Composite detection probability and assessment methods of photoelectric airborne

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As the detection performance of airborne photoelectric system is difficult to evaluate, this paper proposes a quantitative calculation method of target information fusion detection probability for infrared sensor and low light level sensor, analyzes the influencing factors of target detection probability from three aspects of radiation characteristics of target and background, transmission characteristics and imaging characteristics of detector, establishes the detection probability calculation model of target information fusion, based on fuzzy Bayesian network theory, according to target features of airborne photoelectric sensors and threaten effect, gives out fuzzy Bayesian network model of target threat assessment. Experimental results show that as fusion quality factor is less than 1, the quality of fusion image declines compared with the source image; the target threat is obtained through Bayesian Network algorithm, the simulation of the threat assessment processing proves the validity of the model and the reliability of the results. Methods proposed in this paper can calculate the target detection probability of image fusion in airborne photoelectric system and assess the target threat.

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1. Introduction

Airborne photoelectric system is gradually developed into passive infrared detection system with all kinds of threats, which has advantages of high anti-jamming ability, high measuring accuracy and strong stealth. Target detection probability is one of the most important parameters to evaluate target detection performance in airborne photoelectric system [1-4]. With the development of target information fusion techniques, an effective method for quantitative evaluating the target detection probability of infrared and low light level in airborne photoelectric system is needed. Jia Qinglian and others studied the target detection probability for infrared tracking system according to temperature difference between target and background and detector characteristics [5], Zhou gang and others analyzed target detection and recognition probability of static infrared imaging system based on infrared detection characteristics and the minimum distinguishable temperature difference [6]. However, the recent researches for target detection probability in airborne photoelectric system mostly concentrate in a single system or on the decision-level fusion [7]. Target threat assessment can be made according to different target characteristics and weapon performance characteristics through airborne photoelectric detecting device, provides important evidences for the commander's decision. Fuzzy Bayesian network makes a breakthrough in continuous variable node problems beyond the conventional discrete-time Bayesian Network. This paper establishes target detection probability calculation model for target information fusion of infrared sensor and low light level sensor from three aspects of target and background radiation characteristics, transmission characteristics and detector imaging characteristics, classifies target feature information of airborne photoelectric system using triangle fuzzy membership degree method, establishes fuzzy Bayesian network topology structure model of target threat assessment, calculates fusion evidence according to Bayesian probability reasoning.

2. The detection probability calculation method of target information fusion

Infrared sensor and low light level sensor works from low light level wavelength to infrared wavelength, however, spectral characteristics of the same target are different in low light level and infrared wavelength [8]. In low light level wavelength, the reflection spectrum of target is mainly needed for detection, while, targets its own radiation is needed in infrared wavelength. The ratio of the spectral distribution of target and background is regarded as target reflection contrast ration in low light level wavelength [9], target reflection contrast ratio is r_c, its expression is shown in formula (1).

$$r_c = \int_{\lambda_1}^{\lambda_2} \frac{T_r(\lambda)\cdot|TR(\lambda) - BR(\lambda)|}{BR(\lambda)} d\lambda \tag{1}$$

In (1), $T_r(\lambda)$ is the spectral reflectance of the target, $TR(\lambda)$ and $BR(\lambda)$ are each of the spectral distribution of target and background, λ_1 and λ_2 are respectively the upper and lower cutoff wavelength of integration. Reflection radiation spectral distribution of the target is the product of the sky radiation intensity per wavelength with the reflection coefficient of the target, assume r_λ is the target reflection coefficient, its expression is in (2).

$$TR(\lambda) = S(\lambda)\cdot r_\lambda \tag{2}$$

In formula (2), $S(\lambda)$ is the radiation distribution of the sky. In the same scene, targets and background are in the same sky radiation, B_c is the reflectance of the background, it can be approximated as formula (3).

$$rc = \int_{\lambda_1}^{\lambda_2} \frac{T_r(\lambda)\cdot |T_r(\lambda) - B_c|}{B_c} d\lambda \tag{3}$$

