Fixed mounted infrared 2D and line cameras for industrial non-contact temperature measurement

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New uniform camera electronics were developed for different stationary line and 2D infrared cameras for non-contact temperature measurement. The 16bit analog/digital converter used enables a maximum pixel rate of 10 MHz. The electronics are based on a System Of Programmable Chip (SOPC) solution using a PLD with an embedded processor. The ability to reprogram the PLD allows an inexpensive adaptation to different sensor types and various industrial applications. The embedded processor executes the signal processing. In addition, the embedded processor controls and monitors the camera head, monitors the operation of the chopper/shutter motor and internal temperature sensors, and can be used to control a number of functions such as triggering or frame rate. The PC communicates with the micro-controller via an asynchronous interface. The other essential components of the digital signal-processing unit include a serializer, a flash memory and a SRAM. The new 16bit camera electronics have been incorporated into the 2D infrared cameras PYROVIEW 256 with a pyroelectric array (256 × 128 pixel) and PYROVIEW 320 with a microbolometer array (320 × 240 pixel). In addition the newly developed 16bit camera electronics also provide the basis for faster line cameras PYROLINE 256 with pyroelectric arrays of 256 × 1 and HZK 256 with an InGaAs linear array of 256 × 1.

1 Introduction

The infrared (IR) sensor market is developing rapidly. Meanwhile, a growing number of high-performance focal plane arrays is used for commercial applications. The progress in the sensitivity and resolution of the sensor arrays leads to higher demands on the IR camera systems, too. For example the increased pixel numbers result in higher data rates and the lower sensor NETD values require higher dynamic ranges.

Furthermore, new two-dimensional (2D) and linear arrays are put on the market at ever shorter intervals. It becomes more and more difficult and expensive to develop appropriate camera systems within the same time. So the basic idea was to develop a camera system with universal electronic components which can be inexpensively adapted to different IR sensor types and various industrial applications.

The paper presents this newly developed stationary IR camera system designated for uncooled high-performance focal plane arrays. Two prototypes of 2D camera systems containing a 256 × 128 pyroelectric and a 320 × 240 microbolometer array respectively, are introduced. The technical properties of both systems are described. The newly developed camera electronics also provides a basis for high-speed IR line cameras which are equipped, for example with pyroelectric or InGaAs photodiode linear arrays. These cameras are also described.

2 Uncooled IR Camera System

The newly developed IR camera system is based on a universal device concept [1,2]. Each system consists of a camera head and a PC plug-in board which are connected via fiber optic cable. Fig. 1 shows the system setup.

