Infrared Radiation of Unmanned Aerial Vehicles

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Abstract. The growing number of unmanned aerial vehicles (UAVs) is affecting the development of aviation in recent years. Small civilian UAVs are readily available to commercial organizations as well as to the public. They pose new risks to both people and their property on the ground, as well as to flight safety, where potential collisions with UAVs in the air pose a threat to passenger aircraft. Unlike a manned aircraft, small UAVs do not have an ATC transponder, so it is invisible to TCAS systems, and because they are quite small, it is difficult to detect them visually. The fly of an UAV is impossible without using of an engine that is a thermal or electric machine with an elevated temperature and accordingly an elevated infrared (IR) radiation, which may be detecting by IR sensors. Therefore, the proposing to increase surveying of airspace for the presence of UAVs using infrared surveillance systems.

1. Introduction

Modern unmanned aerial systems are complex functional systems. During their development the latest achievements in the field of microelectronics, programming, small-sized high-performance motors, composite materials and other complex technologies are used. Therefore, it is difficult to detect such air objects with existing radars, but an unmanned aerial vehicle is an object that moves in air by engine, mainly a heat engine or an electric motor [1]. If the engine is a heat machine in the form of a gasoline or turbojet engine with sufficiently high body temperatures and hot exhaust gases, about 400… 700 °C, such a UAV can be detected using modern infrared systems, such as IRST (Infrared search and track). And if the UAV is equipped with an electric motor, it is much more difficult to detect, because the temperature of the running electric motor does not exceed 80 °C. Therefore, it is necessary to calculate the radiation flux power of a UAV with electric motors and to investigate the possibility of its detection by existing infrared sensors.

2. Heat transfer by rays

Radiant heat transfer is a complex process of heat transfer, which is caused by the transformation of the internal energy of a substance into the energy of electromagnetic waves, the propagation of these waves and the absorption of their substance.

Carriers of radiant energy are electromagnetic vibrations [2]. These oscillations can be characterized either by the frequency ν (1/s),or the wavelength λ (m). These two characteristics are related to the known relation:

$$\lambda = \frac{c}{\nu},$$

where c is the speed of light (in vacuum with $c \approx 3*10^8$ m/s).

Rays arising from the temperature and physical properties of bodies are called thermal rays, and their process of propagation by thermal (infrared) radiation (λ=0.4÷200μm)or thermal radiation.

Thermal radiation is a property of all bodies. All heated bodies radiate into the surrounding space. When contacted with other bodies, this energy is partially reflected, partially absorbed, partly passed through the body. That part of the energy absorbed by the body is again converted to thermal energy. The part that is reflected (or passed) enters and is absorbed or re-reflected by other bodies. Thus, after a series of absorptions and reflections, the radiated energy is fully distributed between the surrounding bodies. Therefore, everybody not only continuously emits, but also absorbs energy.

The radiant energy passing through an arbitrary surface per unit time is called the flux of radiation Q, W.

The radiation flux coming from a unit of surface area in all directions of the hemispherical space is called the radiation flux density E, W/m^2.

$$E \equiv \frac{dQ}{dF},$$

where dQ is the flux of radiation through the elementary plane dF. Of course, the radiant flow coming from the entire body surface (F) is equal

$$Q = \int_F E dF .$$

Radiation flux is a characteristic of radiation that does not distinguish between the rays of different wavelengths. These quantities are called integral, and radiation with different wavelengths is called integral. Fixed wavelength radiation is called monochromatic. The distribution of radiant energy over the wavelengths of radiation is characterized by the spectral intensity of radiation E_λ, W/m^2, which is given as a derivative:

$$E_\lambda \equiv \frac{dE}{d\lambda},$$

where dE is the radiation flux density with wavelengths from$\lambda$to$\lambda+d\lambda$.

The last formula implies the relation between the integral flux and the spectral intensity:

$$E = \int_0^\infty E_\lambda d\lambda .$$

Next, consider the concepts that describe the interaction of radiation with matter (shown in Figure 1).

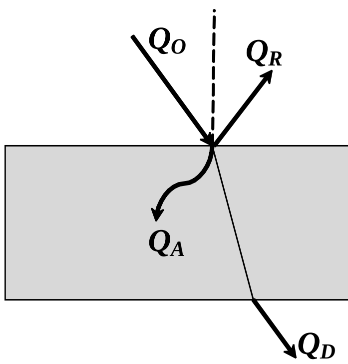

Figure 1. Scheme of distribution of radiant energy

From all the radiant flux Q_0 incident on the body, part Q_A is absorbed, part Q_R is reflected, and part Q_D passes through the body. In this case, if there are no sources of energy in the body, the energy balance equation takes the form:

$$Q_0 = Q_R + Q_A + Q_D \,.$$

Dividing both parts of the last equality by Q_0, we obtain the relation:

$$R + A + D = 1 \,, \quad (1)$$

where $R \equiv \dfrac{Q_R}{Q_0}$ is reflection coefficient;

$A \equiv \dfrac{Q_A}{Q_0}$ is absorption coefficient;

$D \equiv \dfrac{Q_D}{Q_0}$ is transmittance coefficient.