The radiation characteristics of targets can be described by Planck's law. When the wavelength is $\lambda(\mu m)$ and temperature is T, radiance of the black-body is $M_\lambda = c_1\lambda^{-5}\left(e^{c_2/\lambda T} - 1\right)^{-1}$, $c_1 = 3.741844 \cdot 10^{-12} W \cdot cm^2$ is the first radiation constant, $c_2 = 1.438833\, W \cdot cm^2$ is the second radiation constant. Set ε_λ as the spectral emissivity of the target, the radiance of target at a certain infrared wavelength is $M(\lambda) = \varepsilon_\lambda M(\lambda)$. Whether the target can be detected depends on the radiation difference between target and its background for infrared imaging. Therefore, assume R_C is the radiation contrast ratio, formula (4) is its definition.

$$R_C = \frac{\int_{\lambda_1}^{\lambda_2} T_M(\lambda)dt - \int_{\lambda_1}^{\lambda_2} B_M(\lambda)dt}{\int_{\lambda_1}^{\lambda_2} B_M(\lambda)dt} \tag{4}$$

In formula (4), T_M is the radiance of target, B_M is the background radiance. Spectral responsivity is to describe sensitivity of photoelectric devices; it is the responsiveness of the devices to monochromatic incident radiation. Differences between spectrum distribution of detector and target have influences on detection quality of the detector, we use spectral matching coefficient [10] to describe the characteristics of the low light level and infrared sensors, spectral matching coefficient is defined in (5).

$$\alpha = \frac{\int_{\lambda_1}^{\lambda_2} S(\lambda)R(\lambda)d\lambda}{\int_{\lambda_1}^{\lambda_2} R(\lambda)d\lambda} \tag{5}$$

In (5), $D(\lambda)$ is normalized spectral response of detector, $T(\lambda)$ is normalized spectral distribution of target. In the actual target detection, due to absorption and scattering effect of atmosphere, infrared radiation energy of the target and the reflected energy of low light level may attenuate [11]. Transmission characteristic of infrared radiation can be represented through spectral transmittance, transmittance is ratio of attenuation energy through atmospheric and the initial total energy, it can be expressed by $\tau_{IR} = e^{-\varepsilon R}$, R is the transmission distance, ε is the atmospheric attenuation coefficient. In the condition of low light level night vision, visual range is relatively small, atmosphere can be considered to be homogeneous, atmospheric transmittance changes slowly in this band.

Target detection performance of single detection sensor is the combining results of radiation characteristics target and background, transmission characteristics and imaging characteristics of the detector. The detection performance of infrared sensor is shown in formula (6), detection performance of low light level sensor is in (7).

$$P_{II} = \theta \cdot C_I \cdot \tau_I \cdot \alpha_I \tag{6}$$

$$P_{LL} = \theta \cdot C_L \cdot \tau_L \cdot \alpha_L \cdot L \tag{7}$$

when $\theta \cdot C_I \cdot \tau_I \cdot \alpha_I < 0$ and $\theta \cdot C_L \cdot \tau_L \cdot \alpha_L \cdot L < 0$, (6) and (7) are not formed. θ is location and size factor, C is radiation contrast radio of the target and background, τ is the infrared atmospheric transmittance, α is spectral matching coefficient for targets and the infrared detector.

Regards target detection as a binary decision problem consists of two parts of target and background, assume the detection probability of target detected by the detector is $d_i(H_1)$, probability of target cannot be detected by the detector's is $d_i(H_0)$, probability of target detected by infrared and low light level fusion system is $F(H_1)$. In condition of various detectors working independently, the detection probability of multi information fusion can be seen as a probability union of target detected by single detector, the expression is shown in (8).

$$P[F(H_1)] = P[d_1(H_1) \quad d_2(H_1) \quad d_1(H_1) \cdots d_i(H_1)] \tag{8}$$

In the target information fusion of low light level sensor and infrared sensor in airborne photoelectric system, we set up F_I, F_L, M_I and M_L are respectively the amplitude of the signal and the noise standard deviation of infrared and low light level, two types of noise are assumed to be white noise. $I_0(x)$ is the zero-order Bessel function[12]. SNR is signal-to-noise ratio of airborne photoelectric system, using MAP (maximum posteriori probability) rule, the probability density P_I and detection threshold F_{IT} for output signal of infrared sensor can be obtained, which are shown in (9), the probability density P_L and detection threshold F_{LT} for output signal of low light level sensor are shown in (10).

