MACH filter synthesizing for detecting targets in cluttered environment for gray-scale optical correlator

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ABSTRACT

We have recently demonstrated a compact, high speed, gray-scale optical correlator for target detection. The capability of the direct gray-scale scene input and the gray-scale (real-valued) filter modulation enables us to implement a near-theoretical optimal filter on the optical correlator. This paper describes filter synthesizing algorithm for detecting targets in cluttered background input scene and the projection from the complex filter version to the real version for implementation on the gray-scale optical correlator. It is based on optimal–tradeoff MACH filter. It was found that using an appropriate simulated noise image to substitute the commonly used white noise in the filter design procedure is a very effective way to suppress clutter noise while maintain high tolerance for distortion. Both simulation and experimental results are provided.

Keywords: correlation filter synthesizing, gray-scale optical correlator, noise and clutter suppression

I. INTRODUCTION

Since its introduction in 1994, MACH filter and its variations (e.g., optimal-tradeoff MACH filter)[1, 2] have proven to be a powerful correlation filter algorithm. It offers good performances in three major criteria simultaneously, i.e., the easy detection of correlation peak, good distortion tolerance, and the ability to suppress clutter noise. However most optical correlator can not accommodate the complex value as the theoretical optimum filter demands.

We have recently developed the first compact grayscale optical correlator and demonstrated real-time target recognition and tracking.[3, 4, 5] The unique advantages of the optical correlator include high-speed (1000 frames/sec), compactness (camcorder-size), and grayscale input and filter modulation capability. The grayscale input modulation capability enables the direct interface with a variety of sensor inputs (visible, IR, or UV Focal Plane Array). The gray-scale bipolar-amplitude filter modulation capability has made possible, for the first time, the direct implementation of near "theoretical" optimum MACH filter on optical correlator. This greatly increases the performance of optical correlator and expands the scenario an optical correlator can handle from simple to more realistic noisy/cluttered scene input.

In the following, we will first introduce an effective way to improve MACH filter's ability to suppress noise/clutter while maintaining high tolerance for distortion. We then describe the projection from complex theoretical filter to bipolar-amplitude (real-valued) SLM for implementation on the gray-scale optical correlator. Both simulation and experiment results will be given to demonstrate the correlator's ability to implement near-theoretical optimal MACH filters.

II. MACH FILTER SYNTHESIZING WITH NOISY/CLUTTERED BACKGROUND

MACH filter itself is designed to explicitly maximize a performance measure called Average Correlation Height (ACH) while minimizing Average Similarity Measure (ASM). In practice, some other performance measures, e.g., Average Correlation Energy (ACE) and Output Noise Variance (ONV), also need to be balanced to better suit different application scenario. To achieve those conflicting goals simultaneously, an optimal tradeoff approach, first introduced by Refregier,[6] can be used in which one try to minimize to the following energy function:

$$\begin{aligned} E(\mathbf{h}) &= \alpha(\mathrm{ONV}) + \beta(\mathrm{ACE}) + \gamma(\mathrm{ASM}) - \delta(\mathrm{ACH}) \\ &= \alpha\mathbf{h}^{+}\mathbf{C}\mathbf{h} + \beta\mathbf{h}^{+}\mathbf{D}_x\mathbf{h} + \gamma\mathbf{h}^{+}\mathbf{S}_x\mathbf{h} - \delta\left|\mathbf{h}^{T} m_x\right| \end{aligned}$$

Part of the SPIE Conference on Optical Pattern Recognition X
Orlando, Florida • April 1999
SPIE Vol. 3715 • 0277-786X/99/$10.00

The resulting optimal-tradeoff (OT) MACH filter (in frequency domain) is given as[2]

$$\mathbf{h} = \frac{\mathbf{m}_x^*}{\alpha\mathbf{C} + \beta\mathbf{D}_x + \gamma\mathbf{S}_x}$$

where α, β and γ are nonnegative OT parameters. $\mathbf{m}_x$ is the average of the training image vectors $\mathbf{x}_1, \mathbf{x}_2, \ldots \mathbf{x}_N$ (in frequency domain) $\mathbf{C}$ is the diagonal power spectral density matrix of additive input noise. Since exact knowledge about $\mathbf{C}$ is not always available, white noise covariance matrix, i.e., $\mathbf{C}=\sigma^2\mathbf{I}$, is often used. $\mathbf{D}_x$ is the diagonal average power spectral density of the training images:

$$\mathbf{D}_x = \frac{1}{N}\sum_{i=1}^{N}\mathbf{X}_i^*\mathbf{X}_i$$

where $\mathbf{X}_i$ is diagonal matrix of training image. $\mathbf{S}_x$ denotes the similarity matrix of the training images :

$$\mathbf{S}_x = \frac{1}{N}\sum_{i=1}^{N}(\mathbf{X}_i - \mathbf{M}_x)^*(\mathbf{X}_i - \mathbf{M}_x)$$

where $\mathbf{M}_x$ is the average of $\mathbf{X}_i$.

