A Real-Time Multistage IR Image-Based Tracker

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ABSTRACT

In this paper we describe a real time algorithm for a missile-based IR tracking system. A correlation-based tracker is considered to be the primary tracker, while a feature-based tracker is chosen to provide support on a secondary level. A prescreener runs concurrently with the trackers to provide a list of probable target centroids. This information is used to provide a level of confidence to the tracker. The tracker subfunctions are implemented in both programmable logic hardware and software operating on digital signal processors. The maximum sustained pixel data rate that can be processed is 10 MHz, which will provide a 60 Hz tracker with a 256 x 256 input image and a 30 Hz tracker for a 512 x 512 input image. The prescreener function is implemented in reprogrammable hardware subfunctions that operate up to the full 10 MHz pixel rate producing target centroids.

Keywords: Correlation, Features, Tracker, Infrared, Prescreener, Centroids

1. INTRODUCTION

This paper will discuss both the algorithm components and the hardware capabilities required to implement a multi-stage infrared (IR) missile tracker in real time. In practice, there are several issues that need to be considered when developing an imaging infrared missile tracker. The detection and tracking algorithms are required to be robust to changes in the target signature which will vary depending on the time of day, environment, and atmospheric conditions, as well as aspect and depression angles. In addition, the number of pixels on target will vary dramatically from the first to last frame of the missile flight.

2. TRACKER OVERVIEW

This tracker algorithm has two main components. The first, known as the primary tracker, consists of a correlation tracker. The correlation tracker begins tracking on a predesignated target. In the event that the primary tracker does not meet a predetermined set of conditions, the secondary tracker takes over. The correlation tracker is implemented in multiple digital signal processors (DSPs) utilizing a dedicated frame memory containing both intensity and edge image data for each entire frame. These frame memories are updated at the full 60 Hz frame rate and can be addressed by any of the DSPs. The secondary tracker is a feature-based tracker in which segments corresponding to each target centroid are extracted from the IR image and various features associated with them are calculated. The features are input into a similarity metric that incorporates target statistics acquired during the primary tracker mode. A high degree of similarity ensures a valid target track. Once the similarity measure reaches a predetermined threshold, the primary tracker is again enabled. The feature–based tracker utilizes a single DSP in conjunction with the image frame memories to compute and analyze the desired features at a reduced data rate. Image feature statistics will be kept on the tracked object locally within the single DSPs local memory. Figure 2 shows the tracker hardware block diagram.

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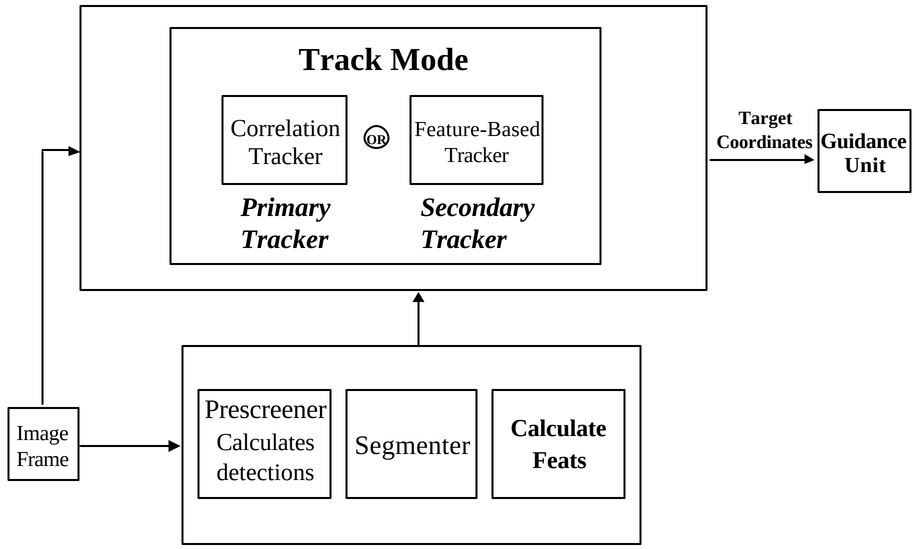

