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Thermal camera system integrated into firefighter helmet

Abstract

The paper presents a firefighter helmet with integrated thermal camera system, OLED display, sensors for monitoring the vital signs of a firefighter-rescuer and communication system for transmitting such data as live thermal video streaming, body temperature, heart rate and ambient temperature. The developed helmet, apart from its typical function as personal protection device against threats associated with firefighter's work, also provides enhanced capability of carrying out rescue missions in low-visibility scenarios, thus increasing the safety of a firefighter itself.

Keywords: thermal camera, observation system for a firefighter, firefighter helmet.

1. Introduction

Recent development in infrared technology and thermal imaging has brought about new applications of thermal cameras in numerous (and still growing) areas of science, technology and even every day's life. Nowadays thermal cameras can be found not only in military equipment [5], law enforcement, medicine [8] or scientific research [6] but also in many more areas of human activity such as automotive industry, security, surveillance and industrial process monitoring systems.

Thermal camera forms an image from infrared radiation originating from observed, visualized objects. Thermal camera consists of several main functional modules, such as: infrared focal plane array (IR FPA) [4], infrared objective lens, electronic circuits to read-out FPA signals, record, process and analyze them. [7, 9]. There are many factors influencing the operation of a thermal camera [1, 2, 3, 9]. In order to assess the overall quality of a particular device, several parameters must be determined and measured, including sensitivity, non-uniformity of an FPA and noise equivalent temperature difference NETD.
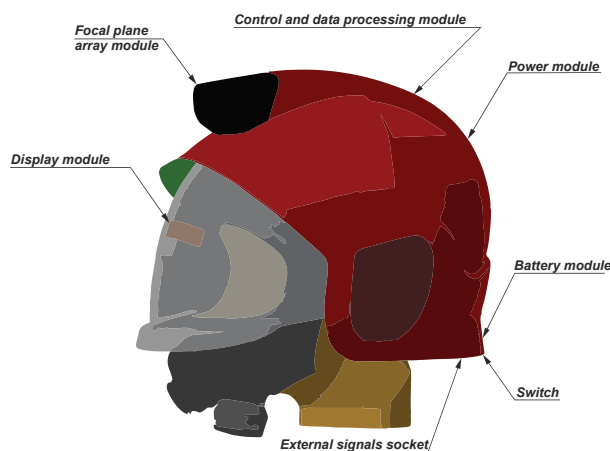

Fig. 1. Placement of electronic modules inside a helmet structure

Firefighter helmet, developed in the frame of a project conducted by a scientific and industrial consortium (Military University of Technology, Central School of the State Fire Service, MASKPOL Inc.) is an innovative product aimed at increasing the personnel safety during fire and rescue operations. Apart from protecting the firefighter's head, its set of sensors effectively increases the effectiveness of a fire and rescue operation e.g. by providing enhanced vision capability in smoky or poorly lit areas through infrared imagery. In the frame of a project a working prototype of a helmet has been developed, with integrated electronic modules, including: observation thermal imaging camera, vital signs sensor monitoring and OLED near eye display. Fitting the data link socket into the helmet will provide the connection between a firefighter and the officer coordinating fire and rescue operations. The placement of particular electronic modules of the developed sensor system inside a helmet structure is shown in Fig. 1.

Thermal camera has been developed using latest generation of uncooled, microbolometer FPA module made of amorphous silicon. This particular array of infrared detectors has a resolution of 384×88 pixels with a pixel pitch of 17 μm. Electronic circuits, optical and mechanical components of the developed camera have all been designed using state-of-the-art technologies, which resulted in size and weight reduction as well as low power consumption of the camera with all required functionalities retained.