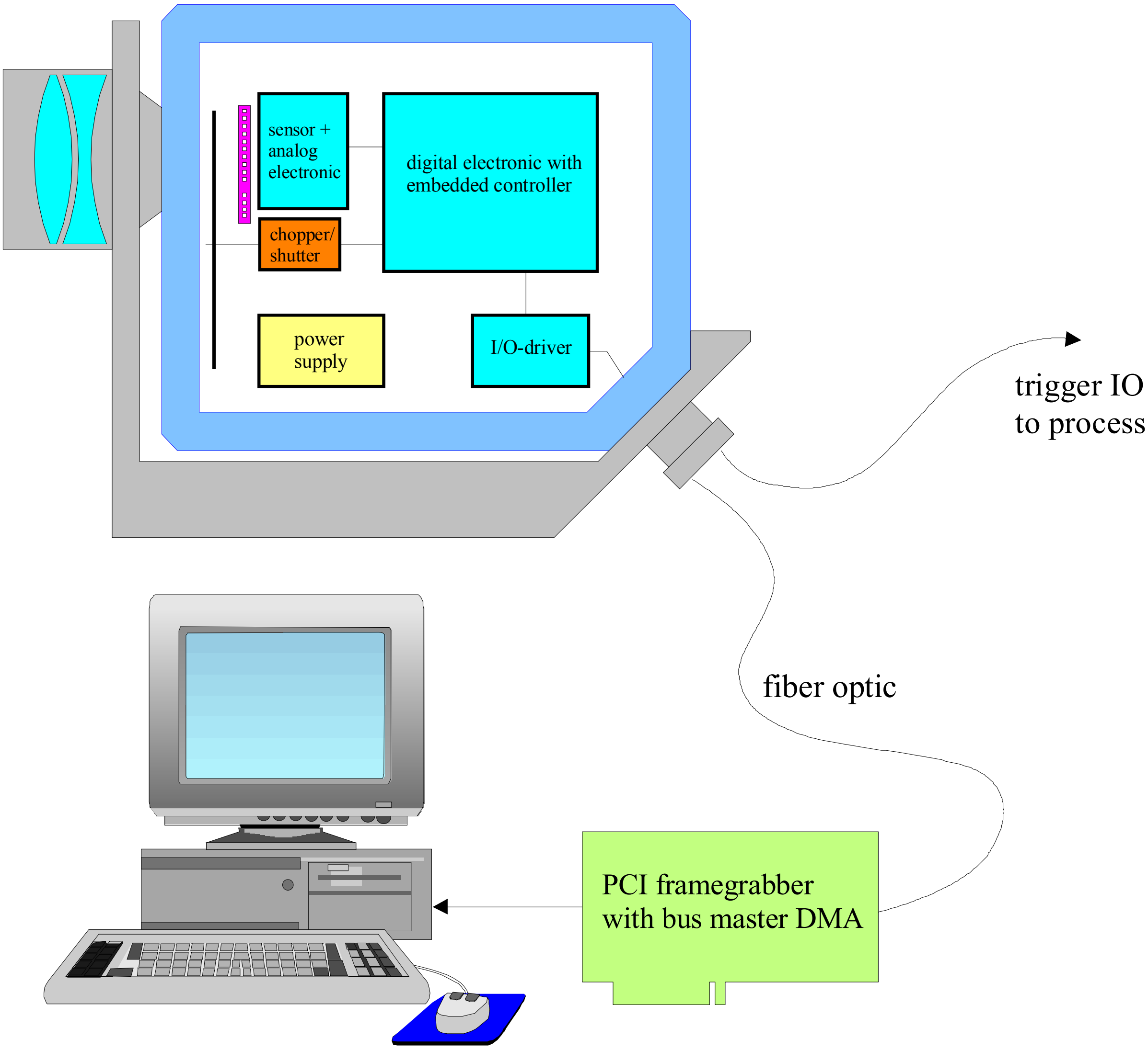

Fig. 1: Set-up of the universal IR camera system

The camera system is designed for stationary use in harsh industrial environments. The robust housing (Fig. 2) may be completed by an air purge for the lens system and an integrated water-cooling option which allows an operation at ambient temperatures up to 150 °C. The camera head is equipped with trigger inputs to synchronize the camera system to an industrial process. The frame grabber is realized as a bus master adapter.

The camera head contains the close-to-sensor electronics and some standard packages. Fig. 3 represents the block diagram of the camera head. The layout is the same for all applicable IR focal plane arrays. Only the optic unit, the sensor PCB and the cooler/chopper PCB have to be adjusted to the special sensor used.

An IR optic images the object radiation onto the sensor array. There are various lens systems available with focal lengths, e.g. 12 mm, 18 mm, 32 mm and 37 mm, respectively. They allow the irradiation of large sensor arrays with diagonal dimensions of 13 mm up to 20 mm.

The sensor array transforms the infrared radiation into a serial electrical signal. It is supplied with various low-noise direct voltages and several clocks which are closely generated on the sensor PCB. The sensor output signal has to be adjusted to the ADC input range. Thus, the sensor PCB contains low-noise clock drivers, low-noise DC supplies, sensor-specific electronics, a pre-amplifier and the analog-to-digital converter (ADC). The ADC determines the maximum pixel rate, which is 10 MHz for a conversion width of 16 bits.

