The Non-linear Tracking of IMM- PHD Filter for Radar-Infrared Sensor Data Fusion

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Abstract. In order to improve the accuracy of multi-target tracking, a feasible data fusion system is proposed for radar and infrared sensor used together, to overcome the defects both small detection range and no distance measurement for infrared sensor, and to avoid the problem of large error in measurement information of single sensor. Radar and infrared data fusion can achieve complementary information. An optimal weighted fusion method for measurement of radar and infrared sensors is derived, and an interactive multi-model PHD nonlinear filtering algorithm is used to improve the accuracy of target tracking. The computer simulation results show that the integrated system and multi-sensor measurement fusion method can improve the accuracy of target state estimation. It is of great practical significance to solve the problem of target tracking estimation of heterogeneous multi-sensor.

1. Introduction
In the modern C4ISR combat system, in order to take the initiative of information battlefield, get the predominance in battlefield, and achieve "see clearly, respond quickly, and hit accurately", the combat side must attach great importance to the acquisition, collection and processing of information data, and get the information superiority. Modern battlefield environment is more and more complex, has been extended to five-dimensional operation system include the land, sea, outer space, sky, electromagnetic, using a single sensor has been unable to meet the new operational requirements, must carry out multi-sensor information fusion [1] to get battlefield information, make full use of complementary and redundancy of multi-sensor and multi-source data to improve data quality, access to accurate battlefield information and situation.

The shipboard air defense and anti-missile system is equipped with radar system and photoelectric system. Compared with homogeneous sensor fusion, heterogeneous sensor fusion system can give full play to the performance advantages between sensors [2], and give full play to the complementary role of application environment. As active sensors, radar can provide a complete and high precision target location information, but high power electromagnetic wave will be radiated when it is working, susceptible to electronic interference and vulnerable to anti-ship ballistic, at the same time, the development of stealth technology and the influence of high sea clutter and low level dead zone, result in the radar detection range is limited and the combat effectiveness to decline [3,4]. However, the passive sensor represented by the infrared sensor has the advantages of not radiating energy into the air, good passive concealment, strong target recognition ability, high accuracy of angle measurement and strong anti-interference ability, etc. But it has some disadvantages, such as close detection range, vulnerability to climate, and inability to provide the relative distance between the target and the sensor.
Therefore, combining radar and infrared sensors effectively will play for the high precision range measurement of radar and high precision azimuth measurement of infrared sensor [5] and provide more accurate target location estimation, improve the ability of target recognition, enhance the system's anti-jamming ability and reliability of system.

In the existing radar infrared fusion tracking method, such as literature [6], the range information of radar and infrared angle information are combined into a new measurement, and the Angle information of radar is completely ignored. Literature [7] proposed the most weighted fusion algorithm of Lagrange number multiplication based on the centralized fusion structure. in literature [8], two sensors are switched under the condition that the infrared measurement of radar is out of sync, which improves the sampling frequency. However, the tracking method of single sensor is still the essence. Work in this paper is that a feasible structure of radar-infrared sensor fusion system is constructed, and PHD filter is introduced to realize multi-target tracking while avoiding complex data association. The measurement dimension expansion method of infrared sensor is derived to achieve optimal weighted fusion of radar-infrared sensor measurement.

2. Centralized Radar-infrared Measurement Fusion

2.1. Model of Multi-sensor Observation

Multi-sensor fusion target tracking algorithm can obtain higher precision state estimation. However, due to the complexity of the algorithm and the long running time, Centralized Measurements Fusion (CMF) is adopted to process the measurement data in consideration of real-time. Assuming that the shipboard radar and infrared system are configured in the same ground, and have passed coordinate conversion, space-time registration and synchronization, the linear discrete system equation of the fusion system is expressed as:

\[ x_k = F_k x_{k-1} + v_{k-1} \]  

The measurement model equation of radar-infrared sensor is as follows:

\[ z_k^{(i)} = H_k^{(i)} x_{k-1} + w_k^{(i)}, \quad i = 1, 2 \]  