2. Design of the thermal imaging system integrated into firefighter helmet

Observation thermal imaging system fitted into helmet structure consists of the following main modules: FPA module, connection and control module, control and data processing module, display module, vital signs sensor module, power module, battery module. Block diagram of the entire thermal imaging system with all main modules and connections is presented in Fig. 2.
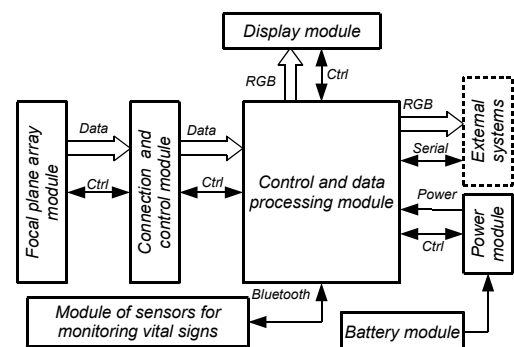

Fig. 2. Block diagram of thermal imaging system divided into main modules

FPA module is one of the key components of the thermal camera, as it detects incoming infrared radiation (in this case in LWIR wavelength range). Main elements in this module are an FPA microbolometer array detector with its power supply, bias voltages circuits and coupling circuits for analog and digital signals. Block diagram of an FPA module is shown in Fig. 3.
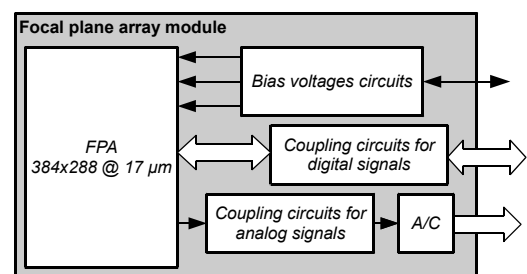

Fig. 3. Functional block diagram of an FPA module

Observation thermal camera mounted in an innovative firefighter helmet utilizes a Pico384 Gen2 FPA array supplied by ULIS company. The array is the main transducer converting infrared radiation into electric signals. This infrared detector consists of an array of uncooled pixel detectors made from amorphous silicon with read-out circuit (ROIC) integrated into the same silicon structure. The array provides analog output as well as digital one, through integrated internal A/D conversion.

Active element of a single pixel detector consists of a membrane made of amorphous silicon, covered with absorber layer [4]. Detector is a 3D microelectromechanical structure (MEMS). Its part responsible for the detection of infrared radiation is physically insulated from the other components, including its casing. As a result absorber and temperature sensor are thermally insulated from the remaining components of the array circuit. Each bolometer (pixel) is connected to ROIC circuit, which converts bolometer resistance into proportional voltage signal. Proper operation of such a detector type (ability to obtain good temperature resolution and low noise figures) requires a low-noise power supply which complies with manufacturer's requirements [1, 2, 3, 4].

All of the electronic components of the thermal camera, with the necessary low-noise power supply circuits have been placed on a single printed circuit board (PCB) and mounted in a casing together with a shutter module (which enables the calibration of the unit). CAD project of the developed camera and real-life photo of an assembled unit are shown in Fig. 4, and Fig. 5.
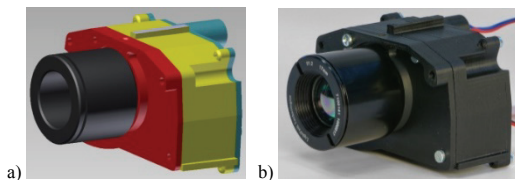

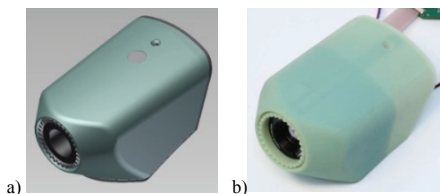Fig. 4. CAD project (a) and photo (b) of the developed and manufactured thermal camera

Fig. 5. CAD project (a) and photo (b) of the developed and manufactured thermal camera inside outer cover , prior to mounting on top of the helmet

Control and data processing module is the most technologically advanced component of the presented system. Its task is to control all of the elements of the system as well as data acquisition and processing, especially thermal imaging data and those from vital signs sensors. Main components of control module are: FPGA device, microprocessor system and communication interfaces. Basic tasks performed by a control and data processing module are [7]: control of the FPA module in order to read-out signal values from all bolometers (pixels), non-uniformity correction of FPA pixels [1, 2, 3, 9], bad pixel replacement [3], interfacing display module. In addition the module provides connection to external systems through communication interfaces, among others it manages data acquisition from vital signs sensors via wireless communication link. Block diagram of control and data processing module is depicted in Fig. 6.

