Fringe-adjusted joint transform correlator based target detection and tracking in forward looking infrared image sequence

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Abstract. The joint transform correlator (JTC) technique has been found to be suitable for real time pattern recognition applications. Among the various JTC techniques proposed in the literature, the fringe-adjusted JTC has been found to yield better correlation output for target detection. We propose a generalized fringe-adjusted JTC (GFJTC) based algorithm for efficient detection and tracking of a target in a video sequence. The proposed algorithm has been found to be suitable for near real-time recognition and tracking of a static or moving target, while accommodating the detrimental effects of background variations as well as other artifacts. The performance of the proposed technique has been verified with real life forward looking infrared (FLIR) image sequences.
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Subject terms: target detection; joint transform correlation; fringe-adjusted filter; joint power spectrum; forward-looking infrared image sequence.

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1 Introduction

The joint transform correlator (JTC)[1] technique has shown remarkable promise for real time optical pattern recognition and tracking applications.[2,3] The main advantages of the JTC are that it does not require any complex filter fabrication, allows real time update of the reference image, permits simultaneous Fourier transform of the reference image and the unknown input scene, and avoids the precise positioning otherwise required in matched filter based correlators.[4]

A new class of JTCs that employs Fourier plane joint power spectrum (JPS) apodization based on the reference image has been found to yield better correlation output. Among the various apodization based techniques, the proposed fringe-adjusted filter (FAF) based JTC appears to be particularly attractive, since it avoids the problems otherwise associated with alternate JTC techniques.[1–3,5–7] The fringe-adjusted JTC[8] employs a real valued filter called FAF at the Fourier plane, and the JPS is multiplied by FAF before applying the inverse Fourier transform to yield the correlation output.[9] The fringe-adjusted JTC has been found to yield better correlation performance than alternate JTCs[1–3,6] for the case of noise free single target and multi-target binary input scenes under normal as well as poor illumination condition.[8–12] However, for noise corrupted input scenes, whenever the reference power spectrum contains very low values, a fringe-adjusted JTC has been found to yield low correlation peak intensity. To overcome this limitation, recently a fractional fringe-adjusted JTC[13] technique has been proposed that employs a family of real valued filters, called generalized fringe-adjusted filters (GFAFs).

Although various JTC techniques have been employed for detecting target(s) from unknown input scenes, very little work has been reported in the literature for target tracking in real-life scenarios. Tam et al.[14] proposed a classical JTC based target tracking technique[14] using sample binary images for a limited number of frames. However, in a real life scenario, target tracking is more challenging because the input scene may contain target like objects; objects much brighter than the target; partially occluded targets; blurry targets; targets blending with the background; and targets affected by rotation and scale variations as well as other 3-D distortions. To overcome the aforementioned limitations, it is necessary to develop a more robust and efficient target tracking algorithm.

In matched spatial filter-based tracking,[15] the reference image is generated from several hundred training images where each training image represents a unique appearance of the desired target with respect to size and/or in-plane and/or out-of-plane rotation and scale variations. We discuss the development and implementation of an algorithm based on GFJTC, capable of detecting and tracking a target in gray-level video sequences acquired by an infrared camera mounted on a moving platform. In our case, the reference is a single image that is updated adaptively from one frame to the next frame of a sequence. Tracking is achieved by applying GFJTC by correlating consecutive frames of a sequence and additional postprocessing of the correlation output. The performance of the proposed technique has been verified with real-life forward looking infrared (FLIR) video sequences.

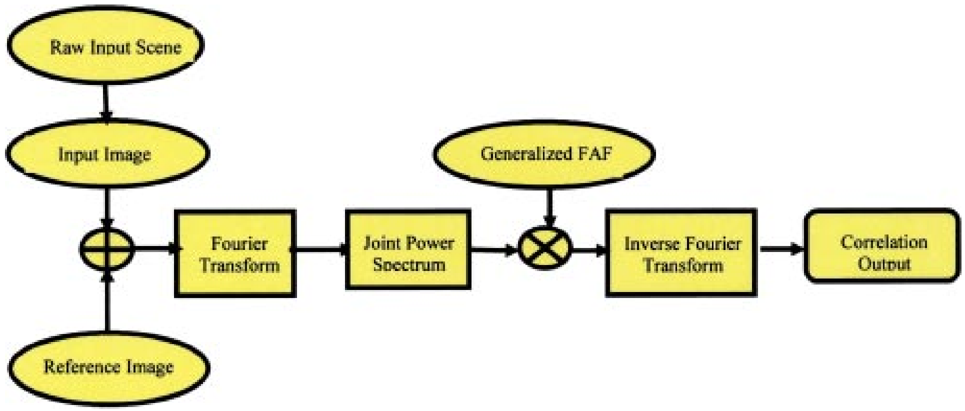

Fig. 1 Fringe-adjusted joint transform correlation algorithm.

