Optical-digital complex for detection of remote mines and mapping of minefields

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Abstract. The article is dedicated to a new method of detecting masked ground and subsurface objects for mapping of minefields and engineering reconnaissance. We proposed to use stereoscopic hyperspectral IR remote sensing in order to increase the reliability of detecting and reducing the frequency of false alarms. Stereoscopic surveying allows exclude skipping of objects masked in vegetation and laid at an angle, and separate the disturbed surface (frangible signs) from ordinary soil and embankments. The results of processing hyperspectral data from two channels are combined into a thematic thermal stereomodel of the terrain, on which the anomalies found by the algorithm are highlighted. The concept of an optical-electronic complex of remote sensing of minefields, structural and optical schemes, applied calculations and design solutions are presented in the first part of article. We described basic algorithms for processing hyperspectral data, the method of combining them into a thermal stereomodel of the terrain with the possibility of classifying objects and cross-linking with a three-dimensional map of the area in the second part of the article.

1. Introduction

Due to the growing number of military zones and conflicts around the world, the danger of landmines and unexploded ordnance is a very serious problem that may affect the countries concerned for many years to come. According to the results of the International Campaign of the Ban Landmines (ICBL) in 2016, the number of people killed and maimed by landmines and explosive devices has reached its peak in the last 10 years [1]. In November of 2016 more than 60 states and regions are classified as mine-affected.

An analysis of known methods and means that may be applicable for remote detection of disguised ground and subsurface objects has shown that all these methods have significant limitations for the mapping of search objects on the terrain. Search for objects by means of magnetometric and induction is usually carried out at a very low rate, correspondingly, for a unit of time such systems are capable of probing only a small section of the terrain [2]. Moreover, such systems cannot detect dielectric (plastic, wooden, etc.) and diamagnetic (duralumin, bronze, etc.) objects (when searching magnetometrically). The seismoacoustic method depends on external oscillations and noise very much, it has a lower resolution than other methods and the apparatuses and, as a rule, has large dimensions and weight [3]. The method of nonlinear radar is able to detect only radio electronic components containing p-n transitions (diodes, transistors, microcircuits), it also has low search rates
and high requirements for receiving equipment [4]. Ground-penetrating radar (the method of subsurface radar) registers signals reflected from the interfaces of the layers of the reconnaissance medium. The detection process is carried out at short distances commensurate with the working wavelength of the EM field and has a strong dependence of the resolving power on the depth of sounding. The method is unable to detect dielectric objects in dry ground because of their low contrast in electrical parameters [5]. Ground-penetrating radar, like all the methods described above, has a low speed of reconnaissance and carries a high level of false alarms.

Since the problem described above is urgent and an effective solution to it has not been found yet, the task is to develop search systems capable of remotely detecting and identifying unexploded ordnance, improvised explosive devices, surface and buried anti-vehicle and antipersonnel mines, the detection of which should correspond to the systems of manual search, while, the detection rate should become an order of magnitude larger.

2. Determination of the physical basis for the proposed method

A particular interest for the remote detection of mines and minefields is the methods based on optoelectronic sensors. They are based on the use of the so-called primary and secondary characteristics (Table 1). First evidence includes the outer contour and shape of the mine, the contrast with respect to the surrounding background, the uniformity of the image (uniformity of brightness or irradiance) within the mine contour. Second evidence includes such unmasking signs of the observed space as withered vegetation, loosened soil, traces left by the mine-laying machine.

| Table 1. Physical basis for the proposed method. |
|--------------------------------------------------|
| **Detection of mines laid in the ground**          |
| **by primary signs:**                             |
| The mine, laid in the ground, has a greater       |
| thermal resistance than the soil.                 |
| During the day, the soil above the mine will be   |
| warmer than the surrounding soil.                 |
| In the evening hours, a layer of soil above the   |
| mine gives up its heat energy faster than the     |
| surrounding soil, and it looks cooler.            |
| **by secondary signs:**                           |
| The mines laid in the ground are also found       |
| through soil disturbances and plant stress.      |
| Excavation of soil to laid a mine of leads to     |
| the appearance of small particles on the surface. |
| The mine is a moisture barrier for the ascending  |
| and descending flow of ground water, which leads  |
| to the (temporary) accumulation of water over the |
| mine after the rain and to the more dry soil over |
| the mine in the period of dry weather.            |

