

A method for automatic gas detection using wide-band 3-14 μm bolometer camera

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Abstract

Recently, the wide-band 3-14 μm high sensitive VOx bolometer detectors have been developed. Based on such detector, a new camera was designed and fabricated, mainly for industrial gas leakage detection. NETD of the camera is below 35 mK at 30 Hz frame rate. In order to detect gases, a novel image processing method was developed. It uses the *Gaussian Mixture-based Background Segmentation* model together with *Structural Similarity Index* and histogram comparison using Bhattacharyya distance. The software was written using Java language with OpenCV library.

The examples of the detection results are presented for ammonia, propane-butane and methane. One should notice that due to the lower sensitivity of bolometers in contrast to cooled, photon sensors, the detection of methane and other hydrocarbons is much more difficult using bolometer cameras. Fortunately, methane has 2 absorption lines in MWIR and LWIR bands. This is the unique feature and advantage of using wide-band bolometer camera for industrial applications.

1. Introduction

Industrial gas detection became a new application for thermal cameras today [9]. Due to the chemical structure of the gases and their concentration in atmosphere, absorption of light varies in the different wavelength ranges of the electromagnetic waves. This is a well-known phenomenon widely used in spectrophotometry. The infrared camera for gas detection is different comparing to a classical thermal camera for temperature measurements. First of all, such cameras are typically equipped with one or more band pass optical filters corresponding to the absorption characteristics of chosen gases. In some cases, the interference filters are cooled down to reduce its own radiation of the wavelength the detector is sensitive to. In consequence, the cooled filters can improve the sensitivity of the gas detection. Almost all available thermal cameras for gas detection are the cooled and photon ones. It makes IR system extremely expensive, heavy with relatively short time of continuous operation due to the high-power consumption [8,9].

As all know, due to the progress in semiconductor technology, the uncooled bolometer IR cameras are more and more sensitive today. Moreover, there are already available bolometer detectors for wide-band 3-14 μm wavelength spectrum range based on VOx technology [8]. Using such detectors, one of the first wide-band uncooled cameras has been recently developed and tested in the industrial environment [10,11]. Dedicated software was prepared for this camera to be used as typical thermal camera for temperature measurement and in addition, for gas detection.

2. Broad-band 3-14 μm bolometer camera

Thermal detector technology is in rapid progress today. There are 2 main massively produced bolometers: based on amorphous silicon (α -Si) and vanadium oxide (VOx). The thermal sensitivity of VOx is slightly better reaching $\alpha = dR/dT > 5\%/\text{K}$. The most sensitive resistive bolometers are now made from vanadium oxide. The latest achievement in VOx technology announces 17 μm-pitch detector with NETD < 22 mK [8]. With such sensitivity it is possible to make wide-band microbolometer detector operating in 3-14 μm spectral range. One should bear in mind that for low-temperature objects (e.g. in room temperature) in MWIR spectral range, the intensity of radiation is much lower comparing to LWIR band. In microbolometer's focal plane arrays, due to the thermal insulation, the sensor matrix is hanging over the substrate. It forms the optical cavity resonator inside the detector, and in consequence, the spectral characteristic of any bolometer sensor has the significant attenuation at about 5-6 μm subband (due to the $\lambda/2$ resonance) – fig. 1 [6].

From the theory of standing waves, one can estimate the intensity of radiation for different wavelength at the detector position if the mirror is at the distance d behind it – eq. (1), fig.1.

$$\frac{I}{I_0} \sim \left[\sin\left(\frac{2\pi}{\lambda}d\right) \right]^2 \quad (1)$$

As one can notice in fig. 1, due to the interference, the minimum of radiation intensity is for the wavelength $\lambda=5 \mu\text{m}$. This estimation neglects thickness of the absorption and active semiconductor sensor layers. If all is taken into account (10 nm Ti absorber, 160 nm semiconductor), the minimum intensity shifts towards ~6 μm wavelength range [6].