2 Generalized Fringe-Adjusted JTC Based Algorithm

In a JTC, the unknown input scene and the known reference image are displayed side by side in the input plane, illuminated by a coherent, collimated laser beam. The input joint image plane is located at a distance of one focal length from a lens, which Fourier transforms the input joint image at the Fourier plane. The Fourier transformed patterns constructively interfere with each other to create an interference pattern called a joint power spectrum. This interference pattern is recorded in real time using a square law device such as a charge-coupled device (CCD) camera. The joint power spectrum is inverse Fourier transformed by another Fourier transform lens to yield the correlation output. For a match, two correlation peaks or bright spots are produced, and for a mismatch, negligible or no correlation peaks are produced.

The block diagram for the fringe-adjusted JTC algorithm is shown in Fig. 1, where the reference and the unknown input image are introduced in the input plane using a spatial light modulator (SLM), such as a liquid crystal television illuminated by a laser light source. If $r(x,y+y_0)$ represents the reference image, and $t(x,y-y_0)$ represents the input scene containing n objects $t_1(x-x_1,y-y_1)$, $t_2(x-x_2,y-y_2),\ldots,t_n(x-x_n,y-y_n)$, respectively, and if the input scene is also assumed to be corrupted by noise $n(x,y-y_0)$, the input joint image becomes

$$f(x,y)=r(x,y+y_0)+\sum_{i=1}^{n} t_i(x-x_i,y-y_i-y_0)+n(x,y-y_0). \quad (1)$$

Applying a Fourier transform to the input joint image of Eq. (1) yields the JPS, given by

$$\begin{aligned}|F(u,v)|^2 &= |R(u,v)|^2+\sum_{i=1}^{n}|T_i(u,v)|^2+|N(u,v)|^2 \\ &+2\sum_{i=1}^{n}|T_i(u,v)||R(u,v)|\cos[\phi_{ti}(u,v)-\phi_r(u,v)-ux_i-vy_i-2vy_0] \\ &+2|R(u,v)||N(u,v)|\cos[\phi_r(u,v)-\phi_n(u,v)+2vy_0)]+2\sum_{i=1}^{n}|T_i(u,v)||N(u,v)| \\ &\times\cos[\phi_{ti}(u,v)-\phi_n(u,v)-ux_i-vy_i] \\ &+2\sum_{i=1}^{n-1}\sum_{k=i+1}^{n}|T_i(u,v)||T_k(u,v)| \\ &\times\cos[\phi_{ti}(u,v)-\phi_{tk}(u,v)-ux_i+ux_k-vy_i+vy_k], \end{aligned} \quad (2)$$

where $|R(u,v)|$, $|T_i(u,v)|$, and $|N(u,v)|$ are the amplitudes, and $\phi_r(u,v)$, $\phi_{ti}(u,v)$, and $\phi_n(u,v)$ are the phases of the Fourier transforms of $r(x,y)$, $t_i(x,y)$, and $n(x,y)$, respectively; u and v are mutually independent frequency-domain variables scaled by a factor $(2\pi/\lambda f)$; λ is the wavelength of the collimating light; and f is the focal length of the Fourier transforming lenses.