| **Detection of mines installed on the surface**    |
| **by primary signs:**                             |
| Landmine, heated by the sun, has a higher         |
| contrast relative to the background.              |
| This contrast is also present if the mine is      |
| painted for masking.                             |
| Differences in shape or colour in different      |
| parts of the mine can lead to complex,           |
| distinctive signs of thermal activity due to     |
| different solar absorption.                      |
| **by secondary signs:**                           |
| Spectral signatures of scattered radiation on the |
| surface of mines differ from the signatures of    |
| soil and vegetation.                            |
| Homogeneous material and flat shapes mines      |
| give rise to a uniform field in hyperspectral    |
| images.                                         |
| The polarimetric signature of unstructured       |
| surfaces, such as grass, is random, which leads  |
| to unpolarized radiation.                        |
| Smooth material surfaces have a polarized        |
| signature.                                       |

According to the analysis of the published sources [6-12], the long-wavelength infrared (8-11 microns), which is the most effective spectral zone for remote detection of mines and minefields, is promising for experimental study. Optoelectronic systems of the visible and near-IR range are capable of detecting objects only on secondary signs, which are not always reliable and sufficient to make a
decision about detection, while devices operating in the LWIR range can detect both primary, and secondary signs. However, broadband IR detection has unstable characteristics (low signal level, high level of interference), partly due to diurnal temperature fluctuations, environmental and meteorological conditions, soil and its surface effects, which leads to the decrease of probability of detection, or to the increase of false alarms.

Hyperspectral IR survey has a higher performance because it allows us to divide the spectral range of detection of the IR device into hundreds of groups of different wavelengths with a spectral resolution of the order of 5-10 nm [13], the intensity of each of which varies depending on the emissivity and the true temperature of the soil surface. It allows us to separate the disturbed surface from ordinary soil and embankments (Figure 1).

![Figure 1. Spectral signatures of various objects.](image.png)

3. The development of the concept of an optical-digital complex

The concept of an optical digital complex was developed to solve the following tasks:

- providing detection of hidden surface and subsurface engineering objects with the evaluation of their characteristics (size, linear dimensions, shape);
- carrying out mapping and classification of the area for information support of humanitarian demining operations.

We proposed to use stereoscopic hyperspectral IR survey in order to increase the reliability of detecting and reducing the frequency of false alarms. Stereoscopic survey makes it possible to exclude the skipping of objects masked in vegetation and laid at an angle. The results of processing hyperspectral data from two channels are combined into a thematic stereomodel of the infrared region, on which the anomalies found by the algorithm are highlighted.

The resulting thermal stereo model of the terrain is combined with a digital three-dimensional model of the study area to visualize the results of the optical digital complex of remote engineering reconnaissance and mapping of minefields.

Optical-digital equipment is placed on the suspension of an unmanned aerial vehicle, and the complex itself consists of the following elements:

1. Optoelectronic equipment containing the following functional blocks:
   1.1. A small-sized two-channel LWIR hyperspectral device (8-11 μm).
   1.2 A camera of the visible range of high resolution with variable focal length, located on a 3-axis gyrostabilizer.
   1.3 Block of primary processing and transmission of information, which coordinates the work of the whole complex.
2. Software for data processing of optoelectronic equipment and output of monitoring results on the operator’s automated workplace.
Table 2. Tactical-technical characteristics of the optical-digital complex.

| Parameter (units of measure) | Value |
|------------------------------|-------|
| Weight of optical-digital complex, kg | No more than 7 |
| Power consumption, W | ~80 |
| Effective survey height, m | 50 |
| Speed of data acquisition without blurring, m/s | up to 5 |
| Mapping time 10 hectares, minutes | 26 |
| Operating temperature range, °C | -40…+55 |

Two channels of the hyperspectrometer, one of which has an angular offset relative to the first, receive data from one area of the terrain in different viewing planes. To cover two bands (2 different fields of view) with one spectrometer and detector, two parallel slits are installed in the focal plane of the IR hyperspectrometer, with an offset whose size corresponds to the height of the spectrum of the first band. The first channel is installed at an angle of 45˚ to the nadir axis for obtaining hyperspectral images in an inclined projection of the terrain. The second channel scans the nadir (normal to the Earth's surface) and receives hyperspectral (hypercube) terrain data in the orthographic projection. To transfer radiation from the input lenses to the slit, mirror optics is used: the Schmidt prism and the reflecting prisms.