In spite of it, wide-band spectral absorption characteristic enlarges the possible applications of the IR systems, especially in industry. It was one of the main reasons to develop a new camera for industrial applications, particularly for gas detection, such as ammonia, methane, carbon oxide, etc., fig. 2 [10,11]. The developed wide-band IR camera VOXgas640 has sensitivity NETD < 35 mK – fig. 2. It is equipped with the motorised wheel for 2 filters and the shutter.



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Using USB 2.0 interface, the sequence of thermal images containing 640x480 pixels can be sent to a computer at the frame rate of 30 Hz. In the case of simultaneous transmission and rendering the preview images, the transfer rate decreases down to 15 Hz. VOXgas640 camera is controlled by the *IRviewer* software for typical thermography application and, in addition for gases' detection.

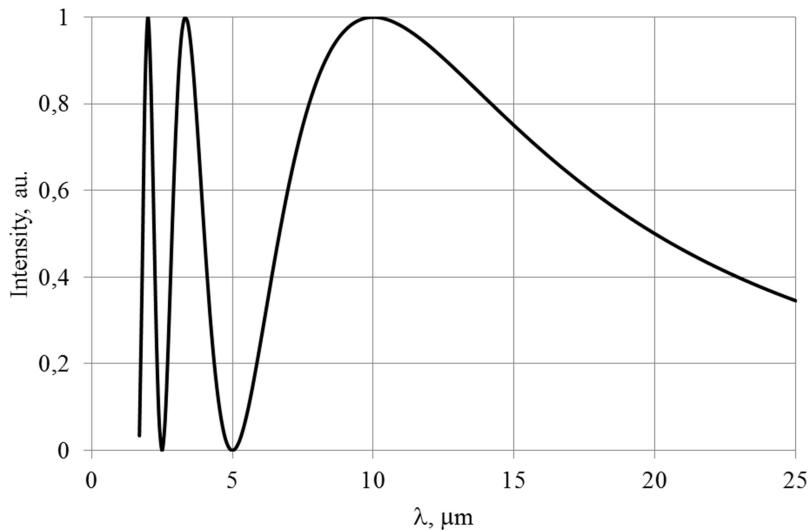


Fig. 1: Theoretical absorption characteristic for 2.5 μm mirror-detector cavity

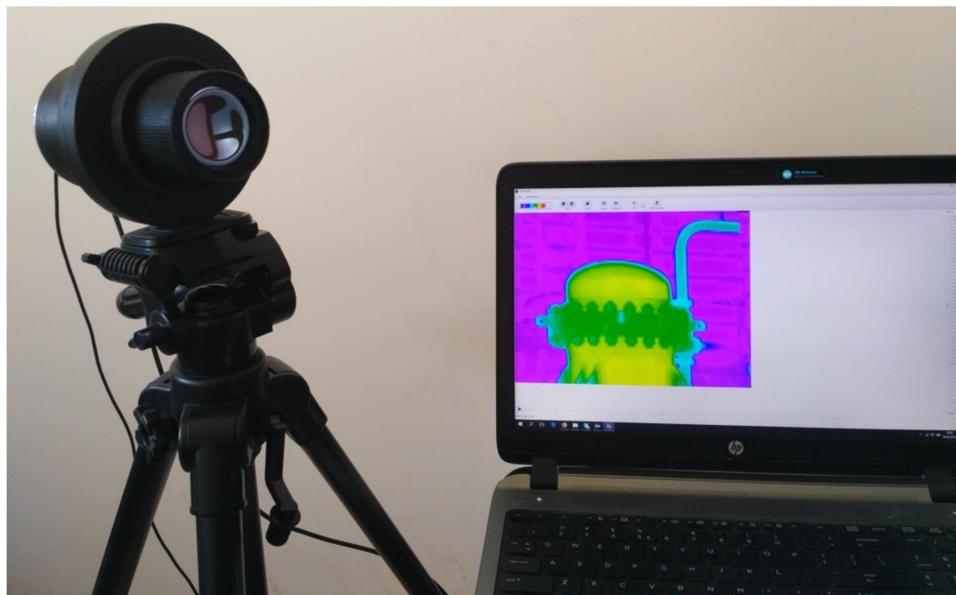


Fig. 2: Industrial, wide-band 3-14 μm , high sensitive bolometer camera

3. A new method and software for gas detection

The algorithm of gas detection is based on the procedures developed and used for movement detection using CCD cameras operating in the visible spectrum of electromagnetic waves. Before starting to work out the method presented in this research, one noticed that the gas is visible in IR images as a weak semi-transparent moving and fluctuating object similar to a cloud. Gas is comparable to a smoke but it is almost fully transparent. Moreover, gas is the moving object of low spatial and temporal frequency in contrast with the noise and other moving bodies located in the field of view of the camera. The key problem to detect a gas is the right background temperature. It is recommended to have the thermal background both stable and uniform. Background should have either lower or higher temperature by at least few degrees Celsius than the observed gas. In general case, it is hard to fulfil such requirements, especially in industry where the background is rather complex and sometimes changeable or even random. Therefore the proposed algorithm should adapt itself to the different environment conditions.

The proposed method of gas detection is presented in fig. 3. One can notice a few main stages of the algorithm.

- Pre-processing by low pass Gaussian filtering for noise reduction.
- Continuous on-line updating of the reference frame - any frame with low level of differences with previous ones calculated by using *Gaussian Mixture-based Background Segmentation*.
- Simultaneous calculation of 3 measures of object movement: *Histogram Comparison Bhattacharyya Distance*, *Structural Similarity* and *Difference of Images Indexes*.
- Final decision of gas leakage using conjunction criterion based on actual and reference images comparison.