The generalized fringe-adjusted filter, which can be used as a versatile tool for various practical applications, is defined as

$$H(u,v)=C(u,v)[D(u,v)+|R(u,v)|^m]^{-1}, \quad (3)$$

where m is a constant, and $C(u,v)$ and $D(u,v)$ are either constants or functions of u and v. When $C(u,v)$ is properly selected, one can avoid having an optical gain greater than unity. With very small values of $D(u,v)$, the pole problem otherwise associated with an inverse filter is overcome. When $m=0$, $D(u,v)=0$, and $C(u,v)=1$, the GFAF-based JTC corresponds to the classical JTC. When $m=2$, $D(u,v)\ll|R(u,v)|^2$, and $C(u,v)=1$, the GFAF-based JTC corresponds to the fringe-adjusted JTC or inverse filter based JTC. And when $m=1$, $D(u,v)\ll|R(u,v)|$, and $C(u,v)=1$, the GFAF based JTC corresponds to the phase-only JTC. The aforementioned three cases correspond to the complex matched filtering ($m=0$), inverse filtering ($m=2$), and phase-only filtering ($m=1$).[16] Thus, all important types of matched filter based correlators can be implemented in real time using the proposed fractional power fringe-adjusted JTC while avoiding the limitations of matched filter based correlators. For clear input scenes without noise, the fringe-adjusted JTC yields the highest correlation output, whereas for input scenes with noise, the fractional power phase-only JTC yields better correlation output than the fringe-adjusted JTC. If $C(u,v)=1$ and $|R(u,v)|^m \gg D(u,v)$, then Eq. (3) may be approximated as $H(u,v) \approx |R(u,v)|^{-m}$. The fringe-adjusted JPS is obtained by multiplying the JPS of Eq. (2) by the filter function $H(u,v)$, given by

$$G(u,v)=H(u,v)|F(u,v)|^2 \approx |R(u,v)|^{-m}|F(u,v)|^2. \quad (4)$$

In Eq. (2), the first three terms correspond to the zero-order peak, the fourth term corresponds to the desired cross-correlation between the reference image and the input scene objects, the fifth term corresponds to the cross-correlation between the reference image and the noise term, the sixth term represents the cross-correlation between noise and input scene, and the last term corresponds to the cross-correlation between the different input scene objects. If multiple identical targets are present in the input scene, then in addition to the desired autocorrelation peaks between the reference and the targets, other correlation peaks will be produced due to the autocorrelation between the targets themselves [corresponding to the last term of Eq. (2)] that yield false correlation peaks (called false alarms) in the output plane.

Most recently, a Fourier plane image subtraction technique has been proposed,[11] which can be achieved by recording the input-scene-only power spectrum $(\Sigma_{i=1}^{n}|T_i(u,v)|^2)$, and the reference-only power spectrum $(|R(u,v)|^2)$ separately. Since the reference image is known, $|R(u,v)|^2$ may be precalculated and stored in the computer. Both the input-scene-only power spectrum and the reference-image-only power spectrum are then subtracted from the JPS of Eq. (2). Thus, the modified JPS obtained using the Fourier plane image subtraction technique may be expressed as

$$\begin{aligned} P(u,v) &= |F(u,v)|^2 - \sum_{i=1}^{n} |T_i(u,v)|^2 - |R(u,v)|^2 \\ &= 2\sum_{i=1}^{n} |T_i(u,v)||R(u,v)|\cos[\phi_{ti}(u,v)-\phi_r(u,v) \\ &\quad - ux_i - vy_i - 2vy_0] \\ &\quad + 2|R(u,v)||N(u,v)|\cos[\phi_r(u,v)-\phi_n(u,v) \\ &\quad - 2vy_0]. \end{aligned} \quad (5)$$

The subtraction operation eliminates the zero-order term, the false alarms generated by the similar input scene targets, as well as the cross-correlation terms between other objects that may be present in the input scene. Notice that the subtraction operation does not require any additional hardware. By exploiting the previously mentioned Fourier plane image subtraction technique,[11–19] the fractional power fringe-adjusted JTC can significantly reduce the effect of noise and clutter, which may be present in the input scene, and eliminate the cross-correlation terms generated by the input scene targets. The modified JPS of Eq. (5) is then multiplied by the GFAF of Eq. (4) to yield the modified fringe-adjusted JPS, given by

$$O(u,v)=H(u,v)P(u,v) \approx |R(u,v)|^{-m}P(u,v). \quad (6)$$

An inverse Fourier transform of Eq. (6) yields the correlation output that will consist of pairs of delta functions corresponding to the input scene targets and negligible cross-correlation output between the reference and nontarget objects, as well as the noise term.