Figure 1 Tracker Components

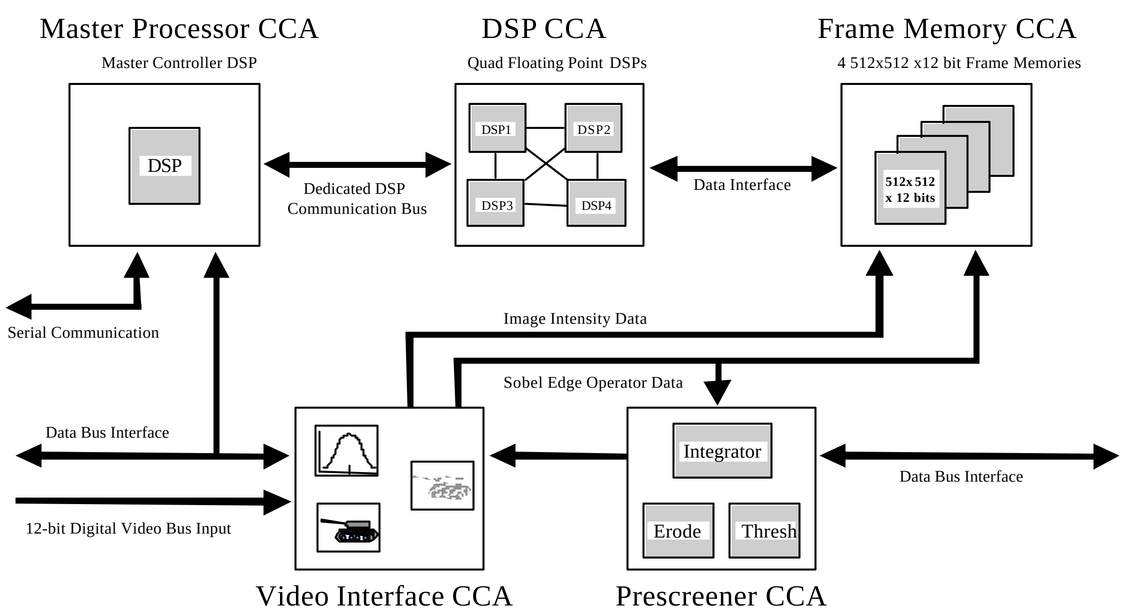

Figure 2 Tracker hardware Diagram

3. CORRELATION TRACKER

The correlation tracker is the primary tracker of the system. It calculates the minimum mean square error[3] (MMSE) between a rectangular window of pixels referred to as the reference window and another larger rectangular region of search window pixels as shown in Figs 3 and 4. The tracker hardware will support up to a 128 x 128 search window and 64 x 64 reference window sizes at the full 60 Hz frame rate. The correlation coefficient corresponding to the pixel location of the minimum of the MMSE surface is calculated and provides a measure of the validity of the track.

$$MMSE(\hat{x},\hat{y}) = \min\left(\sum_{x,y} \left| \tilde{f}_{current}(x,y) - g_{history}(x+\hat{x}, y+\hat{y}) \right|^2 \Big/ N^2 \right)$$

$$= \min\left(\sum_{x,y} \left(\tilde{f}^{\,2}_{current}(x,y) - 2\tilde{f}_{current}(x,y)\, g_{history}(x+\hat{x}, y+\hat{y}) + g^2_{history}(x+\hat{x}, y+\hat{y}) \right) \Big/ N^2 \right)$$

where

$\tilde{f}_{current}(x,y) =$ the current search window gated by a mask of ones the size of $g_{history}$

and

$g_{history}(x,y)$ = the reference window used in the correlation.

The first term in the above equation is referred to as the "correction term" and is essentially a normalization term. The middle term is referred to as the correlation term while the last term is a constant.

Since correlation in the spatial domain is essentially equivalent to multiplication in the frequency domain, it is often more efficient to process in the frequency domain using FFTs. So the MSE can be computed in the frequency domain as:

$$MSE(w_1,w_2) = F^2(w_1,w_2)M^*(w_1,w_2) - 2F(w_1,w_2)G^*(w_1,w_2) + G^2(w_1,w_2).$$

The first reference window is obtained by extracting a region of the image that is centered on the target and just large enough to encompass the entire target. The sizes of the search window and the reference window will vary frame to frame depending on the range to the target. The search window is defined to be a rectangular region surrounding the target that is at least twice as large as the reference window.

Once the minimum location corresponding to the target is obtained, its coordinates are sent to the guidance and control unit and the gimbal is slewed to that location.