At first, every frame is filtered using low-pass *Gaussian blur filtering* [1,2] with standard deviation $\sigma = 5$ and 9x9 mask. It reduces the influence of noise and small artefacts that can affect the final gas detection. One has to bear in mind that bolometer cameras have the higher value of *NETD* and noise level. During the gas detection, typical span of the camera is low, and in consequence, noise has its significant impact on the results of processing.

Next step is the *Gaussian Mixture-based Background/Foreground Segmentation* to select the reference images being later compared with all incoming ones [3]. At this stage, the background is removed. The *Gaussian Mixture-based Segmentation* algorithm models each background pixel using a mixture of 3 to 5 Gaussian probability distributions. It allows foreseeing the most probable color or value of the pixel that correspond to non-changing part of the image – the background. The decision that the pixel belongs to the background is taken if the probability values of pixels remain the same or they are very close to each other for a certain number of consecutive frames. This procedure allows updating the reference image during the gas detection. On-line renewing the reference image is necessary because the scene can vary and then remain stable for some time, especially if an alien object (e.g. a person) appears and moves in front of the camera. The criterion for getting the reference image is the low number of pixels (< 5%) that are recognised as belonging to the foreground of an image.

The essential part of the algorithm is based on calculation of 3 measures that characterise the moving object in the sequence of images. It is done by on-line comparing every incoming frame with the reference image. The first comparing feature is based on histograms and uses the Bhattacharyya distance in between them, implemented in *OpenCV* image processing library – eq. 1 [4,7].

$$d(\mathbf{h}_1, \mathbf{h}_2) = \sqrt{1 - \frac{\sum_i \sqrt{\mathbf{h}_1(i)\mathbf{h}_2(i)}}{\sqrt{\sum_i \mathbf{h}_1(i)} \sqrt{\sum_i \mathbf{h}_2(i)}}} \quad (1)$$

where \mathbf{h}_1 and \mathbf{h}_2 are the histograms of the image 1 and 2.

After many experiments with different gases, the criterion to classify the image containing the gas was chosen as $0.03 < d(\mathbf{h}_1, \mathbf{h}_2) < 0.3$.

The second measure is *Structural Similarity Index* of 2 images [5]. Similarity index is a global measure which takes into account the difference of luminance, contrast and structure in the compared images. The simplified form of *Structural Similarity Index* is presented in the form of eq. (2) [2,5].

$$SSIM = \frac{(2\mu_1\mu_2 + c_1)(2\sigma_{12} + c_2)}{(\mu_1^2 + \mu_2^2 + c_1)(\sigma_1^2 + \sigma_2^2 + c_2)} \quad (2)$$

where: μ_1 , μ_2 , σ_1 , σ_2 are the mean values and standard deviations for both images, σ_{12} is the covariance of the images and c_1 and c_2 are the constants that protect SSIM not to exceed very large value if the denominator of eq. (2) is too low.

