Track closely-spaced moving objects

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An iterative computational method uses IR images to evaluate the positions and trajectories of moving objects in a cluster.

Warhead and decoy discrimination relies on IR sensors to track individual objects moving through the air. Closely spaced objects (CSO) cannot easily be tracked as they create a pixel-cluster in the IR imaging. The lack of resolution in images obtained using the standard IR radiation model makes it difficult to distinguish the numbers, positions, and radiant intensities of objects (see Figure 1). Previous approaches to increase the resolution, to what is known as super-resolution, used a single IR measurement (single-frame data). These approaches required multi-target tracking techniques, such as joint probability data association (JPDA) or multiple hypothesis tracking (MHT), to estimate the trajectory of each object from single-frame data. However, this did not give high-resolution results and, therefore, could not reliably track the trajectory of several objects at once. A recent attempt to replace the single-frame by a multi-frame approach involved constructing a multi-frame objective function describing the position and trajectory of each object. This objective function was then optimized by the least-squares criterion to obtain better super-resolution. An advantage of the multi-frame approach was that it did not require multi-target tracking data-processing techniques.

The multi-frame approach has three drawbacks. First, it requires optimization of the objective function, which presents challenges because that function is high-dimensional and non-linear. Second, the standard IR radiation model postulates a single IR frequency fluctuation, which is not consistent with empirical observations of multiple IR frequencies. Therefore, the postulate may need to be refined to achieve higher resolution in IR measurements. Third, the approach requires a heavy computational load to use the standard object identification method, known as the penalized-likelihood model-selection scheme. To address these drawbacks, yet still retain the advantages of the multi-frame approach, we developed a new method called reversible jump Markov chain Monte Carlo (RJMCMC).

Figure 1. Sketch of the closely spaced objects (CSO) on the infrared focal plane. y: Position on horizontal axis. x: Position on vertical axis. d: Length of focal plane pixel. f<sub>opt</sub>: Focal length of the sensor.

Figure 2. Infrared focal plane pixel cluster representation at first frame.
Based on the Bayesian theory, RJMCMC collects fresh evidence through an iterative process and repeatedly modifies an initial confidence in the truth of a hypothesis. Our study exploits this model to identify CSO.

Our method concomitantly models the distinct IR signals emitted by all the objects in a cluster. In the basic Bayesian model, the signal (or object) number and the model parameters are treated as random variables. In each iteration of the Bayesian method, the initial belief (or prior probability) is modified after iteration to obtain the posterior probability. Using this approach, we defined the joint-prior probability distributions of object numbers and model parameters, then the method determined the joint-posterior distributions. We then drew samples from the posterior distribution using our RJMCMC method and estimated the number of objects and model parameters. The main advantage of the RJMCMC method was that it allowed for Bayesian inference when the posterior function was complicated. In addition, it can work even when the number of CSO is unknown.

With this method, we modeled the mid-course trajectories of CSO projected on the IR focal plane. They appeared to follow a straight line with a constant velocity. We then applied a Bayesian model to define a posterior distribution of the variables including the objects’ initial states (i.e. their projection on the IR focal plane), their radiant intensities, their sensor noise variance, and their attributed number. The advantage of this model is that it integrates parameters, such as radiant intensities, and eliminates their frequency fluctuation, thus removing one of the drawbacks of using the standard IR radiation model. Another advantage of the RJMCMC method is that it maximizes the posterior distribution and, therefore, improves resolution.

We tested our method on a simulation involving three CSO at mid-course. We collected 10 focal plane images at one-second intervals (see Figure 2). The signal-to-noise ratio of each object was selected randomly between 10 and 20. We then set the iterative number of RJMCMC to 20,000 and performed 100 Monte Carlo simulations. We demonstrated that we could identify each object correctly in 94% of cases.

Next, we calculated the root mean-square-error (RMSE) of the estimates of the projected position for each object (see Figure 3). This RMSE was less than 0.09 pixel, and it was less than half of the minimum separation (about 0.45 pixel) on the focal plane. This means that we were able to estimate the position of each object with high accuracy.

We also plotted the normalized RMSE (NRMSE) estimates of the radiant intensity for each object (see Figure 4). This NRMSE was less than 0.25, and the intensity results were closely related to the estimated position. This means that the proposed method can efficiently estimate the radiant intensity of each object.

Finally, we calculated the central processing unit time using MATLAB to give an estimate of the computational efficiency of our method on a 2.40GHz PC. The average time of computation for each test was 1884.5 seconds. This means that our proposed approach was computationally effective to determine position and trajectory of CSO.

In summary, we proposed a Bayesian method that provided the precise position (super-resolution) and trajectory estimates for CSO observed at mid-course using multi-frame IR data. The confidence interval in the identification of the number of individual objects can be refined by increasing the number of iterations of the RJMCMC. In future work, we will focus on a more exact dynamic ballistic model and extend the Bayesian

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approach to both super-resolution and ballistic trajectory estimation of CSO at mid-course using IR multi-sensor and multi-frame data.

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References