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Analysis possibility of detection hidden object based on hyperspectral and multispectral data

Abstract. *Risks to the safety of public zones (generally available for people) are related mainly to the presence of hidden dangerous objects (such as knives, guns, etc.) and their usage. Modern system for the monitoring of such zones attempt to detect dangerous tools using multispectral cameras working in different spectral ranges: the visible radiation, near, medium and long range infrared and recently also in terahertz range. In order to develop methods and algorithms to detect hidden objects it is necessary to determine the thermal signatures of such objects of interest. Cameras used for measurements were working in spectral range 0.7-12.5 μm. An infrared imaging Fourier transform spectroradiometer was also used, working in spectral range 7.7-11.7 μm. Analysis of registered thermograms and hyperspectral datacubes has yielded the thermal signatures for: two types of guns, two types of knives and home-made explosive bombs. The determined thermal signatures will be used in the development of method and algorithms of image analysis implemented in proposed monitoring systems.*

Streszczenie. *Zagrożenia bezpieczeństwa publicznego w strefach publicznych (ogólnie dostępnych dla ludzi) są przede wszystkim związane z wykryciem ukrytych niebezpiecznych obiektów (takich jak noże, pistolety, itp.) oraz ich użyciem. Nowoczesne systemy monitorowania tych stref posiadające wielowidmowe kamery, pracujące w różnych zakresach spektralnych: promieniowaniu widzialnym, krótkim, średnim i dalekim zakresie podczerwieni i ostatnio również w falach terahercowych pozwalają na wykrywanie niebezpiecznych narzędzi. W celu opracowania metod i algorytmów, które umożliwiają wykrywanie ukrytych niebezpiecznych obiektów konieczne jest określenie parametrów sygnatur takich obiektów. Podczas pomiarów zastosowano pomiarowe kamery pracujące w zakresie spektralnym 0,7-12,5 μm oraz dodatkowo obrazowy Fourierowski spektroradiometr podczerwieni, pracujący w zakresie spektralnym 7,7-11,7 μm. Analiza zarejestrowanych termogramów i hiperspektralnych danych datacubes pozwoliło na określenie sygnatur termicznych: dwóch rodzajów pistoletów, dwóch typów noży i domowych improwizowanych ładunków wybuchowych. Wyznaczone sygnatury termalne zostały użyte w opracowanych metodach i algorytmach analizy obrazów, które mogą być zaimplementowane w systemie ochrony. (**Analiza możliwości wykrycia ukrytych obiektów na podstawie wielowidmowych i hiperspektralnych danych**).*

Keywords: hyperspectral detection, multispectral detection, datacubes analysis, thermograms analysis.
Słowa kluczowe: hiperspektralna detekcja, wielowidmowa detekcja, analiza termogramów.

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Introduction

Safety of public access areas and elements of critical infrastructure is nowadays a primary application of security systems utilizing advanced image analysis methods. Modern security system monitoring the public areas or places like shopping malls, airports, railway stations require advanced, multispectral threat detection capabilities. Review of available data on terrorist attacks conducted in such places revealed, that in most cases weapons or explosives were hidden under clothing [1, 2]. It is then an important feature of multispectral detection system to be able to reveal the presence of certain concealed objects on the basis of signature database implemented in the system. Another possible solution is a high resolution infrared camera. The infrared cameras also seem to be very useful in the search for concealed objects. Because of the fact that infrared cameras can detect the temperature differences on the surface of the object, it is justified to investigate the possibilities of applying these type of imagers for detection of hidden items [8]. Multiband detection systems are utilizing cameras operating in several spectral bands – usually visual and near, mid and far infrared. Sometimes imaging spectrometers are also applied to provide simultaneous image analysis in several narrow spectral sub-bands [3].

The term signature is used by scientists to describe the appearance of objects to infrared sensors. The signature depend on many factor, including the shape and size of the object, its temperature and emissivity, reflection of external sources (earthshine, sunshine, skyshine) from the object's surface, the background against which it is viewed and the waveband of the detecting sensor. Determination of all of the aforementioned signature components for selected dangerous objects (different types of handguns, knives, improvised explosive devices) will make it possible to develop algorithms for their automated detection in multispectral security systems [4].

In order to determine the signatures of selected dangerous objects that can be used in a terrorist attack, the laboratory experiment was conducted. Its aim was to register and measure selected signatures, using state–of–the–art measurement systems operating in visual spectral band, near, mid and far infrared and also terahertz range. The cameras used during the measurements was able to record signature data in broad spectral range. Additionally the application of imaging spectrometers provided precise, selective spectral data on recorded signatures.