Fig. 2: Camera head

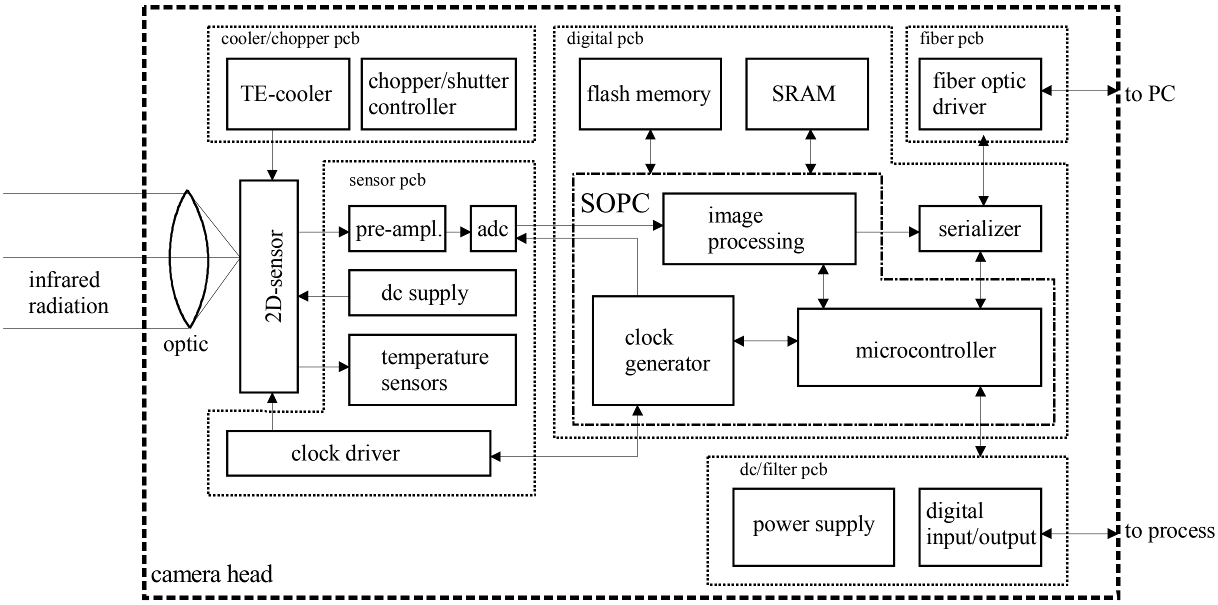

Fig. 3: Block diagram of the camera head

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The digital PCB is based on a System of Programmable Chip (SOPC) solution using a PLD with an embedded processor. This allows an inexpensive adaptation to different sensor types and various industrial applications by re-programming the PLD. The PLD fulfills the tasks of a clock generator and a microcontroller and executes the signal processing. The microcontroller task controls and monitors the camera head. Among other functions it monitors the operation of the chopper/shutter motor and internal temperature sensors. It can also be used to control various functions, such as triggering or frame rate. Two trigger inputs – frame trigger and single trigger – are included to synchronize the camera system to an industrial process. The single trigger starts the recording of a single image. The frame trigger starts a set of images, where each separate image could be additionally released by the single trigger. Without triggering, the camera operates at its maximum frame rate.

The PC communicates with the microcontroller via an asynchronous interface. A serializer, a flash memory and a SRAM are the other essential components of the digital PCB. Fig. 4 shows a fabricated digital PCB.