Figure 2. Diagram of the developed two-channel IR hyperspectrometer.

3.1 Energy calculation of the diffraction part of the optical system

The maximum investigated flux that can take place in the study of the underlying surface of the Earth may be considered to be the flux emitted by the black body (with a black coefficient equal to one) having a temperature of about 320K. The integral flux of a black body with this temperature, radiated in the spectral range 8-11 μm, is:

$$\Pi_{8-11} = 4.4 \cdot 10^{-3} W / cm^2 sr.$$  

The solid angle in which the individual pixel of the receiver matrix receives the radiation is:

$$\Omega = \frac{S_{gr}}{h^2} \approx 5.525 \cdot 10^{-8} sr,$$

where $S_{gr}$ - land space, the size of which is covered by one pixel in the receiver (47x47mm$^2$), $h$ - distance from the device 50 m.

If we take into account the area of the entrance window of the device $S_d = 12.57 cm^2$, the total optical transmission can be taken as $\tau = 0.7$, then the integral flux at the receiver, obtained from the black body at $T = 320K$:

$$\Phi = B_{b,11} \Omega S_d \tau = 4.4 \cdot 10^{-3} \cdot 5.525 \cdot 10^{-8} \cdot 12.57 \cdot 0.7 = 2.14 \cdot 10^{-9} W.$$
If we take into account the energy of one photon for a wavelength of 10 μm is $E_{\text{max}} = 2 \cdot 10^{-20} \text{ J}$, then the number of quanta per one pixel of the receiver from the integral flux in the spectral range: $N_q = 1.07 \cdot 10^{11} \text{ quanta/second}$.

The hyperspectral device has a spatial coding of wavelengths. The integral radiation arriving at the grating is divided into several spectral bands required for recording, and each of these separated parts of the radiation is registered by a separate pixel (in fact, more often one pixel accounts for only a part of this small flux, since one spectral interval must be recorded, at least, two pixels). Therefore, at best, one pixel has (in this interval, in the first approximation, we can assume that the energy is distributed uniformly over the entire spectral range) $N_{q, \text{peak}} = N_q / M$, where $M$ - number of spectral ranges. If $M = 200$, then $N_{q, \text{peak}} = 5.35 \cdot 10^8 \text{ quanta/second}$. With the registration system selected and the device parameters selected, the averaging time is about 10 msec, the conversion efficiency is 0.8 [14].

The magnitude of the signal is $N_{\text{sig}} = 4.28 \cdot 10^6 \text{ electrons}$, the magnitude of the noise is $N_{\text{noise}} = 5000 \text{ electrons}$. The signal-to-noise ratio in the spectrum from the maximum signal is $\chi \approx 856 \approx 29 \text{ dB}$.

![Optical scheme of the diffractive part of the developed hyperspectrometer.](image)

**Figure 3.** Optical scheme of the diffractive part of the developed hyperspectrometer.

| Parameter (units of measure) | Value |
|-----------------------------|-------|
| Spectral range, μm          | 8 – 11 |
| Power consumption, W        | 32    |
| Number of pixels of infrared FPA | 640x512 |
| Pixel size, μm              | 15x15 |
| Frame frequency, Hz         | up to 210 |
| Temperature sensitivity, mK | 10    |
| F-number (1st and 2nd channels) | f/2       |
| Angular field (1st and 2nd channels) 2ω, deg | 8 |
| Viewing band (1st and 2nd channels) for a height of 50 m, m | 14 |
| The space of the earth's surface, covered by one pixel of the receiver, cm² | 2.19 |
| The spectral resolution dλ, nm | 8 |

In addition to the hyperspectral device, the optical-digital complex includes a camera of the visible range mounted on a 3-axis gyrostabilizer, which receives a series of images in different spatial planes along the flight path at a given time interval. Based on the received images, using the 3D reconstruction algorithms, a high-resolution digital model is installed and then imported into the final geographic information system (GIS).
Table 4. Tactical-technical characteristics of the camera of the visible range.