Control and data processing module is built using two main electronic chips: FPGA device and a microcontroller chip. FPGA device performs tasks requiring considerable computing power, such as processing of image data. It is responsible for the generation of signals controlling the FPA read-out process and also performs non-uniformity correction, bad pixel replacement

and generates signals for the display module. Microcontroller, in turn, performs all of the control functions for the electronic components integrated into innovative firefighter helmet.
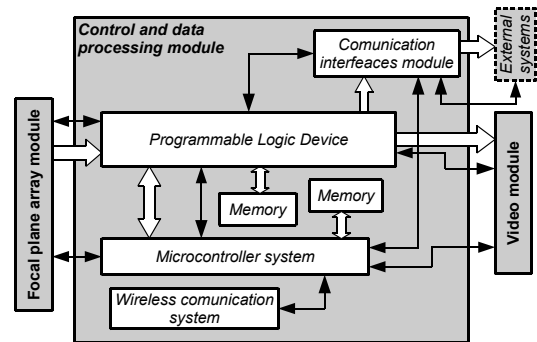

Fig. 6. Block diagram of a control and data processing module

Microprocessor used in control and data processing module is a STM32F437 chip produced by STMicroelectronics, a member of Cortex-M4 family of 32-bit processors, with low power requirements and abundance of peripheral resources.

FPGA device of choice is EP4CGX30 chip produced by ALTERA, from Cyclone VI family. It combines required computing capability with relatively low power requirements. Several functional modules have been implemented in FPGA device for real-time processing of thermal image data. Those are FPA readout module, NUC module, bad pixel replacement module, image processing module and image visualization module. Photos of control and image processing module (consisting of two PCBs: Digital signal processing module and wireless communication system module are shown in Fig. 7.
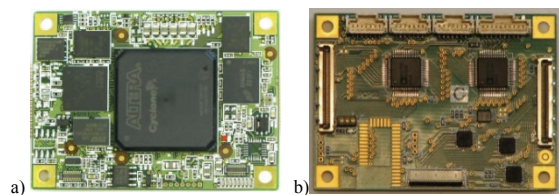

Fig. 7. Photos of control and image processing module: digital signal processing module (a) and wireless communication system module (b)

Another technologically advanced component of the presented system is an infrared objective lens for LWIR spectral range ($8 \div 12$ μm). Advanced design is necessary to achieve such features as low f-number, high transmission, small overall dimensions, low weight and wide range of operating temperatures. Additionally, aberrations should be well corrected in the optical system and the circle of confusion should be smaller than FPA pixel pitch (17 μm).
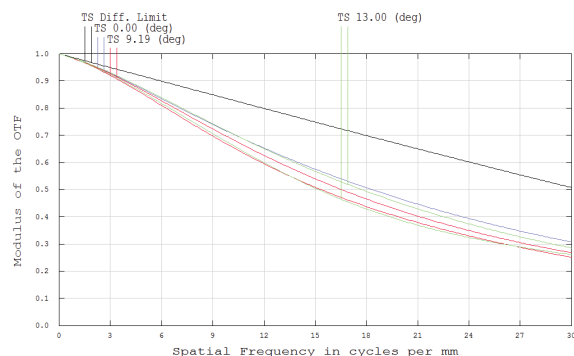

Fig. 8. MTF function for the designed lens

As a result innovative design solutions and materials have to be applied to achieve desired performance figures of the designed camera lens. That included the use of germanium infrared aspherical optical elements in the proposed optical system, which also reduced the number of refractive elements (and also resulted in smaller, lightweight design). Presented objective lens has the following parameters: field of view: 22°×17°, f-number: 1.2, FPA size: 384×288, pixel pitch:17μm, focal length: 17 mm, athermalization range: from -40°C to 60°C.

Lens design has been verified using ZEMAX software. Modulation transfer function MTF calculated for the designed lens are presented in Fig. 8.

Innovative helmet design introduces the capability to view the surrounding scenery using thermal camera and monitors the firefighter's vital signs. Thermal camera image and other information must be presented in a way not hindering firefighter's actions during fire and rescue mission. It was achieved by designing near-eye display module mounted on moveable arm, which can be lowered to the eye level when needed or easily hidden inside helmet structure. The module utilizes OLED microdisplay with the resolution of 800 × 600 pixels, produced by eMagin corporation.