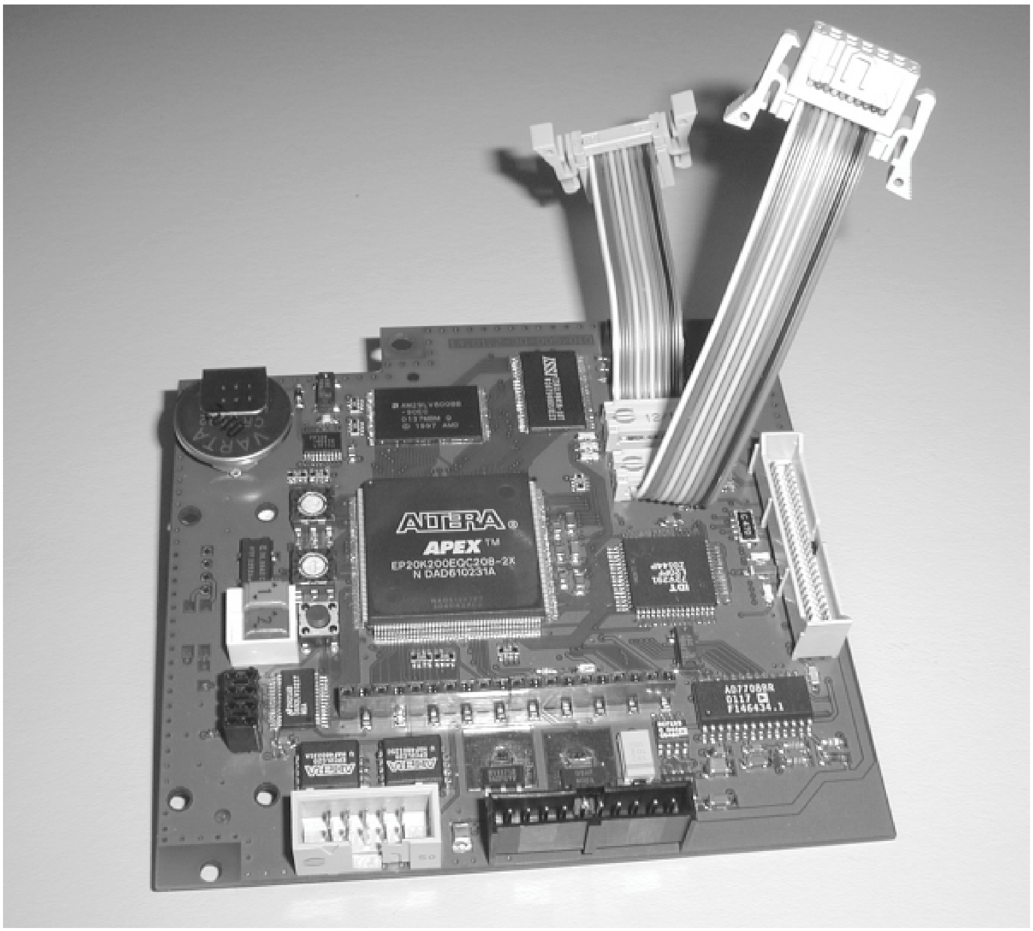

Fig. 4: Digital PCB

A DC/DC PCB for the power supply, the thermo-electric cooler and the controller for chopper or shutter motor, respectively, are additional components of the camera head.

The data communication to the PC is serial. All in all, three bytes, two data bytes and one control byte are communicated. The bytes are fed to a 10:1 serializer one at a time. Two bits are used as control information. Only the asynchronous interface signal for the microcontroller is transferred from the PC to the camera head.

3 Dynamic Range

In addition to the well known demands on IR camera systems such as high responsivity, high spatial resolution and low NETD values, industrial applications usually require large measurement temperature ranges. Therefore, a sufficient dynamic range is an essential condition for an industrial use.

The dynamic range is defined as the ratio between the maximum signal and the minimum resoluble signal:

$$DB\,[dB] = 20 \cdot \log \frac{\text{maximum signal}}{\text{minimum resoluble signal}} \,. \tag{1}$$

Both the maximum and minimum signal can be quantified by including the irradiance E. The minimum resoluble signal is then the amount of irradiance which corresponds to the effective noise value. The noise of IR cameras is usually transformed to the system input and expressed by the NETD value. For a given NETD the dynamic range amounts to:

$$DB = 20 \cdot \log \left| \frac{E\,(T_{Obj})}{NETD \cdot \partial E \,/\, \partial T_{Obj}} \right| \,. \tag{2}$$

Presuming a constant NETD value, the dynamic range is independent on the detector area and the *f*-number.