Since the target is constantly changing contrast due to aspect and depression angle changes, the reference window being used at each frame is actually a lag filtered version of the previous reference window and the current window. Assume that $g_{history}$ refers to the reference window being used in the *i*th frame correlation calculation, the equation for determining it is given by

$$g_{history_i} = x * g_{current_i} + (1-x) * g_{history_{i-1}}$$

where

$g_{history_i} =$ the weighted reference window at frame *i*;

$g_{current_i} =$ a reference window size region centered on the target extracted from the current frame *i*,

$g_{history_{i-1}} =$ the reference window used for correlation in the previous frame *i*-1,

and

$x =$ the reference window update rate (<1).

If the correlation value of the corresponding MMSE drops below a given threshold, T1, for M1 out of N1 times, the value of x is increased to account for a target signature change, possibly due to turning. This incorporates the new target signature information into the reference window. It is not increased too quickly in case the target is temporarily occluded by a slight obscuration.

If the correlation value of the corresponding MMSE drops below a given threshold, T2, for M2 out of N2 times, the tracker switches to the feature-based tracker.

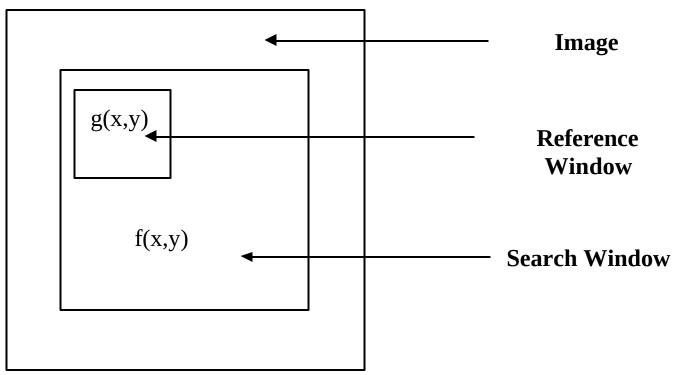

Figure 3 Correlation Windows

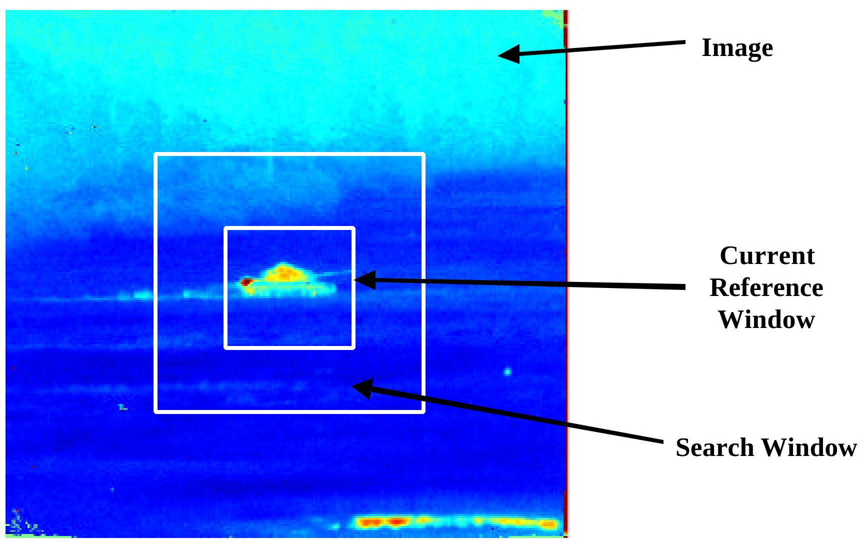

Figure 4 Example Correlation Regions

4. FEATURE-BASED TRACKER

The feature-based tracker operates on the idea that if the correlation tracker confidence drops due to some artifact in the imagery or minor obstruction, the general features of the target will still be present and can be used to form a measure of the track validity. While the correlation tracker is operating, features of segments associated with target detections provides by the prescreener (which is discussed in the next section) are computed. The moving mean and variance of these features over P frames are calculated and stored for later use in a similarity measure. The Mahalanobis distance metric[1] is used to determine the degree of similarity of a current target segment to past observations of the target being tracked. In this formulation, it is assumed that the chosen features are essentially uncorrelated and thus a diagonal matrix containing the inverse variance of each of the features replaces the inverse covariance matrix. The similarity metric is given by

$$M = \sum_{i=1}^{N} W_i \frac{\left(X_i - \overline{X}_i\right)^2}{d_i^2}$$

M = Mahalanobis distance

W_i = weighting coefficient on ith tracking feature

X_i = value of ith tracking feature for current cycle

$\overline{X}_i$ = mean of ith tracking feature

d_i^2 = variance of ith tracking feature

If there is one detection provided by the prescreener corresponding to the search window region, the Mahalanobis distance is calculated. If it is smaller than T2 for M3 out of M4 times, the target corresponding to the detection is considered to be a valid track and its pixel coordinates are sent to the GEU and the tracker returns to the primary mode of tracking.