Near-eye display located between a mask and face protection shield requires additional optical system – an eyepiece. It is an optical system consisting of a lens and a mirror which makes it possible for an human eye to see an image displayed at close distance. Design concept of an eyepiece is schematically presented in Fig. 9, whereas the CAD project and real photo of assembled module is shown in Fig. 10.
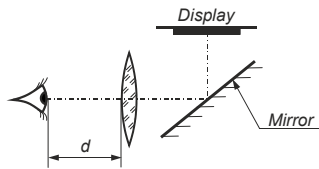

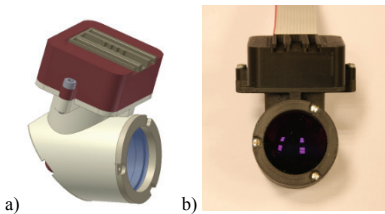Fig. 9. Elements of an eyepiece

Fig. 10. Project (a) and photo (b) of the assembled module with OLED display, ready to be mounted inside the helmet

Temperature in close proximity is a crucial information and one of the most important physical quantities for a firefighter, allowing to recognize possible life-threatening situation. Ambient temperature in close proximity is measured using HEL-707 sensor produced by Honeywell.
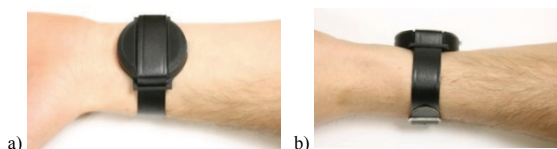

Fig. 11. Photos of the wrist-wearable vital signs sensor module

Sensor was placed in the upper part of a helmet shell to measure the temperature above firefighter's head. Applied sensor is capable of temperature measurements from -75°C to 540°C with accuracy of 0.5°C.

Vital signs sensor module is a complementary element of the helmet-mounted system. It monitors heart rate and body surface temperature of a firefighter. Because those specific measurements require different sensor location, it constitutes a separate, wrist-wearable element of the system. It is an autonomous microprocessor system, connected to the main unit via wireless data link.

Heart rate is measured using photoplethysmography (PPG), one of the optical heart rate monitoring methods. In PPG method blood flow changes are monitored by an optical sensor, consisting of a light source and a photodetector. There are two variants of this method – one uses light signal transmitted through a tissue whereas the other utilizes reflected light. In the presented system a reflection photoplethysmography sensor was applied as it can be used more comfortably. The body (skin) temperature is simultaneously measured in the same spot where the heart rate sensor is located. The developed, wrist-wearable vital signs sensor module is shown in Fig. 11.

A prototype helmet was made in the frame of the project in order to visualize all the system components and integrate electronic modules into the helmet structure. Firefighter helmet was designed in such a manner that its normal use in fire and rescue missions (including the usage of breathing apparatus) is not hampered by all those additional components installed in it. CAD project and physical model of innovative helmet with all electronic components included are presented in Fig. 12.
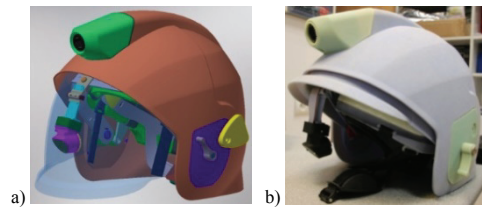

Fig. 12. CAD project (a) and real photo (b) of the developed model of innovative firefighter helmet with all integrated electronic modules

3. Testing of the prototype firefighter helmet

Developed helmet system contains many mechanical, optical and electronic components. Main electronic modules: FPA, display and control and data processing circuits are connected by a special multicore cable, which is capable of fast data transmission and provides adequate shielding against electromagnetic interferences.
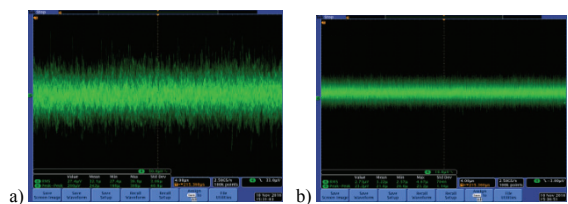