3 GFJTC Based Tracking

In addition to performing raw pattern matching, a JTC can be particularly useful for tracking images in a real environment where targets move in challenging scenarios corrupted by noise, clutter, and other artifacts. By correlating successive frames, for instance, the location of one or more targets can be found between two consecutive frames. The proposed GFJTC based algorithm for target tracking involves the following four steps

- Image preprocessing, which involves procedures such as formatting and correction of data to facilitate better visual interpretation.
- Image segmentation, which is useful for identifying regions of interest in a scene or annotating the data. By using segmentation, the search for the target is reduced to a suitable region of the image by using some *a priori* knowledge on the scene. The segmentation helps to achieve consistent tracking results for scenes with arbitrary object motion.
- Recognition stage, which tests each target by cross-correlation technique, and if validated, is classified according to the database of reference images.
- Tracking stage, which keeps track of the moving target of interest in successive frames.

3.1 *Preprocessing*

The preprocessing operation is mainly intended for correcting the distortions of image data. Preprocessing functions involve those operations that are normally required prior to the main data analysis and extraction of information. The images are preprocessed to simplify subsequent operations of target detection and tracking without losing relevant information. After taking each frame, intensity normalization is carried out to all pixels of that frame to adjust the average intensity level. After that, the mean value of that frame is subtracted from all pixel values of the image to remove the background. Finally, the application of local enhancement helps in improving the useful features of the target in the input scene relative to the background, clutter, and other artifacts. It may be mentioned that subtraction operations may generate negative values. For optoelectronic or optical implementation, such negative values can be implemented by using a combination of an intensity SLM and a phase-only SLM.[13]

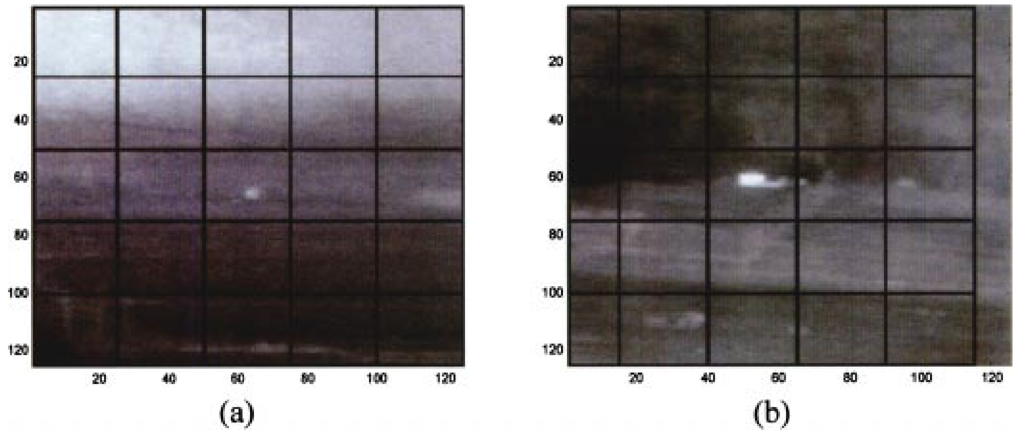

Fig. 2 Segmentation for the first frame of 128×128 pixels for (a) image frame from sequence L14_15 (sequence 1), and (b) image frame from sequence L19_04 (sequence 2).

3.2 *Segmentation*

Image segmentation is useful in target detection and tracking applications for identifying regions of interest.[20–22] The main purpose of segmentation is to identify regions of interest corresponding to targets in the unknown input scene. Recently, a subimaging technique was proposed[23] that involves multilayered segmentation and requires that the target image size must be within 25% of the subimage size. In addition, there is no provision for searching and detecting objects in the first frame of a sequence, and it assumes that the target location is known *a priori*. In Ref. 24, a high resolution image reconstruction technique is proposed by utilizing a number of shifted low-resolution subframes. In this work, we utilize the reverse procedure, where each frame available from a sequence is divided into a number of equal-sized subframes. The size of each subframe is set equal to or greater than the size of the reference image, which is selected from a database or from a ground truth file. The entire input frame is divided into equal-sized subframes using the aforementioned procedure, and the reference subframe is used for searching the unknown target in the entire frame, where the subframe is a 25×25-pixel window. The segmentation operation for two different sequences having different target locations is shown in Fig. 2. Figure 2(a) shows the segmentation for the first frame of a sequence (L14_15, called sequence 1), where the frame is divided into 25 25×25-pixel subframes. For this particular case, the target is in the middle of a subframe. However, for other sequences, the target may fall on the four boundaries of a subframe. To overcome this problem, the segmentation grid can be moved horizontally, vertically, or diagonally, following the subpixel shifting procedure described in Ref. 24. As an example, for the first frame of another sequence (L19_04, called sequence 2), shown in Fig. 2(b), the grid is shifted horizontally in the left direction from the original grid to ensure that the target lies in one subframe. Otherwise, this target will fall between two subframes. The same image segmentation approach is used for all the frames in a sequence.