Stand and measurement methodology

In order to investigate the possibilities of detection of objects covered with various types of fabrics, the measurement methodology was developed. The measurement methodology consists of methods and algorithms used during the measurements as well as the hardware setup. During the measurement sessions, three high performance IR cameras were used: MWIR (3-5 μm) and LWIR (7.5-11.5 μm) and imaging Fourier transform spectrometer (IFTS) operating in 7.5-11.5 μm spectral bands. The applied IFTS unit, Telops HyperCam devices, is a lightweight and compact imaging radiometric spectrometer. The device has a 320x256 FPA detector that can be windowed and formatted to fit the desired image size and to shorten the acquisition time. The MCT focal plane arrays is used to cover the LWIR bands. Spectral resolution is user selectable and ranges from 0.25 to 150 cm^{-1}. This instrument generates a complete spectrum of each pixel in the image, with each pixel having a nominal instantaneous field-of-view of 0.35 mrad. Investigation of the possibilities of detecting hidden object in the terahertz range, was provided by the TS4 camera from ThruVision. The cameras is operating at 250 GHz and offers a resolution of 124x271 pixels [5].

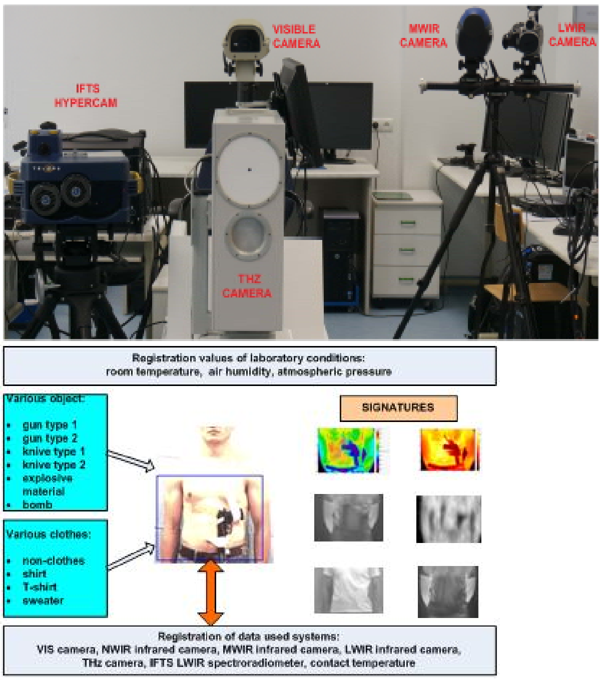

Fig.1. The systems used during the measurements and methodology of signature registration

During measurement session additional contact temperature measurements were conducted using two thermocouples: one placed onto a human body and second onto concealed object. Ambient temperature and humidity were also recorded. Configuration of the measurement equipment during laboratory measurement sessions is presented in Fig. 1. During the measurements, several configurations with various objects (guns, knives, dynamite) and clothes (shirt, T-shirt, sweater) were prepared. A measurement of a single configuration took approximately 30 minutes. The distance between a human body and a set of measurement devices was 5 m (constant during the measurements). Data sets from cameras, IFTS and thermocouples were collected at five minute intervals, consisting of four camera images, spectral signatures, values of atmosphere parameters (air temperature, humidity and pressure) and values of body and object temperatures [6].

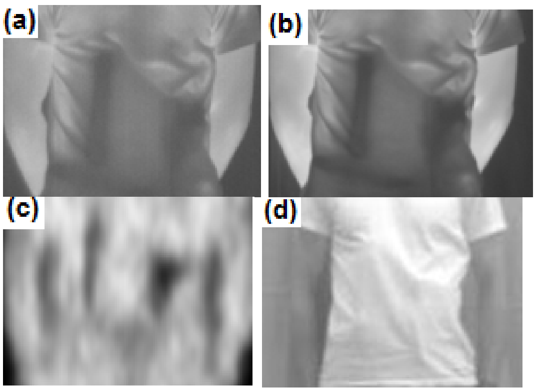

Fig.2. Complementary images; (a) LWIR image, (b) MWIR image, (c) THz image, (d) VIS image with hidden gun and a metallic tube