Fig. 13. a) Sample oscillograms for RMS noise for GSK voltage (2 Hz ÷ 1 MHz), b) RMS noise for VBUS voltage (2 Hz ÷ 100 Hz)

Developed camera module has been put through extensive laboratory testing, in order to verify its properties. Noise tests were conducted using MSO 4104 oscilloscope (Tektronix) fitted with differential preamplifier model ADA400A. The measurements of noise components for all voltages supplying the FPA were conducted with all necessary elements switched on, notably after the proper programming of D/A converters (via control and data processing module) outputting GFID and GSK polarizing voltages. Sample noise oscillograms recorded during measurement session are shown in Fig. 13, whereas Tab. 1

contains RMS noise values measured for all FPA supply voltages in analyzed noise frequency bands.

The measurements of basic parameters of the thermal camera mounted in firefighter helmet have been conducted at the Institute of Optoelectronics of Military University of Technology. Test stand METS-S-12 used for the camera testing consists of an IR radiation standard source with its control unit, rotary test wheel, IR collimator and computer with video grabber card and test software (Fig. 14).

Tab. 1. RMS noise values measured for particular FPA supply voltages

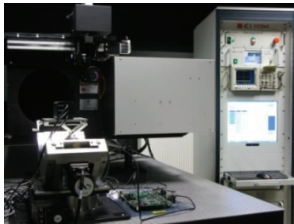| Noise band	RMS noise value [µV]			
	VDDA	VBUS	GFID	GSK
1 Hz ÷ 1 kHz	0.83	2.63	1.85	1.83
1 Hz ÷ 10 kHz	0.69	1.70	3.62	2.91
1 Hz ÷ 10 MHz	22.66	28.36	35.40	29.21

Fig. 14. Photo of a test stand for the measurement of IR camera parameters (accredited laboratory IOE MUT)

Test stand depicted in Fig. 14 was used to determine the following characteristics of the helmet-mounted camera: modulation transfer function MTF, signal transfer function SiTF, minimum resolvable temperature difference MRTD.

Tab. 2. Determined IR camera parameters

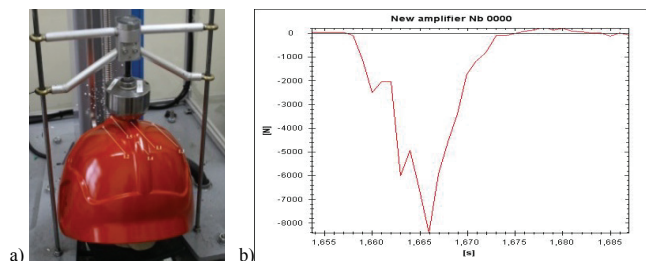| Parameter	Value
Pixel noise	810 µV
NETD	62.6 mK
Sensitivity	8.6 mV/K
Image non-uniformity (std/mean)	0.044

Fig. 15. a) Firefighter helmet during shock absorption and penetration tests,
b) sample plot of recorded impact force versus time

Firefighter helmets are health and life protection devices and as such must conform to several regulations and standards (e.g. EN 443:2008), thus appropriate testing of the prototype have to be conducted. Particularly firefighter actions performed in smoky and dark conditions were verified as well as tests of the helmet itself regarding impacts, shock absorption, penetration, heat resistance and the like. Helmet exhibited adequate protection level in all tests performed. Test stand for checking the mechanical strength of the innovative firefighter helmet is shown in Fig. 15.

4. Summary

As a result of research and construction work in the frame of the realized project the thermal camera has been developed, integrated with firefighter helmet. Additionally a sensors module for the monitoring of firefighter's vital signs has also been created. The wrist-wearable sensors record body temperature and heart rate and transmit data to the main unit inside a helmet structure via wireless data link. Electronic system integrated with the helmet has a built-in interface for relying the thermal video data and sensor readings to external devices.

Developed prototype model of the helmet with integrated thermal camera, vital signs sensors and near-eye OLED display has been tested both in the laboratory and in simulated rescue mission scenarios. Test results proved that the expected technical specifications of both the helmet structure and integrated electronic components have been achieved and the proper operation of a system as a whole during rescue mission conditions has been confirmed. The production is expected at the end of 2018.

5. References

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