3.3 *Recognition Stage*

The fringe-adjusted JTC technique[9,11] has been used for target recognition. At first, the first frame of a sequence is segmented into equal-sized subframes following the previously mentioned procedure. Each of these subframes is introduced as the input scene with the known reference image to form the input joint image. For a match between the reference and the input scene target, the FJTC technique yields a pair of sharp correlation peaks. The cross-correlation peak obtained from the subframe containing the target and the known reference yields the highest peak among all the cross-correlation peaks. Thus the unknown target can be detected in the unknown input scene based on the known reference image. It may be mentioned that the Fourier plane image subtraction technique is also used to eliminate the unwanted zero-order term and cross-correlation terms produced by similar input scene objects, while alleviating the detrimental effects of artifacts that may be present in the unknown input scene. For subsequent frames, the subframe for the input scene is taken from the current frame, whereas the reference image is selected from the preceding frame. Thus, adaptive updating of the reference image and input scene is utilized to ensure that the current frame accurately represents the target location.

3.4 *Tracking Stage*

The tracking algorithm utilizes the GJTC technique for estimating target motion, as shown in Fig. 3. In Fig. 3 the image at time $t=t_1$ corresponds to a subframe from a sequence of frames containing the target; and the image at time $t=t_2$ corresponds to a subframe from the next con-

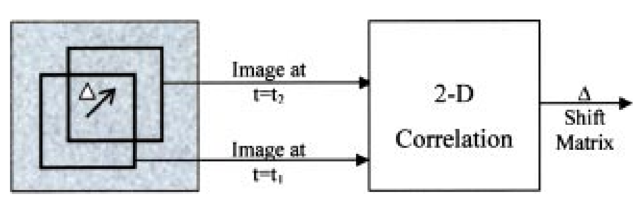

Fig. 3 Image motion determination with 2-D correlation.

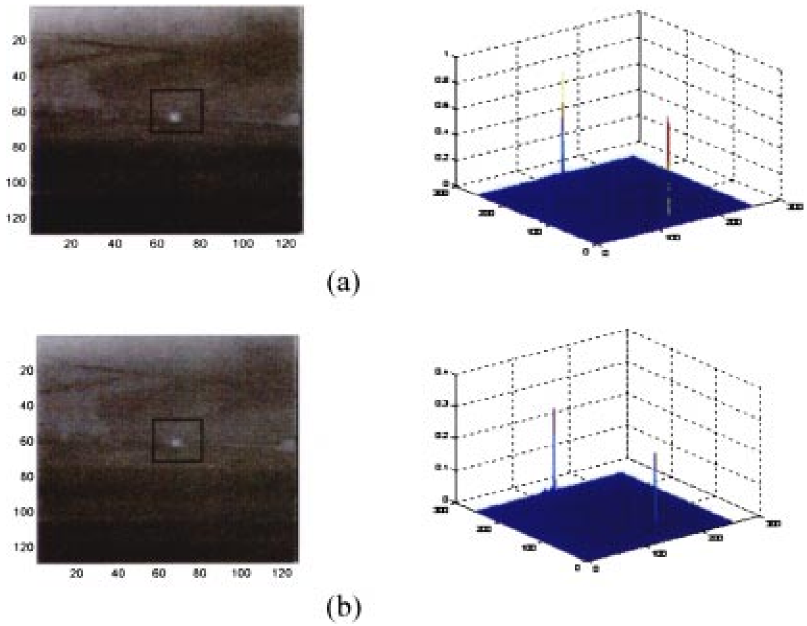

Fig. 4 Target recognition and tracking for sequence L14_15 (sequence 1). *x*-*y* coordinate of correlation peak (a) at frame 51 is (17, 129) and (b) at frame 52 is (15, 130). The difference between these two coordinates provides the direction and number of pixels of target movement.

secutive frame. In this technique, the movement of the target between two consecutive frames of an image sequence is measured to estimate the motion of a given target. If the reference image and the input scene target are the same, a pair of sharp correlation peaks is produced, indicating the relative location of the target in the input scene. Then image motion is estimated by calculating the difference between the position vector of the correlation peak of the current frame and that of the previous frame, which leads to the updated new location of the target.