5. PRESCREENER

The prescreener is the missile target detector. Its purpose is to provide a list of all possible target centroids in each image frame. Range to the center of the infrared image prior to launch is assumed known. From this, it is possible to calculate range for every line in the image and in turn the appropriate number of pixels corresponding to a target at any location in the image. Hardware FPGAs are used to create Sobel[2,3] edge image magnitude and direction images from the input video stream in real-time. These FPGAs can be programmed to apply any user defined 3 x 3 operator. Reprogrammable hardware is available to calculate real-time histogram data about various images within the prescreener process. The histogram data is placed in FIFO memories that are read by the master DSP processor to compute image threshold levels. The first step in the prescreener calculates strong edges in the image by applying the Sobel edge operator. Once the Sobel edge magnitude is calculated, it is thresholded and binarized. The thresholded value is determined from the Sobel magnitude histogram. It is chosen by determining which value corresponds to a given slope of the histogram starting from the maximum bin and working towards the lowest. The image is then integrated with variable box sizes, from a minimum of 3 x 3 to a maximum of 64 x 64, corresponding to possible targets. It is again thresholded according to the histogram. Once the integrated image has been thresholded, it is binarized and the target centroids are calculated by applying the morphological erode operator. The number of erodes necessary to create each centroid is stored and compared to the number that would be necessary to erode a target at the given location in the image. If it is too large or too small, the object is considered to be invalid and that centroid value is discarded. The remaining centroids comprise the detection list for the current image frame. Each of the prescreener functions have been implemented in hardware FPGAs to allow the prescreener algorithm to operate at real-time frame rates; producing a target candidate list for each frame of input image data. Images corresponding to the above steps are shown in Figs. 5-8.