The first term of relation (1) characterizes by the reflectivity, the second by absorption, and the third by the capacity of the body. The dimensionless values of R, A, D vary from 0 to 1. Depending on their values, several boundaries (according to optical properties) body types are distinguished: Absolutely black body, Mirror body, Absolutely white body and Absolutely transparent (diathermic) body.

Absolutely white, black, or transparent bodies do not exist in nature. The coefficients R, A, D depend on the nature of the body, its temperature and the spectrum of radiation that falls on the body. For example, for heat rays, clean air is transparent, and in the presence of impurities of water vapor or carbon dioxide, the air becomes translucent.

Solids and some fluids for thermal rays are almost opaque, hence, in this case D = 0 and, according to formula (1) above the relation holds:

$$R + A = 1. \quad (2)$$

It implies that if the body reflects energy well, it absorbs energy poorly.

In the future, we will mainly consider opaque bodies, which will allow the use of communication (2) (for instance, in the form $R = 1 - A$).

Of great importance is the condition of the surface. The reflectivity of smooth, well-polished surfaces is much higher than that of rough surfaces, regardless of color.

In addition to the fact that the body interacts with external radiation, it itself radiates energy. This leads to the need to introduce a number of concepts. Even if no rays fall on the body, a radiant flow of energy (denote its density E_1, W/m^2) is still emitted from its surface.

This flow is fully determined by the body's temperature and physical properties. Corresponding radiation is the body's own radiation, and the value of E_1 is the radiative power of the surface. At the same time, from the other bodies, radiant energy in the amount of E_2 enters the body, which is the radiation that falls outside (shown in Figure 2).

The fraction of incident radiation in the amount of $E_{abs} = A_1 E_2$ is absorbed by the body - it is the absorbed radiation; the other part - in the amount of $E_{ref} = R_1 E_2 = (1 – A_1) E_2$ - is reflected - this is reflected radiation (here A_1 and $R_1 = 1 – A_1$ are, respectively, the absorption and reflection coefficients).

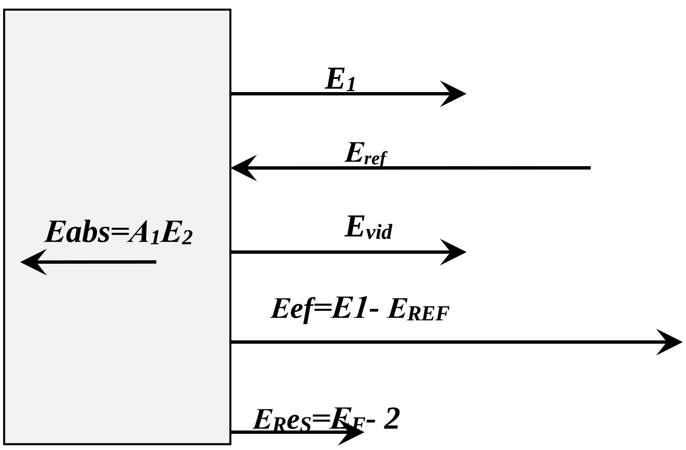

Figure 2. Scheme of radiation types.

The actual radiation of the body in the sum of the reflected (that is, the total radiation coming from the surface of the body) is called *effective radiation of the body* and its specific flux is equal to:

$$E_{ef} \equiv E_1 + E_{ref} = E_1 + (1 - A_1)\, E_2.$$

It is the actual radiation of the body that we feel or measure with devices. Its specific flux is greater than the specific flux of its own radiation by the value $(1-A_1)E_2$. Effective radiation depends on the physical properties and temperature of not only the radiating body, but also of other surrounding bodies, as well as the shape, size and relative location of the bodies in space.

The resulting radiation (characterized by the specific E_{res} flux) is the difference between the effective radiation coming from the body (E_{ef}) and to it (E_2). It can be shown that the resultant radiation is also equal to the difference between the intrinsic radiation (E_1) and that part of the external radiation absorbed by the body ($E_{abs}=A_1E_2$). Thus

$$E_{res} \equiv E_{ef} - E_2 = E_1 - A_1\, E_2\,.$$

The E_{res} value determines the resultant specific energy flow that a given body transmits to its surrounding bodies in the process of radiant heat transfer. If the value of $E_{res}<0$, then this means that the body in radiant heat exchange receives energy, in the opposite condition ($E_{res}>0$) - the body provides energy.