As shown in Fig. 4, for sequence 1 (L14_15), the x-y coordinates of correlation peaks corresponding to two consecutive frames (frames 51 and 52) are (17, 129) and (15, 130), respectively. Consequently, the displacement of the target from frame 51 to frame 52 along the x axis is $\Delta x = -2$ and along y axis is $\Delta y = 1$. Thus, by knowing the location of the correlation peak, a moving target can be tracked using the pixel-wise difference between correlation peaks of consecutive image frames. The resulting system identifies targets of interest, and continuously tracks a target while alleviating the effects of background clutter, occlusion, appearance changes, cessation of target motion, and other detrimental factors.

4 Results

To evaluate the performance of the proposed GFJTC algorithm, we use multiple FLIR image sequences supplied by Army Missile Command (AMCOM). The correlation output obtained from the GFJTC algorithm is used for tracking the desired object. For a match, the peak in the correlation output matrix gives us the approximate location of the target in the specific frame.

To test the performance of the proposed algorithm for target tracking, we select an arbitrary challenging sequence (L22_10, called sequence 3) supplied by AMCOM, which contains 398 frames. Based on the known reference image size information, frame 1 of sequence 3 is segmented into equal-sized subframes (25×25 pixels) following the segmentation procedure described earlier. Each of these subframes is used as the input scene to detect the target in frame 1. By using the known reference image, the correlation output between the reference and the unknown input scene (i.e., a subframe of sequence 3) is obtained using the GFJTC algorithm. From this correlation output, the x-y coordinates ($x = 17$ and $y = 129$) of the correlation peak are determined.

For frame 2 of sequence 3, the entire frame is subdivided into an array of 25×25-pixel subframes. Using the reference image from frame 1 and each of the subframes from frame 2 as the input scene, correlation outputs are obtained using the GFJTC algorithm. By examining the entire set of the correlation outputs, the location of the target is determined. For frame 2, the x-y coordinates of the correlation peak of the target have been found to be located at $x = 17$ and $y = 129$. The difference between the x-y coordinates of the correlation peak for frame 1 and the x-y coordinates of the correlation peak for frame 2 indicates the relative displacement of the target from frame 1 to frame 2. The difference between two subsequent x-y coordinates are denoted by Δx and Δy, respectively. In this case, $\Delta x = 0$ and $\Delta y = 0$, indicating that the target did not move from frame 1 to frame 2. Now to select the subframe from frame 3, the subframe grid is shifted by Δx and Δy along the x and y axes, and the aforementioned procedure is repeated. Notice that the subframe corresponding to the location of the target in frame 2 becomes the reference image for detecting the target from frame 3. Following the aforementioned procedure, the reference image and the input image are adaptively updated to detect and track the target for