During the laboratory sessions the signatures of tested hidden objects were recorded in order to extract features suitable for further analysis (Fig. 2). Several continuous recordings were performed with a constant frame rate of 50 fps and different integration times of the camera detectors. Such a wide variety of recording parameters will allow further analysis and optimal choice of instrument parameters for successful detection of concealed dangerous objects. The recorded data sequences were compared during subsequent analysis and further optimization of data acquisition parameters was possible. The thermal signatures of the hidden objects and of the human and clothes were registered in several time periods according to Fig. 1. The image data recorded by infrared cameras were evaluated using the ALTAIR and ThermaCAM RESEARCHER Pro software packages. The data collected by IFTS and thermal cameras were recorded simultaneously. In order to obtain the best possible data sets for hyperspectral analysis of hidden objects, the spectral resolution was set at 3.1 cm^{-1}. Raw IFTS data were converted using software package supplied with the instrument. The REVEAL software suite is provided with the IFTS for the control, registration and calibration of the raw data, and for the data analysis as well [7]. Additional analysis of the data recorded both during laboratory and field tests were performed using Matlab environment and the developed procedures.

Theoretical analysis

An object placed under clothing modifies the exitance value Φ_W in the adjacent area W, which differs from exitance Φ_S of the neighborhood area S (Fig. 3). Contour lines indicate the compared areas of identical size.

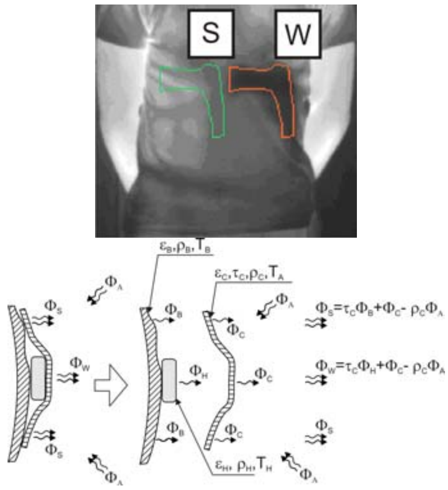

Fig.3. Thermal image of clothing surface with and without an object underneath, thermal radiation model in hidden object detection

Components of total radiant exitance from both W and S surfaces are schematically presented in Fig. 3. Those components include emission from clothing, body, and hidden object with transmissive properties of the clothing taken into account. In order to estimate thermal contrast observed in resulting thermal image, a simplified model was adopted, in which radiant exitances Φ_S and Φ_W (of an areas without and with a hidden object underneath, respectively) are given by the following equations:

$$(1)\quad \Phi_S = \tau_C\Phi_B + \Phi_C + \rho_C\Phi_A, \quad \Phi_W = \tau_C\Phi_H + \Phi_C + \rho_C\Phi_A$$

where: ρ_C – reflection coefficient of a clothing fabric, τ_C – transmission coefficient of a clothing fabric, Φ_B – radiant exitance of a human skin, Φ_C – radiant exitance of a clothing fabric, Φ_A – irradiance of clothing surface, Φ_H – radiant exitance of a hidden object.

Component $\rho_C\Phi_A$ describes ambient radiation reflected from clothing surface. Component $\tau_C\Phi_B$ is a portion of skin radiation coming out through a fabric characterized by transmission coefficient τ_C, whereas $\tau_C\Phi_H$ is a portion of hidden object radiation that passes through the same fabric. A simplifying assumption was adopted in the above relations (1), that the temperature of the fabric surface which results in radiation component Φ_C is close to ambient temperature T_A. It was also assumed that this temperature is approximately identical for all of the surface of considered clothing (shirt, T-shirt, sweater). In thermal equilibrium conditions the energetic contrast K between neighbor areas W and S (as shown in Fig. 3) can be described as:

$$K = (\Phi_S - \Phi_W)/\Phi_S = (\Phi_B - \Phi_H)/\Phi_B \tag{2}$$

Similar relations can be written for spectrally-related parameters. For a given wavelength and temperature values the function describing spectra contrast $cp(\lambda, T)$ is given by the following relation:

$$cp(\lambda,T) = [\phi_B(\lambda,T) - \phi_H(\lambda,T)]/\phi_B(\lambda,T) \tag{3}$$

where: $\phi_B(\lambda,T)$ – spectral radiant exitance of a human body, $\phi_H(\lambda,T)$ – spectral radiant exitance of a hidden object. The values of the above spectra radiant exitances (of a body and an object) can be it turn described as:

$$\phi_B(\lambda,T) = \varepsilon_B(\lambda,T) \cdot m_{BB}(\lambda,T), \quad \phi_H(\lambda,T) = \varepsilon_H(\lambda,T) \cdot m_{BB}(\lambda,T) \tag{4}$$

where: $\varepsilon_B(\lambda,T)$ – spectral emissivity of a human body, $\varepsilon_H(\lambda,T)$ – spectral emissivity of a hidden object, $m_{BB}(\lambda,T)$ – spectra radiant exitance of a blackbody.