Thus, if A = 1, then R = D = 0, that is, all incident radiation energy is completely absorbed by the body, such a body is called completely black. If R = 1, then A = D = 0, that is, all the incident energy is fully reflected, such surfaces are called mirror or (if the reflection is diffuse), completely white. If D = 1, then A = R = 0, that is, all incident radiation energy passes completely through the body, such bodies are called absolutely transparent (diathermic).

3. Calculating the radiation flux power of a quadcopter with electric motors

It is worthwhile to notice that aluminum is used to reduce weight in unmanned aerial vehicles, and the maximum temperature of the electric power plant does not exceed 80°C, we calculate the possibility of detecting a UAV type "QuadroCopter" infrared airspace.

When using other types of UAVs, the detecting ability of the heat exchanger will enhance by increasing the size of the air object and by using other types of power plant (such as internal combustion engines) that have a higher operating temperature.

Thus, the inputs for the calculation are:

- front area of the quadcopter - 0,04 m^2;
- the maximum temperature of the motor is 80°C;
- housing material - aluminum;
- maximum detection range - 5000 m;
- the threshold sensitivity of the radiation receiver (RR) - 10^{-9}W.

To detect a quadcopter object in the air space by its infrared radiation, the following conditions must be fulfilled:

$$\Phi_{QC} - q\Phi_L \geq 0,$$

where Φ_{QC} is the QuadroCopter thermal radiation stream that focuses on the radiation receiver; Φ_L- minimum radiation flux (Limit) or threshold sensitivity of the radiation receiver; q is the signal-to-noise ratio required for a given detection probability.

Hence the signal should always be above noise level, therefore, $q \geq 1$, so the heat radiation flux must exceed the threshold of the radiation receiver $\Phi_{QC} > \Phi_L$.

Determine the energy luminosity of the $M_{e(\lambda)}$ quadcopter made of aluminum. According to [3] the coefficient of thermal radiation of polished aluminum in the temperature range from 50 to 500°C is 0.05.

According to the law of displacement of Vin for the temperature of the power plant of the copter T=80°C, we calculate the maximum wavelength:

$$\lambda_{\max} = \frac{2898}{T} = \frac{2898}{(273+80)} = 8.18\ \mu m$$

As the temperature of the power plant decreases, the maximum wavelength will increase, thus, we will choose for the calculations the average wavelength range λ = 8-14 μm.

We calculate the relative wavelength coefficients for this range

$$X_\lambda = \frac{\lambda}{\lambda_{\max}}, \qquad X_8 = \frac{8}{8.18} = 0.978, \quad X_{14} = \frac{14}{8.18} = 1.711,$$

The relative values of the spectral density of the energy luminosity $z(x_\lambda)$ are calculated in the tables [3] and are:

z(0.978) = 0.2374, z(1.711) = 0.6294.

According to the Stefan-Boltzmann law, we find the energy luminosities of an absolutely black body at three temperatures T=80°C:

$$\mathrm{M_e} = \sigma \mathrm{T}^4 = 5{,}67 \cdot 10^{-8} \times (273+80)^4 = 880.4\ \frac{W}{m^2}$$

Determine the energy luminosity $M_{e(\lambda)}$ of the quadcopter in a given range of wavelengths:

$$\mathrm{M_{e(8\ldots14)}} = \varepsilon_{\mathrm{T}} \sigma \mathrm{T}^4 [z(x_{14}) - z(x_8)] = \varepsilon_{\mathrm{T}} M_e [z(0.978) - z(1.711)] = 0.05 \times 880.4 \times 0.392 = 17.25\ \frac{W}{m^2}.$$

From this equation, it is possible determine the radiation flux of the quadcopter at a minimum distance:

$$\Phi_{1QC} = M_{e(8\ldots14)} \times S_{\text{ц}} = 17{,}25 \times 0{,}04 = 0{,}69\, W.$$

When passing through the atmosphere and the optical heat exchanger system [4], the radiation flux loses its power, so the flow of intrinsic radiation of the object Φ_R entering the radiation receiver, is basically a function of the object temperature, distance to the radiation receiver, area and other components expression:

$$\Phi_R = \frac{\tau_l S_l \varepsilon_O S_O \cos\alpha \sigma T_O^4}{\pi L^2} \text{К} \left[z\left(\frac{\lambda_2}{\lambda_{\text{м}}}\right) - z\left(\frac{\lambda_1}{\lambda_{\text{м}}}\right) \right].$$

where τ_l is transmittance coefficion of the optical system; S_l is area of the lens of the radiation receiver; ε_o is coefficient of thermal radiation of the object; S_o is the surface area of the object;α- the angle between the normal to the radiation surface and the range line; σ- is a constant Stefan-Boltzmann`s coefficient (5,67·10^{-8}W·m^{-2}K^{-4}); T_o is object temperature; $\text{К}\left[z\left(\frac{\lambda_2}{\lambda_{\text{м}}}\right) - z\left(\frac{\lambda_1}{\lambda_{\text{м}}}\right)\right]$ is radiation utilization factor; L is the distance from the object to the radiation receiver.