$$\begin{cases} P_I = \dfrac{Y_I}{M_I} \exp\left(-\dfrac{Y_I^2 + F_I^2}{2M_I^2}\right) I_0\left(\dfrac{Y_I F_I}{M_I^2}\right) \\ F_{IT} = \dfrac{M_I^2}{F_I} I_0^{-1}\left[\dfrac{P(H_0)}{P(H_1)} \exp\left(\dfrac{F_I^2}{2M_I^2}\right)\right] \end{cases} \tag{9}$$

$$\begin{cases} P_L = \dfrac{Y_L}{M_L} \exp\left(-\dfrac{Y_L^2 + F_L^2}{2M_L^2}\right) I_0\left(\dfrac{Y_L F_L}{M_L^2}\right) \\ F_{LT} = \dfrac{M_L^2}{F_L} I_0^{-1}\left[\dfrac{P(H_0)}{P(H_1)} \exp\left(\dfrac{F_L^2}{2M_L^2}\right)\right] \end{cases} \tag{10}$$

In the target information fusion of low light level sensor and infrared sensor in airborne photoelectric system, therefore, the target detection probability of information fusion is (11).

$$P_F = 1 - \{1 - P[d_I(H_1)]\} \times \{1 - P[d_L(H_1)]\} \tag{11}$$

In formula (11), the target detection probability of infrared sensor is $P[d_I(H_1)]$, the target detection probability of low light level sensor is $P[d_L(H_1)]$. Target detection performance of infrared sensor and low light level sensor is the result of radiation characteristics of target and background, radiation transmission characteristics, imaging characteristics of detectors and the expressive features of target and background on target information, thus, the expressive features of target and background on target information can not be ignored. Assume Q_F is the target information fusion quality factor, then target information fusion detection probability of infrared sensor and low light level sensor is shown in (12).

$$P = P_F \cdot Q_F \tag{12}$$

3. Target threat assessment

The main means for detection target threat assessment of airborne photoelectric system is to detect, intercept and identify radiation and scattering light waves by photoelectric devices, detect its technical parameters to determine its location. Infrared sensor uses target its radiation characteristic of infrared system to detect, intercept, redirect and analyze. It can track and identify targets. Target threat is mainly determined by the combat mission and target characteristics. In the course of combat, threat assessment using photoelectric sensor is mainly based on target information of airborne photoelectric system [13-15], including target location, target range, target type and target height. These factors of target are continuous variables, fuzzy classification and determination of the probability distribution on state factors are required when we use Bayesian network to inference.

Fuzzy Bayesian network extends continuous node variable of Bayesian network to fuzzy node variable [16-17]. Assume a problem can be represented by a finite set of nodes $B = \{b_1, b_2, ..., b_n\}$, all possible states of b_i can be represented by B_i. Assume $b_i \in B$ can be blurred into a fuzzy random variables a_i, a_i inherits all possible states of b_i. Then the fuzzy set is shown in (13).

$$U_i = \lfloor B_{i1}, B_{i2}, ..., B_{in_i} \rfloor \tag{13}$$

In (13), the number of fuzzy state of b_i is n_i, B_{ij} expresses fuzzy state of j, $\mu_{ij}(b)$ is the membership level belongs to b_i, it is represented by a conditional probability.

$$\mu_{ij}(b) = P(B_{ij}|b), 0 \le \mu_{ij}(b) \le 1, \sum_{j=1}^{n_i} \mu_{B_{ij}}(b) = 1 \tag{14}$$

Assume $U = \{u_1, u_2, ..., u_n\}$, the variable of a causal dependency in U is represented by a directed arc $D = [(u_i, u_j)| i \ne j; i, j = 1,2,..., n] \subset U \times U$, $\gamma_{u_i}^+$ represents node collection of fuzzy variable u_i, the probability of causal dependency can be expressed as a conditional probability.

$$P = \left[P(u_i|\gamma_{u_i}^+) i = 1,2,...n\right] \tag{15}$$

Thus, fuzzy Bayesian network can be represented in the following triples.

$$F_{BN} = (U, D, P) \tag{16}$$

The result of reasoning is to find the maximum possible state of continuous variable b_i corresponding to fuzzy variable u_i. For fuzzy Bayesian Networks, the node is given a probability vector corresponding to all possible states after reasoning.

