Range (HDR) algorithm is applied. In this mode the imager captures two consecutive frames with different integration time and a proprietary algorithm is used for fusing the two frames into a single image with extended dynamic range. Typical HDR operation is demonstrated in Fig. 8.

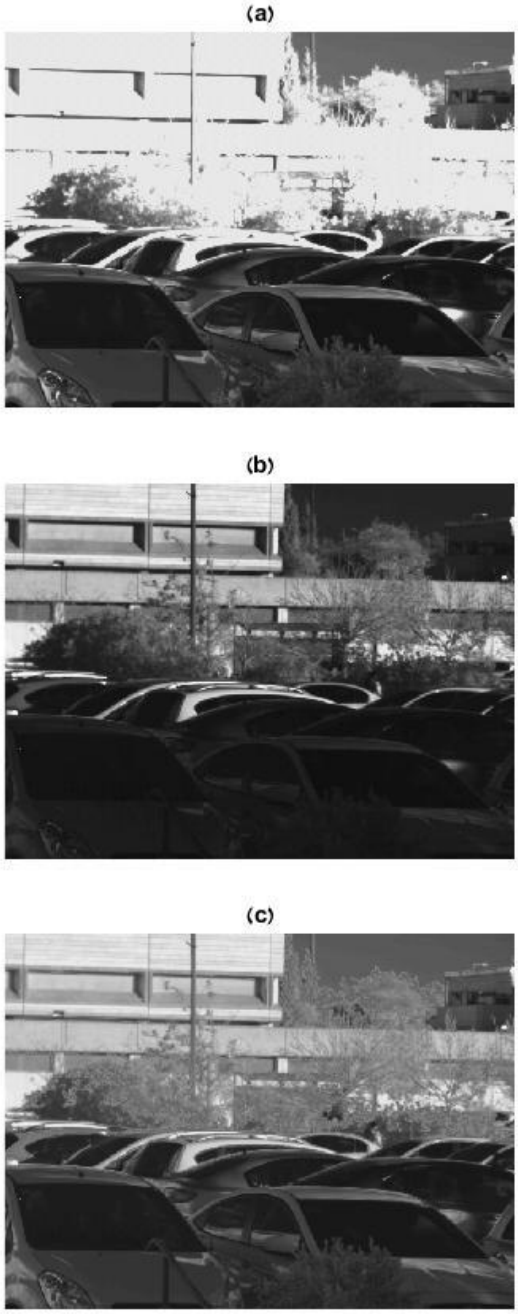


Figure 8: HDR process example:
(a) long integration time image; (b) short integration time image; (c) the resulting HDR image

3.4. AGC/AEC Algorithms

An optional Automatic Gain Control (AGC) algorithm selects the best mode of operation (SIM HDR or LNIM–CDS) based on the scene illumination conditions while Automatic Exposure Algorithm (AEC) dynamically adjusts the detector integration time to optimal value.

3.5. Noise reduction (NR)

The SWIR imager implements a proprietary Spatial-Temporal noise reduction algorithm. The NR algorithm uses a combination of spatial and temporal filtering according to inter-frame similarity. The algorithm preserves maximum level of details while maintaining uniform noise levels across the frame yielding ~x2 temporal noise level reduction under low light level conditions. NR performance is demonstrated in Fig. 9.

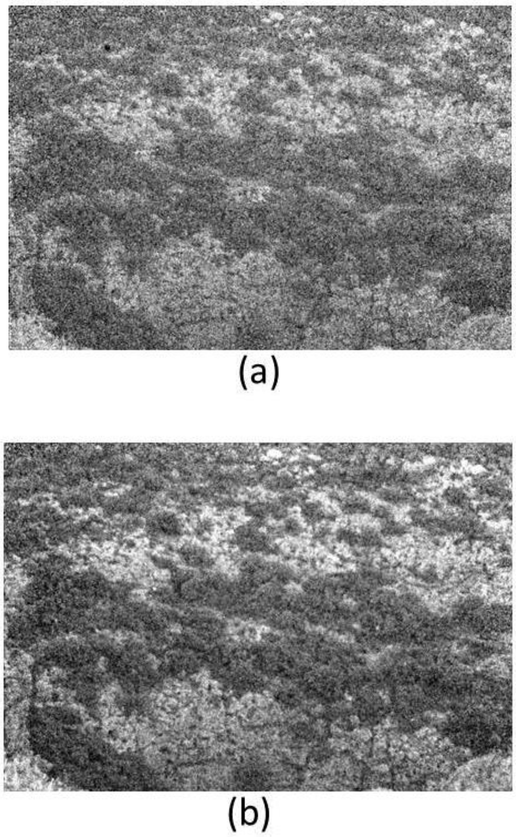


Figure 9: Effect of NR algorithem in low light level scene, (9% well fill); (a) without NR, (b) With NR

3.6. Temperature Based Non Uniformity Correction (TBNUC)

We implement an optional low power Temperature Based Non Uniformity Correction (TBNUC) procedure that based on factory calibration allows TEC-less operation. The TBNUC procedure modifies in real time the NUC coefficient as a function of the FPA temperature thus; low RNU is maintained for different temperatures of operation.
Fig. 9 shows a comparison of Global Standard deviation (STD) of the original raw image (dot blue line), in front of a uniform target, a corrected image using NUC tables calibrated at 40C (square pink line), and of the corrected images using TBNUC procedure (plus red line); at different FPA temperatures.