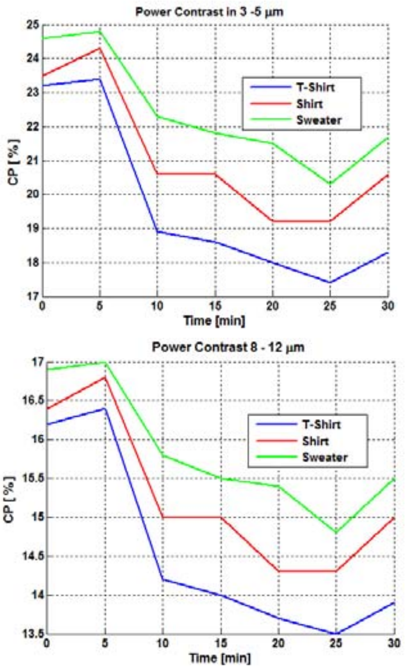

Fig.4. Calculation of power contrast for T-shirt, shirt, sweater in 3 -5 µm and 8 - 12 µm region

Real thermal cameras operate in a finite spectral range $\Delta\lambda = \lambda_{\max} - \lambda_{\min}$, which is determined by a detector spectral response and transmission characteristics of an applied optics. Then it is possible, for a given spectral band $\Delta\lambda$, ambient temperature T_A, body temperature T_B and temperature of a hidden object T_H to define the power contrast $CP(\lambda_{\min}, \lambda_{\max}, T_A, T_B, T_H)$ given by the following:

$$CP(\lambda_{\min}, \lambda_{\max}, T_A, T_B, T_H) = 1 - \frac{\int_{\lambda \min}^{\lambda \max} \tau_C(\lambda, T_A)\varepsilon_H(\lambda, T_H) \cdot m_{BB}(\lambda, T_H) d\lambda}{\int_{\lambda \min}^{\lambda \max} \tau_C(\lambda, T_A)\varepsilon_B(\lambda, T_B) \cdot m_{BB}(\lambda, T_B) d\lambda} \tag{5}$$

where: $\tau_C(\lambda, T)$ – spectral transmission coefficient of a clothing. The results of calculation the power contrast for ranges: 3-5 µm and 8-12 µm is presented on Fig. 4.

Analysis of data registered during experiment

Data analysis was performed according to developed methodology in the same manner for each measurement in order to obtain directly comparable results. The following analysis steps were performed in order to determine the signature of a given dangerous object (e.g. handgun).

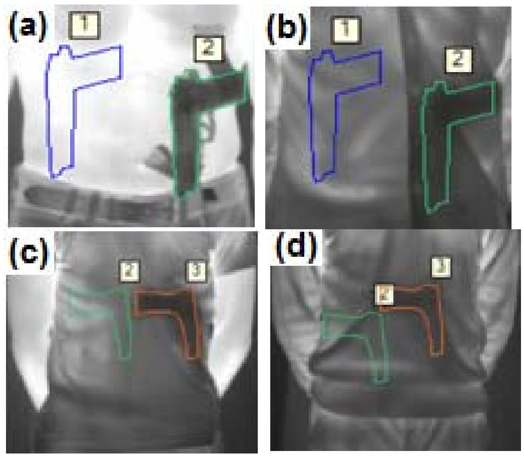

Fig. 5. Analysis of sample data registered by MWIR camera, (a) naked body, (b) shirt, (c) T-shirt, (d) sweater. Gun type1 on images (a) and (b), gun type 2 on images (c) and (d)

For each type of clothing the temperature distribution was evaluated for a selected Region of Interests (ROI) which included concealed object and for the same size ROI (pixel wise) without an object in it. The results of this step of analysis process are shown in Fig.5. By analyzing the recorded thermal images the mean temperature values in selected ROIs were calculated for each type of clothes. The determined thermal properties of analyzed concealed objects are presented in Tab. 1. The same procedure was repeated for each considered type of dangerous object hidden under each type of clothing and the data were recorded at the predefined time intervals, according to the adopted measurement methodology.