4. Calculation and analysis

4.1. Calculation of target detection probability analysis

In the condition of a clear winter night, the detection targets are flying planes, the background is night sky with high visibility and clear visual. The spectral response range of infrared detector and low light level detector are respectively 8~14 μm and 0.35~0.90 μm. The target information is detected by low light level sensor and long wave infrared sensor in airborne photoelectric system.

The location and size factor θ, contrast radio of target and background C, atmospheric transmittance τ and spectral matching factor α and environmental factor L are shown in Table 1. Then we can calculate target information fusion detection probability of infrared sensor and low light level sensor, the results are also shown in Table 1, Table 2 and Table 3. I represents the information detected by infrared sensor, respectively, L is the low light level.

Table 1. Parameters by infrared sensor

Target	θ_I	C_I	τ_I	α_I
Target 1	0.4872	0.7850	0.9084	0.9173
Target 2	0.4730	0.8263	0.9067	0.9173

Table 2. Parameters of low light level sensor

Target	θ_L	C_L	τ_L	α_L	L
Target 1	0.4961	0.5550	0.8700	0.5051	0.0535
Target 2	0.4915	0.4943	0.8700	0.4730	0.0535

Table 3. Target information fusion detection probability of infrared sensor and low light level sensor

	Target 1	Target 2
Infrared sensor	0.3764	0.3931
Low light level sensor	0.0095	0.0079

Calculate the information fusion quality factor by selecting the most sensitive areas in target information, four image fusion algorithms are chosen as follows, including adaptive weighted average fusion (AW), laplacian pyramid fusion (LP), contrast pyramid fusion (CP) and wavelet fusion (W), calculation results of image fusion quality factors and target detection probability of infrared and low light level image fusion are shown in Table 4.

Table 4. Q_F and target detection probability of image fusion

	Q_F			
Fusion methods	AW	LP	CP	W
Target 1	0.5650	1.2870	1.2730	1.3020
Target 2	0.4700	1.1367	1.2368	1.3037
Detection probability of target 1	0.2208	0.4997	0.4950	0.5057
Detection probability of target 2	0.1950	0.4682	0.5000	0.5267

False alarm probability of infrared sensor and low light level sensor in airborne photoelectric system decreases along with the increment of the theoretical threshold, Fig. 1 shows the relation between the detection probability of airborne photoelectric system and the theoretical threshold. Under the same false alarm probability, Fig. 2 shows the relation between detection probability and the signal-to-noise ratio (SNR).

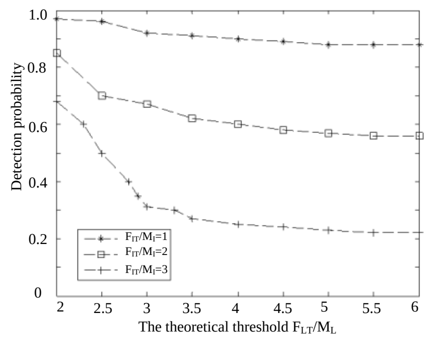


Fig. 1. The relationship between detection probability and theoretical threshold

With the increment of theoretical threshold, the detection probability of infrared sensor and low light level sensor in airborne photoelectric system decreases gradually, under the same theoretical threshold, the higher the threshold of infrared sensor is, the lower the detection probability becomes. Thus, under the condition of a certain false alarm probability, choose the appropriate theoretical threshold and the threshold of infrared sensor to obtain the maximum detection probability.