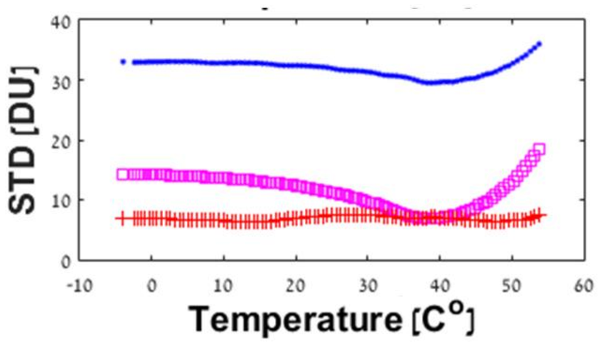


Figure 9: Global STD for various images at SIM operation mode. Raw Data (dot blue line), NUC @ 40˚ C (square pink line), TECLESS (plus red line).

3.7. Image enhancement subsystem

The image enhancement subsystem is an optional block that improves the perceived image for a human observer and converts the image to the dynamic range of a display – typically 8 bits (256 color levels). The Image enhancement processing includes:

- Dynamic Range Compression (DRC)
- Digital zoom
- Graphics and Overlay
- Pseudo coloring

3.8. Dynamic Range Compression (DRC)

DRC compresses the input signal to a displayable signal and enhances signal edges. Compression is locally adaptive and ensures maximum contrast enhancement, regardless of input dynamic range variability. The enhancement is adaptive to scene content and has provisions for preventing overstretching.

3.9. Bad Pixels Replacement (BPR)

BPR algorithm uses a preloaded list of bad pixels to replace all bad pixels on the output image with good pixels generated using smart edge-preserving averaging of adjacent good pixels.

3.10. Digital Zoom

The SWIR Imager implements user configurable X2 and X4 digital Zoom around the center of the image.

3.11. Overlay graphics and Pseudo colours

The Image enhancement subsystem implements graphics and overlay engine that allows overlaying multiple images graphics stored in the device non-volatile memory as well as arbitrary text over the SWIR video. Any area in an image painted in a “transparent” color code is replaced by live video.

SCD provides its customers PC based tool that allows the users to easily upload images and fonts to the device memory.

The graphics engine supports displaying up to 15 simultaneous different colors with user configurable color palette. In addition the SWIR data can be converted from gray-color to color space using pseudo coloring user configurable look-up-table mechanism.

4. SWIR IMAGER – VIDEO CORE

The SWIR Imager is ideally suited for applications where size, weight and power requirements are of key concern. Its basic specification is summarized in Tab. 2.

Parameter	Typical Value
Sensor	InGaAs
Format	640x480
Pitch	15 µm
Spectral Range	0.6-1.7 µm
QE (1.2µm-1.6µm)	>70%
Readout Floor Noise	<40 [e]
NEP	<1[fw]
Image Correction	NUC, BPR, HDR, AGC, DRC, NR
Frame Rate	30 Hz
Time to Image	<10 sec
Latency	Sub frame
Supply Voltage	5V
Power Consumption	<1.4 Watt
Tec-Less operation	Can Be used TEC-Less
Video output 1 (LVCMOS)	8/13 bit Parallel, Glueless VGA AMOLED, BT656
Video output 2 (LVDS)	Camera link, simultaneously with the parallel output
Digital zoom	x2, x4
Polarity invert	Yes
Image flip	Yes
Discrete button input	8
Overlay graphics	Text/ Reticles
Size	31x31x32 mm
Weight	<60 grams
Operation temperature	-40˚C to 71˚C
Storage temperature	-40˚C to 71˚C
Shock	500G @ 0.5msec

Table 2 SWIR Imager specification

The SWIR Imager can be biased by a single 5V voltage source or dual voltage sources, 5V & (1.8 to 3.3V). By using the dual source configuration the power consumption can be reduced by almost 10%.

The SWIR Imager provides two video channels simultaneously, a parallel video channel and Camera-Link LVDS video channel, where the LVDS channel can be disabled to save power consumption. The parallel video channel is field-configured to provide data via BT656 protocol, a parallel LVCMOS protocol or an AMOLED Display mode.
The video core provides up to 8 signals referred to as discrete I/O pins that each can be field-configured to provide a specified functionality. The function assigned to each discrete I/O pin are defined by user changeable control file. Some of the potential signals that can be assigned to the discrete I/O pins are: Black hot / White hot, activated external shutter, Digital zoom, etc.
The SWIR Imager will support, at the near future, an option for transmitting or receiving a frame-synchronization pulse on EXT_SYNC. This feature provides the capability to synchronize frame start between two cores, one configured as Master and the other configured as Slave, or to synchronize the device with a different other video sources, external light pulse source, etc.
The video core is controlled by an asynchronous serial interface, RS232, up to 921,600 baud/sec working with 3.3V LVCMOS logic levels.

5. SUMMARY

In this paper we presented the "SWIR Imager", a state-of-the-art planar InGaAs P-I-N diode array and miniaturized video core, operating in Low Light Level (LLL) and daylight conditions. We have described in detail the image processing algorithms that were implemented in the video core.
The PCB package detector assembled with 31x31mm^2 foot-print video core is fully qualified for military and industrial uses. This video core is aiming to replace Image Intensifier (II) tubes in a Driver Vision Enhancement (DVE) system.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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