Fig. 5 represents the influence of the dynamic range on the maximum measuring temperature for different spectral responsivities and NETD values. The represented curves were calculated for a chopped IR camera system with an *f*-number of 1.0 and a pyroelectric detector which responds only to alternating irradiation. The chopper temperature is 35 °C. All emittance and transmittance values are assumed to be in unity. The detector responsivity is assumed as wavelength independent within the chosen spectral range and the system noise is assumed as signal independent. The calculation for a camera system based on a microbolometer array with blind reference bolometers yields similar results. Fig. 5 shows that measuring ranges of a few 100 °C already result in remarkable high dynamic ranges.

In the presented camera system the analog sensor output signal is digitized with a 16bit resolution to achieve a high dynamic range. Owing to its noise and nonlinearity, the real dynamic range of the ADC is lower than the theoretical one of 96 dB. Available fast 16bit ADCs have an effective number of bits (ENOB) of about 14 which corresponds to an effective dynamic range of 84 dB. The effective dynamic range will be reduced due to signal offsets between the pixels and the signal drift owing to internal temperature changes. Assuming a summarized signal offset of 10000 LSB, the effective dynamic range would drop from 84 to 76 dB. Table 1 shows calculated values of measurement temperature ranges for different spectral ranges, NETD values and the mentioned dynamic ranges of 76 dB and 84 dB, respectively. The nominal measuring ranges can be increased by reducing the system gain which again will cause higher system NETD values.

The investigations underline that IR camera systems with NETD values below 0.1 K require a signal processing unit with at least 16 bit resolution to get practicable measuring ranges for industrial applications.

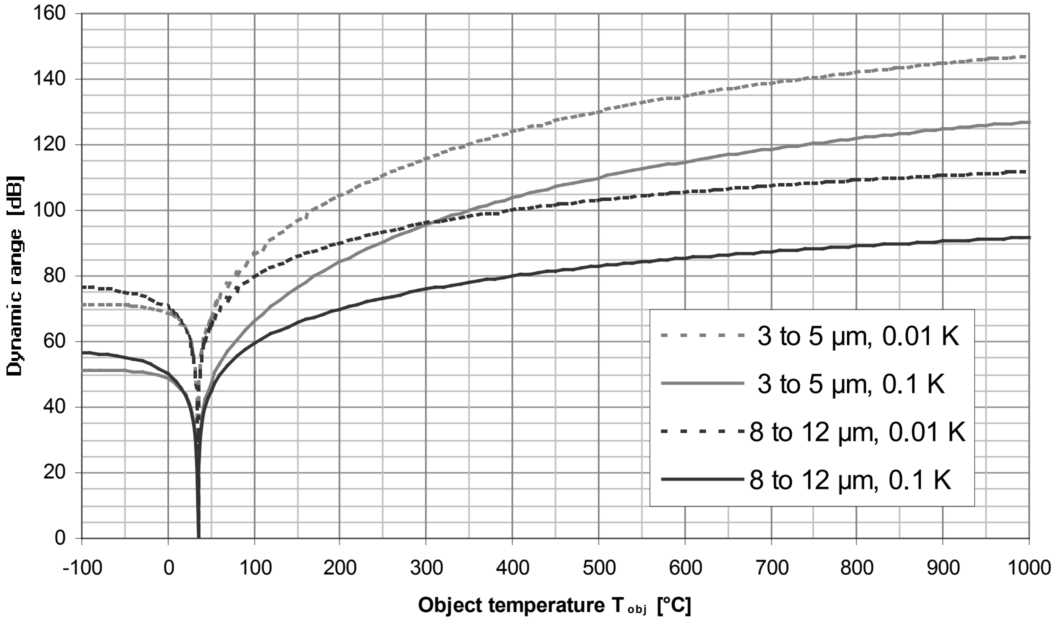

Fig. 5: Required dynamic ranges for different spectral responsivities and NETD values