The gas is assumed to be recognised if $0.7 < SSIM < 0.95$.

The third measure of gas detection is the simple *Image Difference* referring to the subtraction of successive images. After subtraction, the result image is segmented into separated regions (image binarization) by searching the pixels with values within $<100,300>$ range. Next, the program counts the number of these pixels. If this number is lower than half of the overall no. of pixels in the frame, it is assumed that the gas is detected.

The overall method of gas detection using wide-band bolometer camera is presented in fig. 3.

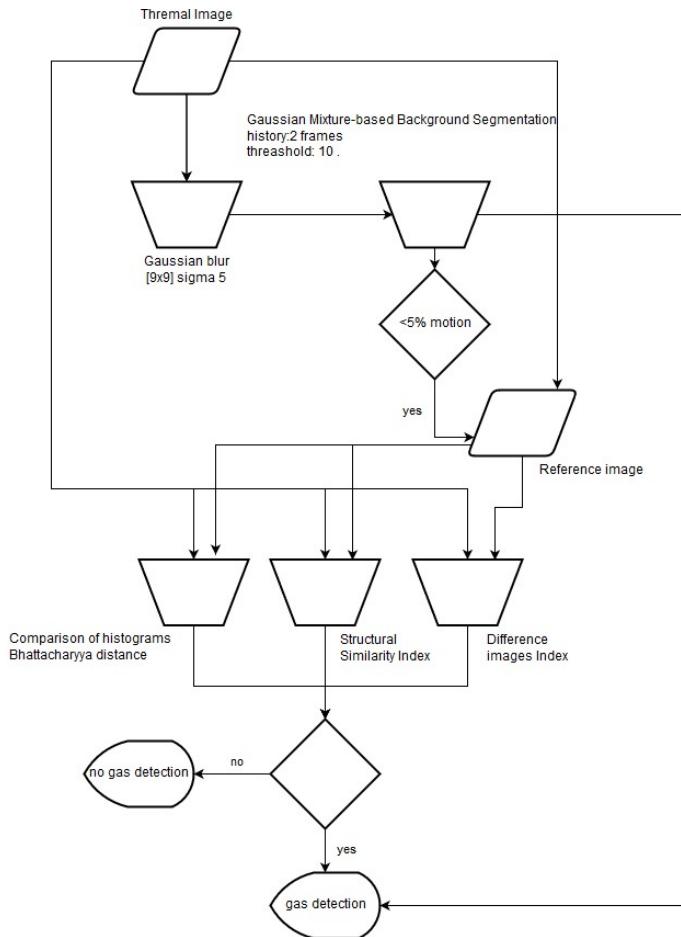


Fig. 3: The method for gas detection using 3-14 μm bolometer camera

4. Exemplary results

The exemplary experiments of the gas detection were performed for 3 gases: ammonia, propane-butane and natural gas with high concentration of methane. Ammonia absorption lines are in *LWIR* spectral range and cover relatively wide spectral range. The main peaks are for about 1800 cm^{-1} (5.6 μm) and 1000 cm^{-1} (10 μm). In addition, there is a small absorption peak at 3400 cm^{-1} (2.9 μm) [12,13].

Methane absorbs the radiation in 2 narrow bands – 3020 cm^{-1} (3.3 μm) and 1300 cm^{-1} (7.7 μm) [13,14]. Most of all hydrocarbons have their absorption lines in *MWIR* range, i.e. 3.2-3.3 μm . These are gases such as: propane, ethane, pentane, butane, octane, heptane, etc.