Prescreener/ Detector

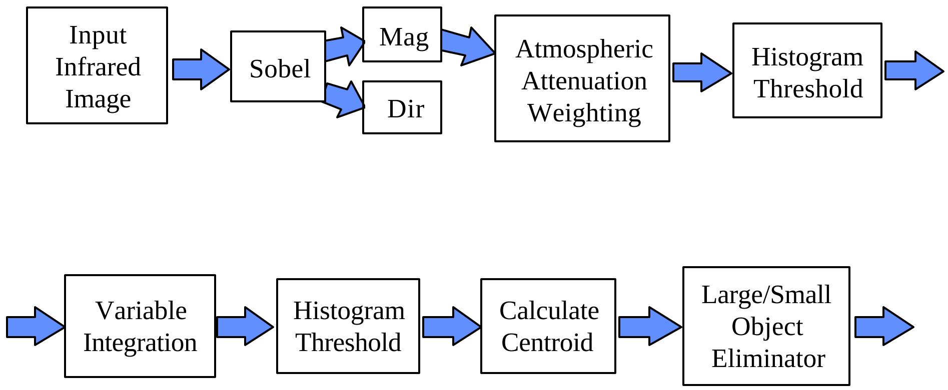

Figure 5 Prescreener Flow

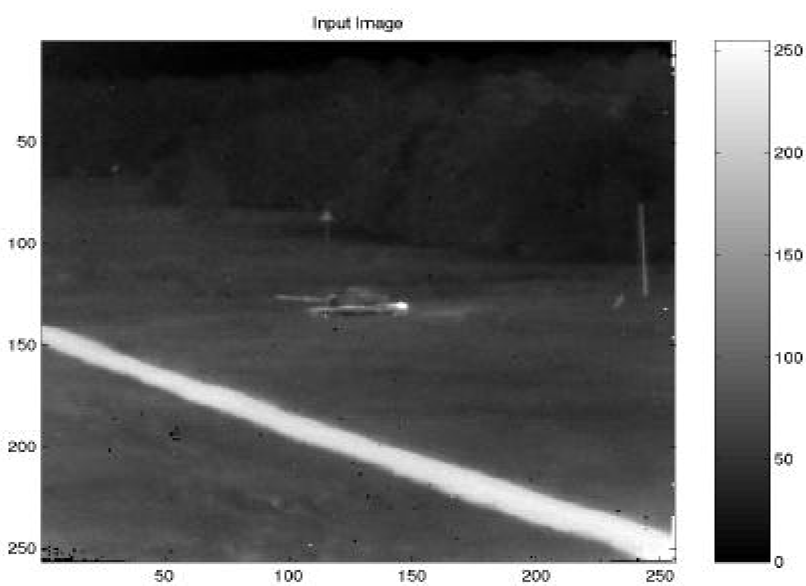

Figure 6 Input Image

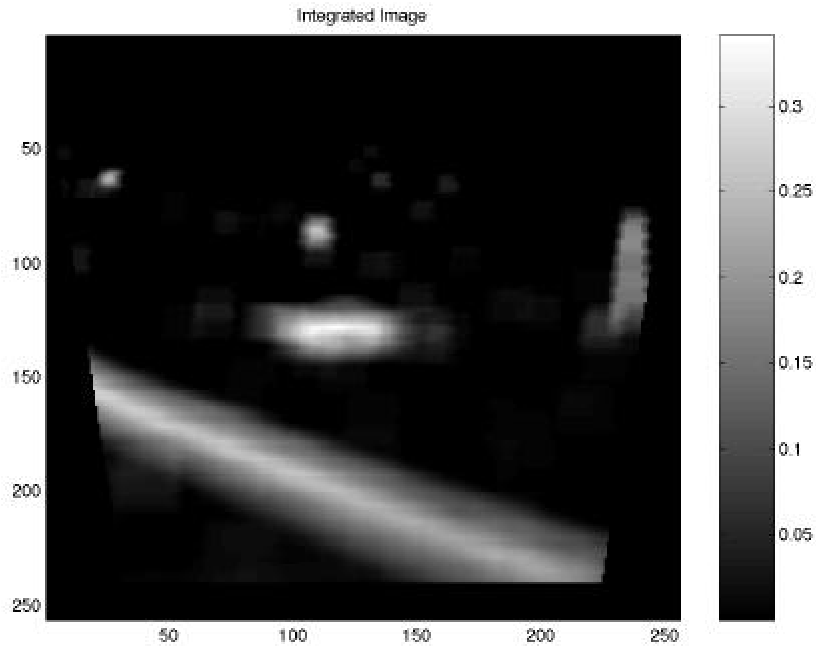

Figure 7 Integrated Image

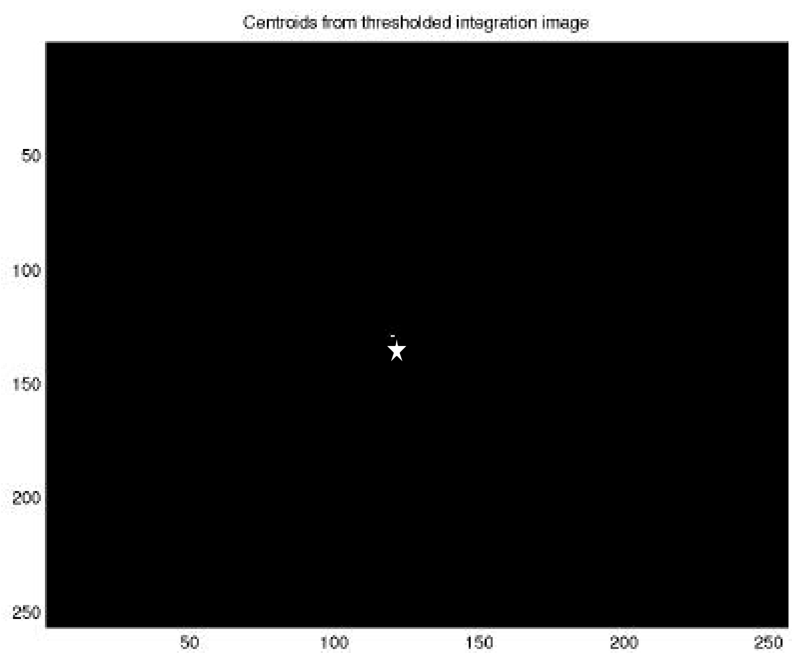

Figure 8 Target Centroid

6. CONCLUSIONS

This paper has outlined the algorithm and hardware components that comprise a real time missile-based imaging infrared tracker. Hardware and software implementations of the tracker concepts have matured to a level where developed algorithms have been implemented in hardware to minimize the required software and to reduce processor load requirements. Due to the processing power and versatility of current state-of-the-art DSP chips, some of the tracker algorithms (i.e., FFT, correlation) meet the overall tracker mode timeline requirements as software components as opposed to dedicated hardware. The tracker concepts have been packaged in both tactical missile guidance flight hardware as well as standard laboratory electronic card formats.

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