4. Results

The calculations are presented in Figure 3 showed that the quadcopter's own radiation flux at a distance of 6000 m is above to the threshold sensitivity of the infrared sensor [5]. Therefore, it is possible the detection of a quadcopter with electric motors at a distance of up to 6000 m.

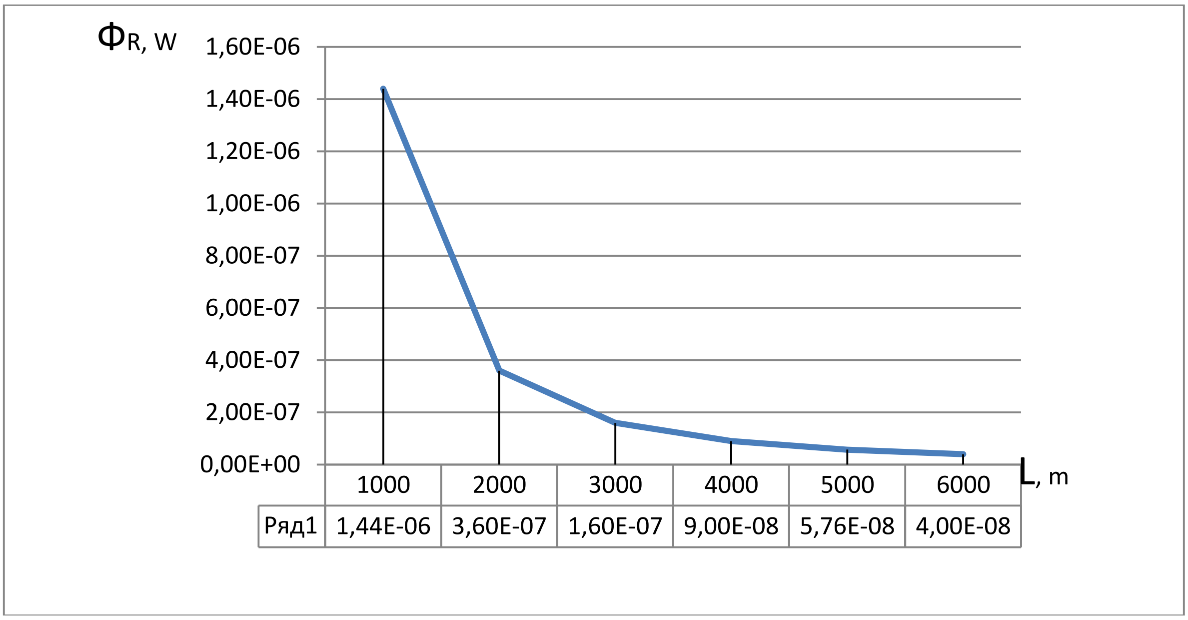

Figure 3. The dependence of the quadrocopter's own radiation flux from the distance to the heat exchanger.

Conclusions

Calculations have shown that modern quadcopters with electric motors can be detected by infrared sensors with a threshold sensitivity of 10^{-9} W at a distance of about 5000 m, which allows the use of infrared systems to detect unmanned aircraft and increase safety their using.

References

[1] Bashinskiy V G, Bzot V B, Zhilin Ye I et al 2014 *Malogabaritnyye bespilotnyye aviatsionnyye kompleksy (MiniUVS)* Monograph (Zaporozhie: AO «Motor-Sych») 261 p

[2] Hadson R 1972 Infrakrasnyye sistemy (Infraredsystemengineering, 1969) Translated from English by Gerchikova Ya B, Golubchina Yu Ye and Kina S G ed Vasilchenko N V (Moscow: Mir) 535 p

[3] Kriksunov L Z 1978 Spravochnik po osnovam infrakrasnoy tekhniki. (Moscow: Sov.radio) 400 p

[4] Lloyd Dzh 1978 Sistemy teplovideniya. (Moscow: Mir) 414 p

[5] Chuzha O O, Smyk A D and Chuzha M O 2019 On-board Warning System about the Proximity of UAVs and other Objects on the Air. *Proceedings of the 2019 IEEE 5th International Conference "Actual Problems of Unmanned Aerial Vehicles Developments, (APUAVD 2019)*. October 22-24, 2019 pp 178-181