In fig. 4-6 and 7-9 the images for ammonia, propane-butane and methane are presented. The images in figs. 4 and 7 are the reference ones. The images in figs 5 and 8 are the raw images with the gas. The images 6 and 9 present the segmented part corresponding to the detected gas. In fig. 10, one can see methane leakage from the home gas burner detected by the wide-band camera and segmented by the developed software. As it was already mentioned, the right background temperature is the crucial condition allowing the gas detection. The experiment presented in fig. 10 was performed for the background having temperature about 10°C lower than the ambient and the gas. Using the *IRviewer* software it is possible to superimpose the thermal image with the binary one after background removing using the proposed algorithm – fig. 10.

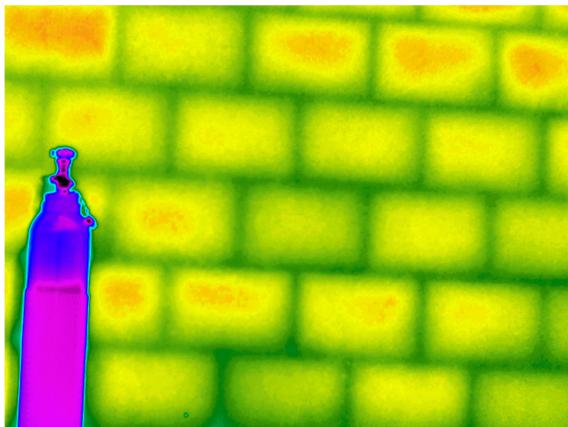


Fig. 4: Reference frame for ammonia detection

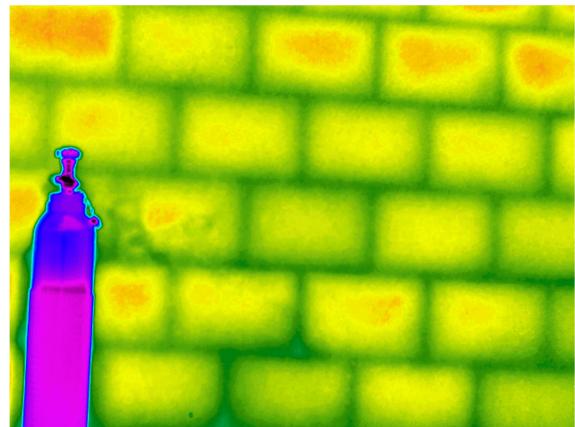


Fig. 5: Analyzed frame with ammonia leakage

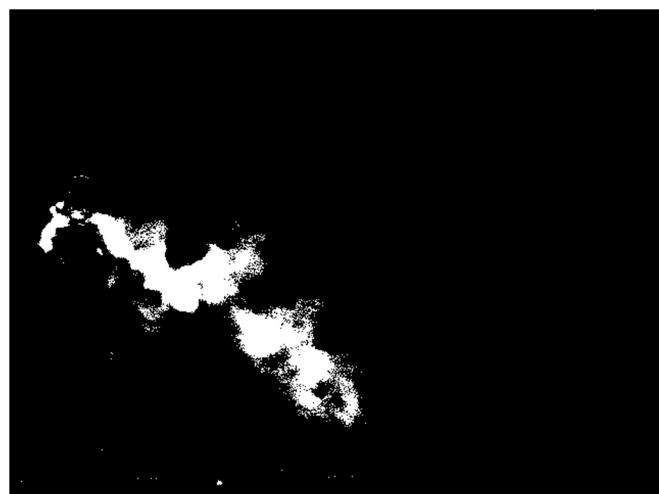


Fig. 6: Segmented image after background removal from the sequence of thermal images during monitoring the ammonia leakage