Table 1. The signature parameters for a hidden gun type 1 for MWIR camera

	Object	Tmax [K]	Tmin [K]	Tmean [K]	ε
Non-clothes	Gun 1	296.17	299.93	297.51	0.78
	Area 2	303.01	304.87	304.15	0.98
Shirt	Gun 1	295.23	296.8	295.75	0.86
	Area 2	297.71	299.64	298.34	
T-Shirt	Gun 1	294.92	296.76	295.44	0.77
	Area 2	297.07	300.89	298.24	
Sweater	Gun 1	294.56	295.36	294.94	0.82
	Area 2	295.13	298.29	296.29	

In order to obtain the value of brightness temperature, the transmission coefficient of different cloth types was taken into account as well as the emissivity differences in MWIR and LWIR spectral bands. The emissivity and transmission of clothes were measured using the spectrometer. The emissivity value of measured clothes was between 0.92 ±0.03 in MWIR range, and 0.94 ±0.02 in

LWIR range. The measured values were used during the calculations of brightness temperatures. In the next step of signature analysis the data recorded by IFTS were evaluated (Fig. 6).

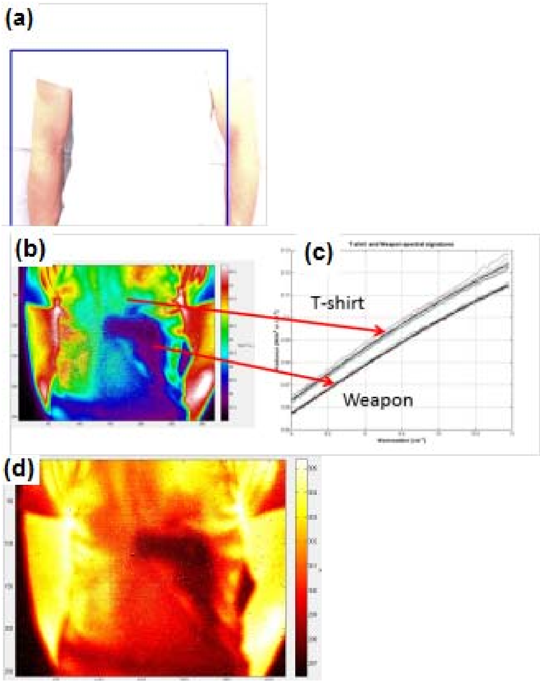

Fig.6. Analysis of sample data registered by IFTS HyperCam T-shirt: visible (a), spectral image (b), spectral radiance (c), broadband image calculate from spectral datacubes (d)

Analysis of spectrometer data revealed the radiance values for selected ROIs as a function of wavelength. It was then determined whether dangerous objects hidden under different clothes exhibit detectable radiance characteristics in selected wavelength bands. However, due to relatively small variations of clothes transmission it was impossible to determine specific spectral bands best suited for object detection. In such case it is not possible to define spectral signatures of dangerous objects, which was confirmed by calculating the brightness temperature on the basis of radiance variations as a function of wavelength. The results of such analysis are presented in Fig.6d. The collected data and results presented in Fig. 5-6 and in Tab. 4. are only examples of selected measurement results. The data recorded by other instruments in different spectral bands were analyzed in the same manner. As a result the quantitative signature characterization of selected dangerous objects were obtained, for different types of clothing. Finally the database of object’s signatures was created and the method was developed for analyzing the image sequences registered by thermal cameras, capable of detection and classification of potentially dangerous objects.

Conclusions

The paper presents the method for the recording of signatures of selected dangerous objects hidden under the clothing. The recorded signatures can be used as a database for automated image analysis procedures which could be implemented in multispectral security systems and increase the probability of detection of concealed dangerous objects, thus improving the protection level.

The real results of analysis of image data recorded by several devices operating in different spectral bands (from visual to terahertz) were presented in this paper. The results show how the changes of temperature values of human body and the object can influence the camera’s ability of detection of the object covered with fabrics. The results presented in the article confirm the fact that it is possible to detect various objects covered with T-shirt placed on a human body using a thermal and terahertz imager in certain conditions.

The results of implementing the database with registered signatures to image analysis method were also presented. According to the results, it is not possible to detect the concealed object with single visible light camera, but the application of multispectral system and method of data fusion give positive detection results. Although it was not possible to achieve 100% detection efficiency or probability of detection (e.g. mobile phone was identified as a dangerous object), the generally encouraging results will lead to the future of efforts aimed at creating efficient signature-based method for image analysis, intended for security applications.

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