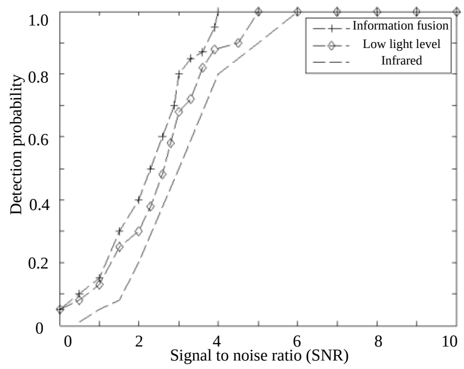


Fig. 2. The relationship between detection probability and SNR

In Fig. 2, under the same false alarm probability, with the increment of SNR, the detection probability of infrared sensor and low light level sensor in airborne photoelectric system increases, in light of the detection probability, the target information fusion of infrared sensor and low light level sensor is better than any single detection sensor, when the SNR increases, the detection probability of fusion sensors increases sharply.

The target location and size factor are related to the distance between target and the airborne photoelectric system, when the distance is far, the detection probability is small, and the longer the distance is, the smaller the the atmospheric transmittance becomes. The environmental illumination is another factor for influencing the detection probability, the environmental illumination is different because the extent of the low light level is different. The bigger the environmental illumination is, the bigger the detection probability becomes. In addition, the spectral matching coefficient of the low-light-level sensor and the target can affect the detection probability, when the environmental illumination is high, the spectral matching coefficient accords with the target much more better than low environmental illumination, then, the detection probability is better.

In order to verify the validity of the calculation method, we use correlation to represent the difference between calculated results and subjective results. The larger the absolute value of the correlation coefficient, the smaller differences between the two becomes, which shows the calculation results are closer to actual results. Fig. 3 shows the comparison of calculation results and the subjective results of target detection detection probability.

In Fig. 3, I represents the infrared, respectively, L is the low light level, the correlation coefficient is 0.8760, the absolute value of the correlation coefficient is between 0-1, 0 is completely unrelated, 1 is completely relevant. According to the correlation coefficient of target detection probability calculation results and subjective results in Fig. 3, results show that target detection probability calculation method of the infrared image and the low light level image fusion are in good agreement with the human eyes, the method can be used to assess the image fusion system for target detection performance.

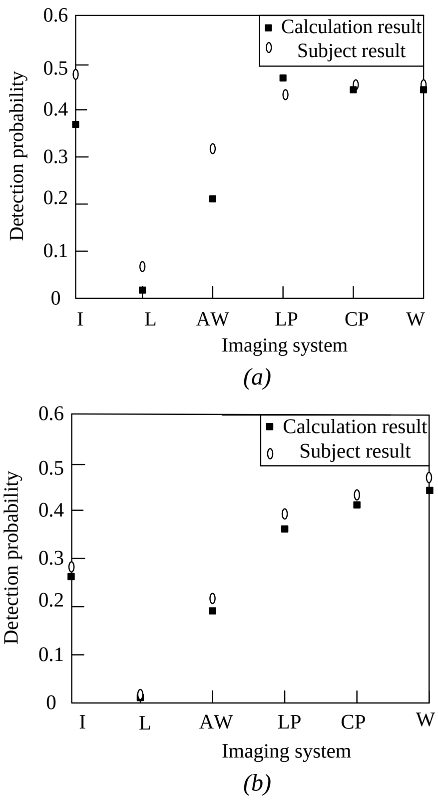


Fig. 3. Calculation results and the subjective results of target detection probability

4.2. Assessment analysis

Assume the target information has been detected by the airborne photoelectric detection system, state vectors of target are that the target flies at a high altitude of 4000 m with attacking weapons, flight speed is about 1000 km/h, the distance is 25 km, threat judgment can be made for prepared according to vectors of target.

The target threat assessment processing uses airborne photoelectric sensors to search and positions for targets firstly, making fuzzy partition for the obtained target characteristics after feature extraction and acquisition. According to relationship among target characteristics, identity and the tactical intention to establish its Bayesian network model. Then using the specify prior probability and conditional probability to initialize the Bayesian network, triggering network reasoning when the property information of new evidence is detected, the obtained posterior probability is used as a prior distribution for the next reasoning. Finally, probability distribution of the node state can be obtained and output target threat assessment results in accordance with decision rules.