| Parameter (units of measure)                        | Value                  |
|----------------------------------------------------|------------------------|
| Spectral range, μm                                 | 0.4 – 0.7              |
| Power consumption of the camera with a stabilizer, W| 8                      |
| Number of pixels of FPA                            | 5144x3800              |
| Pixel size, μm                                      | 7.4x7.4                |
| Dynamic range, dB                                   | up to 77               |
| Frame frequency, Hz                                 | up to 25               |
| Stabilization of the gyrostabilizer (3 axes), ang.sec/s| 18                     |

The accuracy of the survey depends on the difference in altitude of the survey area and the presence of buildings and trees. With automatic data collection, the GSD (the distance between the pixel centers measured on the surface) is approximately 2.2 cm/pixel at the working height.

3.2 Data acquisition with the help of the optical digital complex

The optoelectronic equipment being developed is located on UAVs (mainly of small class and multi-rotor type with a take-off weight of up to 15 kg and a range of 2 to 10 km).

![General view of the developed optical-digital complex placed on board UAV.](image)

Figure 4. General view of the developed optical-digital complex placed on board UAV.

Data collection process:

1. The operator, using the geographic information system (GIS) application on the tablet (or via the PC interface) on the digital map of the locality specifies the launching point and the UAV overflight area by placing an arbitrary figure on the map.

2. According to the data entered by the operator, the algorithm of the geographic information system calculates the sounding path and the necessary survey parameters (speed, path to the start point and the return path, etc.), which are then transmitted via wireless communication channels to the UAV control scheme.

3. After confirming a successful transmission of flight data, the operator gives a command to launch the UAV, which is an automatic piloting is moved to the starting point of remote sensing. When the starting point is reached, a signal is received from the control circuit of the UAV to the control unit of the bcc to start the survey of the terrain.

4. A camera of the visible range, mounted on a 3-axis gyrostabilizer, takes pictures in different spatial planes, linking each of them to its spatial location.

5. The hyperspectral device of the long-wavelength infrared range, which has 2 channels, one of which conducts survey of the terrain along the normal to the sounding path, and the other at an angle of 45 degrees, receives hyperspectral data in two channels, for reconstruction of the stereomodel of the area in the LWIR range.

3.3 The structure of data processing with the help of the optical digital complex

The developed GIS for engineering troops has a functional that allows to combine a 3D model of the visible range with an IR model (Figure 5) for solving problems related to humanitarian mine clearance, such as: detection and identification of hidden ground and subsurface objects; planning
operations on mining and demining; exploration of the area; planning the movement of people, equipment and other tasks.

Figure 5. Structural scheme of data processing the help of the optical-digital complex for remote reconnaissance and mapping of minefields.

The three-dimensional model of the high-resolution terrain is constructed from the received images (in different spatial planes) of the visible range camera and then imported into the GIS system. Hyperspectral data from a two-channel hyperspectral instrument, pass radiometric and atmospheric correction [15]. After that, a thematic classification and search for anomalous objects is made using specified algorithms (comparison with the standard library, the classification by using training samples). The results of processing hyperspectral data from two channels are combined into the thematic stereomodel of the IR range, on which the anomalies found by the algorithm are highlighted. The final GIS must have a functional that allows to combine a digital model of the visible range with a stereomodel of the infrared range. The stereomodel of the IR range should also be able to adjust and selection in the pseudo-colors of different spectral intervals for their visual interpretation by the operator.

4. Conclusion
The choice of a hyperspectral system of the LWIR range for searching and identification of objects hidden both on the soil surface and installed in the ground, based on primary and secondary physical characteristics is justified. A new method of detecting masked ground and soil mines is proposed, based on stereoscopic hyperspectral surveying in the long infrared region in conjunction with a three-dimensional reconstruction of the terrain by a camera of the visible range. The concept of an optical-digital complex for remote sensing of minefields has been developed, the main tactical and technical characteristics of the developed equipment are given, the energy calculation of the diffractive path of the optical system is carried out, the architecture of the geographic information system for processing and stitching data to provide information to the end user is proposed.

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