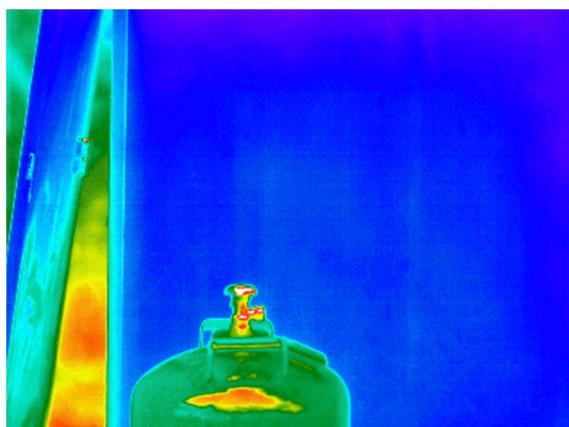


Fig. 7: Reference frame for propane-butane detection

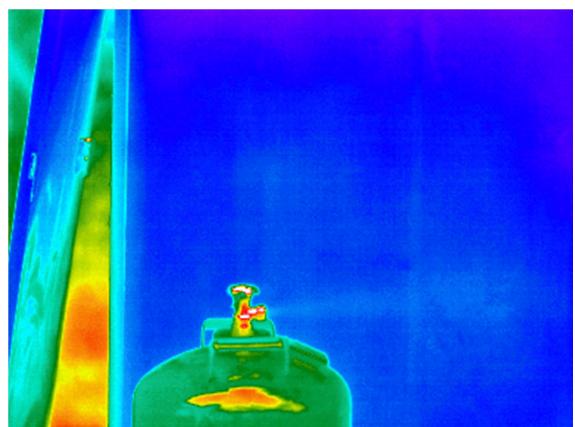


Fig. 8: One of the frames with propane-butane leakage



Fig. 9: Segmented image after background removing from the sequence of thermal images during the propane-butane leakage

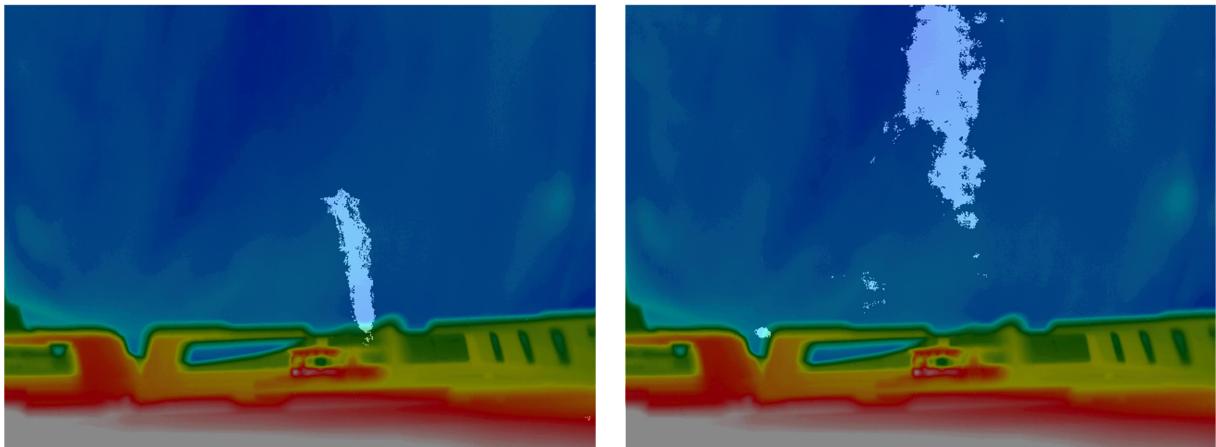


Fig. 10: Detection of natural gas (methane) leakage from home gas burner

5. Conclusions

In this paper, the new high-sensitive, wide-band, recently developed microbolometer camera VOXgas640 was presented. This camera is equipped with wide-band 3-14 μm VOx detector. Due to the high sensitivity ($\text{NETD} < 35 \text{ mK}$), the camera can be used for gas detection in industry. VOXgas640 camera has the motorized wheel with 2 band-pass optical filters to distinguish different gases. It has the shutter for nonuniformity correction and calibrated measurements. Working both in *LWIR* and *MWIR* spectral ranges allows detection of different hydrocarbons having their absorption at 3.2-3.3 μm and above 7 μm . The presented camera transmits images to the computer through fast *USB* channel. There is an option to send images using wireless communication link to any portable device, such as tablet or smartphone.

Dedicated software was written for the camera using Java tools and *OpenCV* library. In spite of typical functions for capturing, recording and displaying IR images, the program implements advanced image processing for gas detection. It applies the algorithms used in optical systems for removing background and movement detection.

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