Where, when \( i = 1 \), \( z_k^{(1)} = \begin{bmatrix} r_k, \alpha_k^{(1)}, \beta_k^{(1)} \end{bmatrix}^T + w_k^{(1)} \) is the radar measurement, \( r_k \), \( \alpha_k^{(1)} \), \( \beta_k^{(1)} \) are the oblique distance, azimuth and pitching angles measured by radar. When \( i = 2 \), \( z_k^{(2)} = \begin{bmatrix} \alpha_k^{(2)}, \beta_k^{(2)} \end{bmatrix}^T + w_k^{(2)} \) is infrared measurement, where \( \alpha_k^{(2)} \), \( \beta_k^{(2)} \) are the azimuth and pitching angles measured by infrared sensor. \( w_k^{(i)} \) modeled as zero-mean Gaussian random processes with covariance \( R_k \).

\[ R_k^1 = \text{diag} [\sigma_{\alpha_1^2}, \sigma_{\beta_1^2}], \quad R_k^2 = \text{diag} [\sigma_{\alpha_2^2}, \sigma_{\beta_2^2}] \]  

where, \( \sigma_{\alpha_i^2} \) and \( \sigma_{\beta_i^2} \) ( \( i = 1, 2 \) ) are the measured noise variance of radar and infrared azimuth and pitching angle, \( \sigma_{r_k^2} \) is the measured noise variance of radar range.

In the case of target tracking with M radars and N infrared sensors, the measured data obtained by them are fused in the fusion center. There are M+N groups measurement data at time \( k \), they are \( Z_{k,1}, Z_{k,2}, \ldots, Z_{k,M+N} \), where \( Z_{k,j}^R \) is given by

\[ Z_{k,j}^R = \begin{bmatrix} r_{k,j}, \alpha_{k,j}^R, \beta_{k,j}^R \end{bmatrix}^T, \quad j = 1, L, M \]  

where \( r_{k,j}^R \), \( \alpha_{k,j}^R \) and \( \beta_{k,j}^R \) are azimuth measurement, pitching angle measurement and distance measurement of radar.

The measurement of the infrared sensor is given by:

\[ Z_{k,j}^I \]
\[ Z_{kj}^l = [\alpha_{kj}^l, \beta_{kj}^l], \quad l = M + 1, L, M + N \]  

(5)

where \( \alpha_{kj}^l, \beta_{kj}^l \) are azimuth and pitching angle measurement of infrared sensor.

The Gaussian noise covariance matrix measurement \( \Theta_{k,j}^R \) and \( \Theta_{k,j}^{I} \) of radar measurement \( Z_{k,j}^R \) and infrared measurement \( Z_{k,j}^{I} \) are given by:

\[
\Theta_{k,j}^R = \text{diag}[C_{k,j}^{R,\alpha}, C_{k,j}^{R,\beta}], \quad j = 1, L, M \\
\Theta_{k,j}^{I} = \text{diag}[C_{k,j}^{I,\alpha}, C_{k,j}^{I,\beta}], \quad l = M + 1, L, M + N
\]  

(6)

Where \( C_{k,j}^{R,\alpha}, C_{k,j}^{R,\beta} \) are the measurement noise of radar range, azimuth and pitching angle, \( C_{k,j}^{I,\alpha}, C_{k,j}^{I,\beta} \) are measurement noise variance of azimuth angle and pitching angle of infrared sensor, and the angle measurement accuracy of infrared sensor is higher than that of radar.

2.2. Radar - infrared Data Weighted Fusion

The radar-infrared measurement data fusion structure was constructed, as shown in figure 1, to avoid the problem of missing target information due to inaccurate radar azimuth measurement. The measurement accuracy after the optimal weighted fusion was significantly improved, which was better than that of a single sensor.

![Figure 1. Centralized radar and infrared sensor fusion structure](image)