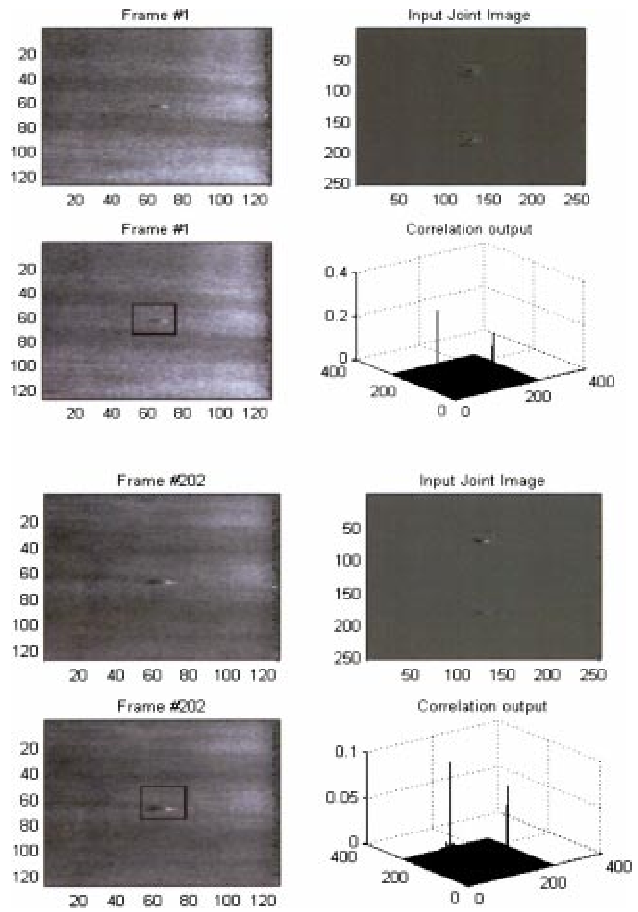

Fig. 5 Tracking results for an object of sequence L22_10 (sequence 3) using GFJTC.

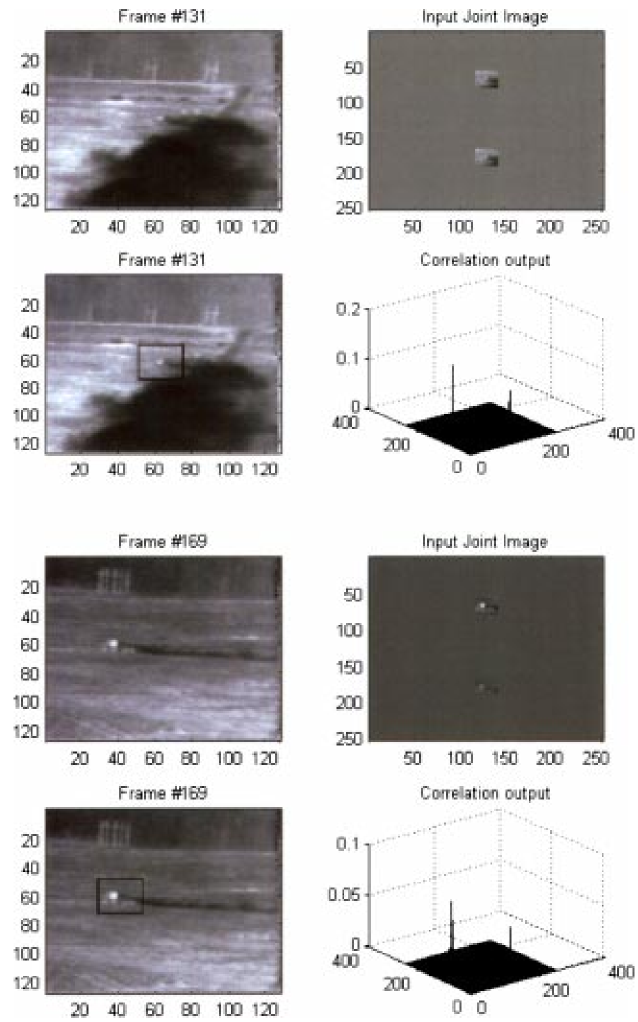

Fig. 6 Tracking results for another object of sequence L19_07 (sequence 4) using GFJTC.

subsequent frames. Satisfactory tracking results are obtained for all frames in our test sequence. Figure 5 shows some examples of tracking results for this sequence.

We also test our algorithm using other sequences. Results for another arbitrary sequence (L19_07, called sequence 4) supplied by AMCOM are shown in Fig. 6. For this sequence, the desired target first appears in frame 131 and it is a moving target. This sequence contains 195 frames and the corresponding tracking results obtained using the GFJTC algorithm are shown in Fig. 6.

5 Conclusion

Moving target tracking is a challenging task and is becoming increasingly important for various applications. We present a robust generalized fringe-adjusted JTC based algorithm for real-time detection and tracking of moving targets in terrestrial scenes. For testing the performance of the proposed system, real life FLIR image sequences are used. The proposed method first detects the target in a frame and then tracks it from one frame to the next frame. Detecting the accurate position of the target in a frame and tracking, the precise displacement of the target from one frame to the next frame must be resolved, which is accomplished by applying the proposed GFJTC algorithm. Simulation results using real life FLIR imagery show that the proposed algorithm is an effective tool for detection and tracking of both static and moving targets. From Figs. 5 and 6, it is evident that the proposed algorithm effectively tracks the desired target.

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Biographies and photographs for other authors not available.