System parameter		Measurement temperature ranges			
Spectral range	NETD	for 84 dB		for 76 dB	
3 to 5 µm	0.1 K	0 to 195 °C	35 to 200 °C	0 to 145 °C	35 to 150 °C
8 to 12 µm	0.1 K	0 to 530 °C	35 to 550 °C	0 to 290 °C	35 to 300 °C
3 to 5 µm	0.01 K	0 to 85 °C	35 to 90 °C	0 to 55 °C	35 to 65 °C
8 to 12 µm	0.01 K	0 to 115 °C	35 to 135 °C	0 to 60 °C	35 to 80 °C

Table 1: Nominal temperature ranges for dynamic ranges of 84 dB
(16 bit ADC with ENOB=14) and 76 dB (considering signal offsets)

4 Realized Systems

Four different prototypes of the camera system have been built and tested so far (Fig. 6). The PYROVIEW 256 is based on a pyroelectric array with 256 × 128 pixels and a pitch of 56 µm. The radiation flux is chopped at 50 Hz. Fig. 7 shows a detail of the sensor assembly. The standard lens at 8 to 14 µm has an f-number of 1.0, a focal length of 18 mm and a field of view of 43 × 23 degrees. Other spectral ranges for this camera type are possible too, e.g. in Fig. 6 a borescope-optic for 3.9 ± 0.1 µm wavelength. The PYROVIEW320 contains a 320 × 240 - element microbolometer array with a 51 µm pitch. The cold shield requires another lens system with a large focal distance of 32 mm, an *f*-number of 1.4 and a field of view of 29 × 22 degrees. The microbolometer camera operates with a shutter to compensate the pixel offsets and to reduce the influence of the internal temperature. The shutter can be synchronized to an external process. This camera has an NETD of about 0.15 K at 30 °C and a maximum frame rate of 50 Hz.

Compared to the pyroelectric camera system, the microbolometer camera shows significantly higher signal offsets between the pixels and a larger signal drift caused by internal temperature changes. The pyroelectric detector responds only to alternating irradiation and reacts therefore only to irradiation differences between the opened and closed chopper. The main disadvantage of a pyroelectric array is the necessity of a mechanical chopper. The electronic control of a chopper motor is more difficult than that of a shutter and the chopper operation causes additional noise. Meanwhile the chopper motor does not cause any long-time stability problems.

Two fast IR-line cameras were developed besides the uncooled 2D cameras described above. The line camera HZK 256 contains a 256-element linear InGaAs-array. This device runs without a chopper at frame rates of 5 kHz. The detail of the detector assembly is shown in Fig. 8. The HZK 256 is preferably used in online temperature measurement of brake disks. The line camera with InGaAs-photodiode arrays can also be used for material identification on fast moving samples by applying the Near Infrared Analysis (NIRA). In this application field the detection of contamination of polypropylen and polyethylen in raw cotton was successfully tested[3,4]. A fast uncooled camera with a 256 element linear pyroelectric array[5] was developed as an additional device. This version of the camera line PYROLINE 256 / MikroLine M2256 operates with an internal chopper frequency of 512 Hz.

Table 2 provides an overview of important technical data for the four camera types. The described high-speed version of the line PYROLINE 256 / MikroLine M2256 with 512 Hz maximum frame rate completes the spectrum of the already existing line cameras. All currently provided line cameras are shown in table 3. With the exception of version PYROLINE 256/512Hz / MikroLine M2256/512Hz, all units are equipped with a DSP for signal processing. This kind of signal processing enables a stand-alone operation without a computer connected at all times. The standard frame rate was increased from 128 Hz to 256 Hz, a difference from earlier discussed line cameras[6].