All measured data at time \( k \) were weighted fusion disposed:

\[
w_{k,j}^{R,\alpha} = 1/\left[ C_{k,j}^{R,\alpha} \left( \sum_{j=1}^{M} 1/C_{k,j}^{R,\alpha} + \sum_{l=M+1}^{M+N} 1/C_{k,j}^{I,\alpha} \right) \right]
\]

\[
\hat{\alpha} = \sum_{j} w_{k,j}^{R,\alpha} \alpha_{kj}^{R,\alpha} + \sum_{l=M+1}^{M+N} w_{k,\hat{l}}^{I,\alpha} \alpha_{kj}^{I,\alpha}
\]

\[
w_{k,j}^{I,\alpha} = 1/\left[ C_{k,j}^{I,\alpha} \left( \sum_{j=1}^{M} 1/C_{k,j}^{R,\alpha} + \sum_{l=M+1}^{M+N} 1/C_{k,j}^{I,\alpha} \right) \right]
\]

\[
\hat{\beta} = \sum_{j} w_{k,j}^{R,\beta} \beta_{kj}^{R,\beta} + \sum_{l=M+1}^{M+N} w_{k,\hat{l}}^{I,\beta} \beta_{kj}^{I,\beta}
\]

\[
w_{k,j}^{R,\beta} = 1/\left[ C_{k,j}^{R,\beta} \left( \sum_{j=1}^{M} 1/C_{k,j}^{R,\beta} + \sum_{l=M+1}^{M+N} 1/C_{k,j}^{I,\beta} \right) \right]
\]

\[
\hat{\gamma} = \sum_{j} w_{k,j}^{R,\gamma} \gamma_{kj}^{R,\gamma}
\]

\[
w_{k,j}^{R,\gamma} = 1/\left[ C_{k,j}^{R,\gamma} \sum_{j=1}^{M} 1/C_{k,j}^{R,\gamma} \right]
\]

(7)

All measured noise data are weighted fusion disposed:
Especially pointed out that infrared sensor cannot obtain distance measurement data, cannot directly implement sensor data fusion. The radar distance measurement is directly used as the virtual distance measurement method of the infrared sensor, so as to avoid the non-positive covariance of the estimation error caused by the traditional extended dimension of the infrared sensor measurement data. After dimension expansion the infrared mixing measurement is as follows:

\[ \tilde{Z}_{k,l} = [\hat{r}_k, \alpha_{k,l}, \beta_{k,l}]^T, \quad I = M + 1, L, M + N \]  

Where \( \hat{r}_k \) is the final result of weighted fusion of the distance measurement data of the radar at time \( k \).

The noise covariance matrix of the infrared mixed measurement is as follows:

\[ \hat{\Theta}_{k,l} = \text{diag}[\hat{C}_{k,l}^{\alpha}, \hat{C}_{k,l}^{\beta}, \hat{C}_{k,l}^{\gamma}] \]  

The results, \( \tilde{Z}_k = [\hat{r}_k, \alpha_k, \beta_k]^T \), obtained by weighting are a set of measurements for multiple sensors.

According to the structure in figure 1, the fusion center carries out centralized measurement fusion according to CMF method, and feedback the final measurement set, \( \tilde{Z}_k \), to infrared sensor 2 and radar 1. Then do the first step of prediction update, take the update result, \( D_k(x) \), as the predicted value of radar 1, The radar 1 do the second step update with the measurement fusion \( \tilde{Z}_k \) and \( D_k(x) \) to further improve the filtering accuracy and takes the update result as the final filtering result.

### 3. Nonlinear PHD Filter Fusion Tracking Process

Due to radar and infrared sensor measurement equation is nonlinear, based on the multiple model PHD filtering algorithm \([9-12]\) for fusion target tracking. The multi-sensor PHD filtering algorithm updates the state filtering results of the single-sensor PHD filter in sequence according to the centralized fusion structure. The filtering process is as follows:

Step 1: PHD filter predictive value \( D_{k-1}(x) \) and fusion measurement data \( \hat{Z}_k = [\hat{r}_k, \alpha_k, \beta_k]^T \), forecast update, obtain the updated value of infrared PHD function \( D_k^I(x) = L_k^I(x)D_{k-1}(x) \). "Pseudo-likelihood function" of infrared sensor, \( L_k^I(x) \), can be expressed as:

\[ L_k^I(x) = 1 - P_{D,k}^I(x) + P_{D,k}^I(x) \sum g_k^I(x) \int P_{D,k}^I(x)g_k^I(x)D_{k-1}(x)dx \]  