According to the targets information through infrared sensor and low light level sensor in airborne photoelectric system, types of platform distribution in condition of no evidence can be got, we can make a fuzzy partition according to the measured velocity, update status by the Bayesian network model, the platform types of probability distribution can be got in condition of speed evidence. Then after adding the target altitude and target routes feature, the final probability distribution of the target platform type can be obtained. Identifying results of the platform type under different evidences are shown in Fig. 4.

State vectors of target threat estimation based on fuzzy Bayesian network model in photoelectric system are target threat assessment, target ability, target intention and platform type nodes. Target threat estimation nodes are represented by root nodes, including strong, moderate and weak. Target ability nodes are divided into strong, moderate and weak, target intention can be divided into attacking, detective and escorting. Target platforms are all being recognized types of target platforms, including bombers, fighters, helicopters and missiles.

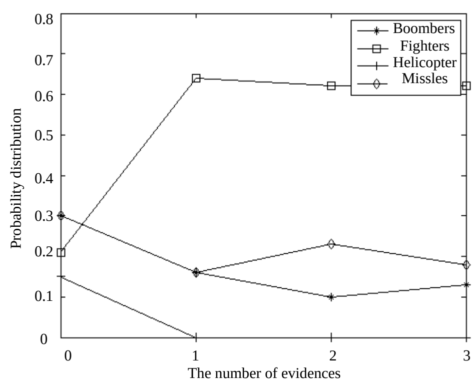
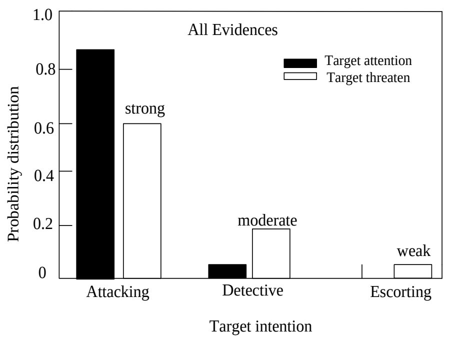
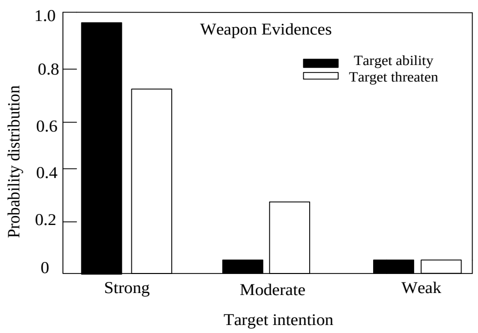


Fig. 4. Recognition results of platform types under different evidences

Based on the platform identification, the target intentions can be assessed by gradually adding course and location evidence information. The probability distribution of the target intention under different evidences are shown in Fig. 5.



(a)



(b)

Fig. 5. Target intention analysis results under different evidences

According to the results in Fig. 5, three probability distributions of target attacking, detective and escorting are respectively 0.9532, 0.2180 and 0, probability distributions of target threat are 0.5624, 0.1980 and 0.0496 under these evidences, probability distribution of target attacking capacity are 0.9775, 0.0147 and 0.0078 if weapons evidence information are added into the network, at this moment, node probability distributions of target threat assessment update for 0.6844, 0.3064 and 0.0092, thus, we can judge the threat degree of target is "strong".

5. Conclusions

In light of the problem that image fusion detection probability in airborne photoelectric system lacks of quantitative assessment method, aim to spectrum contrast ratio of target and background, characteristics of detectors and transmission characteristics, this paper establishes target detection probability calculation model of infrared and low light level image fusion, studies target threat assessment method of photoelectric sensors based on fuzzy Bay network, builds target threat assessment model of photoelectric sensors. Through the actual mission, target detection probability of infrared and low light level image fusion in airborne photoelectric system is calculated, through comparison to the human eye, results show that the proposed method can efficiently calculate target detection probability for infrared and low light level image fusion, the method is feasible. Make target threat assessment according to the obtained target characteristics information, simulation results show that the assessment is with high precision and fast evaluation, and the distinction between target threats is preferable, which indicates that the threat assessment model based on fuzzy Bayesian network can integrate prior information and posterior information, provides guidance for detection performance and target threat assessment of airborne photoelectric system.

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