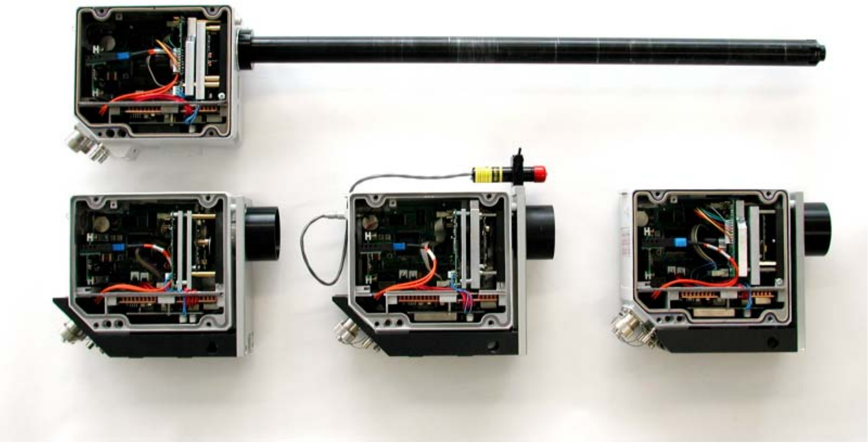

Fig. 6: IR cameras PYROVIEW 256 (on the top), PYROVIEW 320 (below, left), HZK 256 (below, middle), and PYROLINE 256/MikroLine M2256 (below, right), respectively