Step 2: Update \( D_k^I(x) \) and the fusion measurement data \( \hat{Z}_k = [\hat{r}_k, \alpha_k, \beta_k]^T \), obtain the update value of radar PHD function \( D_k^R(x) = L_k^R(x)D_k^I(x) \). \( L_k^R(x) \) is "Pseudo-likelihood function" of radar, it can be expressed as:
\[
L_k^i(x) = 1 - P_{o,i}^k(x) + \sum_{z_k^i} g_{o,i}^k(z_k^i) + \int P_{o,i}^k(x)g_i^k(x)D_{k,i}^{o,i-1}(x)dx
\]

(12)

Step 3: Where \( D_{k,i}^o(x) \) is the global PHD function of fusion filter algorithm. Assumption, there are \( m \) sensors, according to Bayes recursion formula. The recursive relationship, \( D_k(x) \), is as follows

\[
D_k(x) = L_k^o(z_k^o | x)D^{o,i-1}_{k,i-1}(x) = L_k^o(z_k^o | x)L_i^i(z_i^i | x)D_{k,i}^{o,i-1}(x)
\]

(13)

\( L_i^i(z_i^i | x) \) is the "pseudo-likelihood function" of the sensor order \( i \):

\[
L_i^i(z_i^i | x) = 1 - P_{o,i}^k(x) + \sum_{z_i^i} g_{i}^k(z_i^i) + \int P_{o,i}^k(\xi_i)g_i^k(\xi_i)D_{k,i}^{o,i-1}(\xi)dx
\]

(14)

4. Simulation Analysis

4.1. Simulation Parameter Setting

Given that there are two maneuvering targets in the monitoring area, monitoring time 50s, Sampling interval \( T = 0.1s \). The initial state of target 1 is \([5000, -120, 1.5; -8000, -300, 3.5; 3000, -10, 0.5]\), The initial state of target 2 is \([200, 200, 5; 300, 200, 15; 100, 50, 12]\). It is assumed that radar and infrared sensors are configured in the same location and synchronized through spatio-temporal correlation. In simulation, the measurement noise covariance matrix of radar is \( \Theta^r = diag([100, 0.01, 0.01]) \), The measurement noise variance matrix of infrared sensor is \( \Theta^i = diag([0.0001, 0.0001]) \). Applying interactive multi-model gaussian hybrid PHD algorithm (IMM-GM-PHD), Model subset: CV, CA and CT, Prior probability: \( \mu_0 = [1/3, 1/3, 1/3] \), Transfer matrix between models: \( \pi = [0.9, 0.05, 0.05; 0.05, 0.9, 0.05; 0.05, 0.05, 0.9] \)

4.2. Analysis of Simulation Results

Figure 2 shows the comparison between the simulated target trajectory and radar-infrared fusion tracking filter trajectory. Figure. 3 and Figure. 4 are the comparison results of the root mean square error(RMSE) of the infrared individual tracking and fusion tracking filtering errors of target 1 and target 2 in the 20 times of 3d radar simulation. It can be seen from figure 3 and figure 4 that radar-infrared fusion tracking accuracy is significantly higher than that of single sensor observation and tracking, indicating that the interactive multi-model nonlinear PHD fusion tracking filtering algorithm is effective and applicable. The tracking accuracy of radar or infrared sensor is related to the relative position of the target, so the multi-sensor fusion tracking can integrate the advantages of each single sensor, realize information complementarity, and accurately estimate the target state.
5. Conclusion
For the advantage of infrared sensor, such as excellent concealment, not susceptible to electronic interference, excellent low altitude detection performance, high angle measurement accuracy, and the characteristics of radar, such as high ranging accuracy, but low angle measurement accuracy, we study how to use them together to realize information complementation, estimate target state accurately, and improve system reliability and stability. The research on radar and infrared multi-sensor fusion tracking was carried out, and the feasible structure of radar-infrared sensor fusion system was constructed. In order to give play to the respective advantages of radar and infrared sensor, the method of infrared sensor measurement and dimension-expanding was derived, and the optimized weighted fusion of radar-infrared sensor measurement was realized. IMM-GM-PHD nonlinear filtering algorithm is used to improve the tracking accuracy. MATLAB simulation shows that the fusion system and multi-sensor measurement fusion method can achieve high-precision target tracking. It will be of great engineering value to the future multi-objective tracking system, and has important practical significance for solving the problem of heterogeneous multi-sensor target tracking estimation.
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