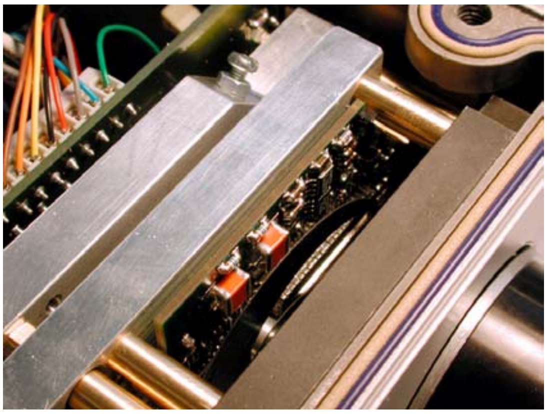

Fig. 7: Detail of the IR 2D camera IR camera HZK 256

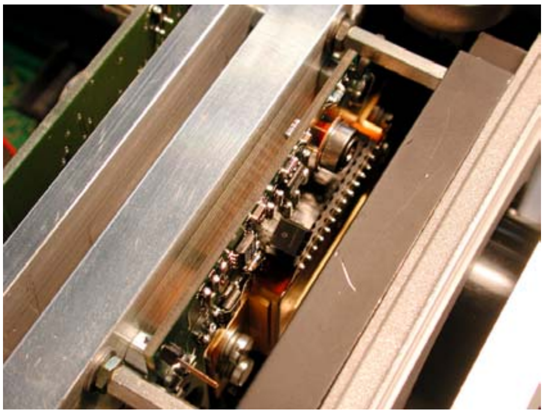

Fig. 8: Detail of the high-speed line PYROVIEW 256

Type	PYROVIEW 256	PYROVIEW 320	HZK 256	PYROLINE 256L/512Hz MikroLine M2256/512Hz
Detector	pyroelectric array (256 x 128)	microbolometer (320 x 240)	InGaAs array (256 x 1)	pyroelectric array (256 x 1)
Spectral range[a]	8 to 14 µm	8 to 14 µm	1.4 to 1.8 µm	8 to 14 µm
Measurement temperature range[a]	0 to 350 °C	–20 to 120 °C (0 to 500 °C)	250 to 900 °C (3 ranges)	100 to 800 °C
Aperture[a]	43° x 23°	29° x 22°	20° x 0.15°	40° x 0.3°
Spatial resolution (> 50 % modulation)	3 mrad	1.5 mrad	1.5 mrad	3 mrad
Measurement distance	10 cm to infinity	50 cm to infinity	50 cm to infinity	10 cm to infinity
Accuracy[b]	2 K up to 100 °C or 2 % of true value	2 K up to 100 °C or 2 % of true value	2 % of true value	2 % of true value
NETD[b]	< 0.3 K (30 °C, 25 Hz)	< 0.15 K (30 °C, 25 Hz)	< 0.5 K (300 °C)	< 0.5 K (32 Hz)
Max. frame rate	50 Hz	50 Hz	5000 Hz	512 Hz
Interface	fiber optic / PCI-card			
Digital inputs (trigger) Digital output (alarm)	2 x unsymmetrical 2 x optically coupled, electrically isolated open-collector outputs			
Connectors[c]	round connector with thread interlocking (16 pins) interlocking fiber optic- connector (2 fibers) water supply tubing (nominal width 4 mm, 2 bar max) compressed air tubing (nominal width 4 mm, 2 bar max)			
Housing	IP65, optional with integrated water cooling system, air purge, swivel base			
Weight	ca. 3.2 kg			
Supply voltage	18 to 36 V DC / 10 to 20 VA			
Operating temperature	camera: 0 to 40 °C, 0 to 120 °C (with water cooling) system cable: –25 to 150 °C fiber optic: 0 to 70 °C			
Storage condition	–20 to 70 °C, relative humidity 95 % max			
Software	computer control and display program for Windows ®			

[a] different on request

[b] black body, ambient temperature 25 °C

[c] depending on configuration

Table 2: Selected technical data of different IR cameras for industrial temperature measurement

Table 3: Overview IR line cameras PYROLINE / MikroLine

Model	Format	f_{max}	Spectral range [µm]				Measuring range						Lens	
	X × Y	Hz	LWIR	MWIR	Glass	NWIR	Standard / °C	NETD / K		Optional / °C	NETD / K		Standard	Optional
			8 to14	3 to 5	4.8 to 5.2	1.4 to 1.8		32 Hz	f_{max}		32 Hz	f_{max}	° FOV	° FOV
Standard:														
PYROLINE 128L MikroLine M2128L	128 ×1	256	×				50 to 550	0.5	1.5	0 to 80	0.2	0.5	40	60
PYROLINE 128M MikroLine M2128M	128 ×1	256		×			450 to 1250	0.5	1.5	200 to 800	0.5	1.5	60	40
PYROLINE 128G MikroLine M2128G	128 × 1	256			×		450 to 1250	1	3	250 to 1250	1	3	60	40
PYROLINE 128N MikroLine M2128N	128 × 1	256				×	600 to 1300	1	3				60	20
PYROLINE 256L MikroLine M2256L	256 × 1	256	×				50 to 550	0.5	1.5				40	60
PYROLINE 256M MikroLine M2256M	256 × 1	256		×			450 to 1250	0.5	1.5				60	40
PYROLINE 256G MikroLine M2256G	256 × 1	256			×		450 to 1250	1	3				60	40
PYROLINE 256N MikroLine M2256N	256 × 1	256				×	600 to 1300	1	3				60	20
Option: sensitive														
PYROLINE 128L/128Hz MikroLine M2128L/128Hz	128 × 1	128	×							0 to 80	0.1	0.2	40	60
Option: fast														
PYROLINE 128L/512Hz MikroLine M2128L/512Hz	128 × 1	512	×				50 to 550	0.5	2	0 to 80	0.3	1	40	60
PYROLINE 256L/512Hz MikroLine M2256L/512Hz	256 × 1	512	×				100 to 800	0.5	2				40	60

5 Conclusion

A new stationary IR camera system designated for uncooled high-performance focal plane arrays was developed. The realized prototypes show high resolution and sensitivity values which allow its use for sophisticated commercial measuring tasks.

The camera system is especially suited for the most different applications in the field of non-contact temperature measurement. The system is designed in such a way that its behavior will be kept constant regardless which kinds of sensors and which wavelength ranges have been chosen.

Acknowledgements

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