By choosing different values of α, β and γ, one can control the OT-MACH filter's behavior to suit different application requirements. For example, when $\beta=\gamma=0$, the resulting filter behaves much like a MVSDF filter with relative good noise tolerance but broad peaks. If $\alpha=\gamma=0$, then the filter is more like a MACE filter, which generally gives sharp peaks and good clutter suppression but is very sensitive to distortion. For $\alpha=\beta=0$, the filter is a MACH filter which itself is designed with high tolerance for distortion.

As mentioned above, since an exact knowledge of $\mathbf{C}$ is not always available, the usual approach is to substitute with the white noise covariance matrix in the filter design. In practice, we found this would lead to unsatisfactory correlation results when the input scene is very noisy or cluttered. For example, for detecting a target (an airplane) in a cluttered environment as shown in Fig.1a, the best controlling OT parameters were found to be around $\alpha=\gamma=0.01$ and $\beta=1$ (when white noise is assumed) to maximally suppress the noise and give sharp peaks. But even with such great emphasis on noise suppression, the filter still gives false detection caused by clutters (see Fig.1b, detection is marked on the input image with a square box). Besides this, since γ is very small compared to β, the resulting filter is a MACE-like filter and hence is sensitive to interclass distortion. In fact, 4 out of 16 test images (with 8 of them used as training images) have a significantly reduced peak intensity for target which causes false detection.

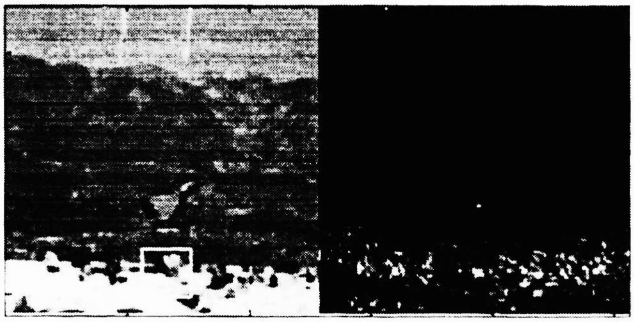

Figure. 1a. Input image.
1b. Correlation output using OT parameters $\alpha=\gamma=0.01, \beta=1$, and white noise in filter design.

To improve the performance of MACH filter in noisy/cluttered environment, we found that it is necessary to have better representation of noise characteristics in the filter design even though the exact knowledge about the noise may not be available. One way to do this is to use a simulated noise/clutter image to substitute the simple white noise. For the input scene as in Fig.1a, for example, one can use a simulated noise/clutter image, such as the one shown in Fig.2a, as the noise background. By using Fig.2a for calculating input noise in the filter design, the best OT controlling parameter were found around $\alpha=\beta=0.01$ and $\gamma=1$, which indicates a MACH-like resulting filter. The correlation output is shown in Fig.2c where the clutter noise is greatly suppressed. As expected, the filter's performance is also more robust for distortion. In fact, all 16 test images (with 8 of them used as training images) produce similar peak intensities for target.

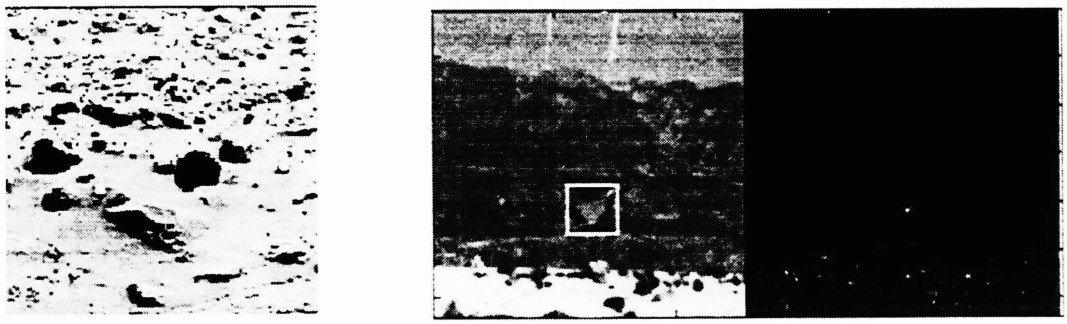

Figure 2a. Simulated noise background to substitute white noise in filter design.
2b. Input image.
2c. Correlation output using $\alpha=\beta=0.01$, $\gamma=1$ and the simulated noise image in 2a. in filter design

Notice that the noise image of Fig.2a is not the same noise/clutter background as in Fig.1a (it is actually a portion from one of the landscape pictures taken from Mars), only the characteristics in two figures bear some resemblance. To further find out whether the selection of one particular noise image is critical to the correlation performance, we have tried different noise images. Though performances do vary from case to case, most of them improve the correlation quite significantly. Figure 3 shows one such example. On the other hand, using a simulated noise image such as Figs.2a or 3a in filter design will cause little performance deterioration when the input is free of or different from such noise/clutter. This can be seen from Fig.4 in which the Fig.2a is used as simulated noise background.

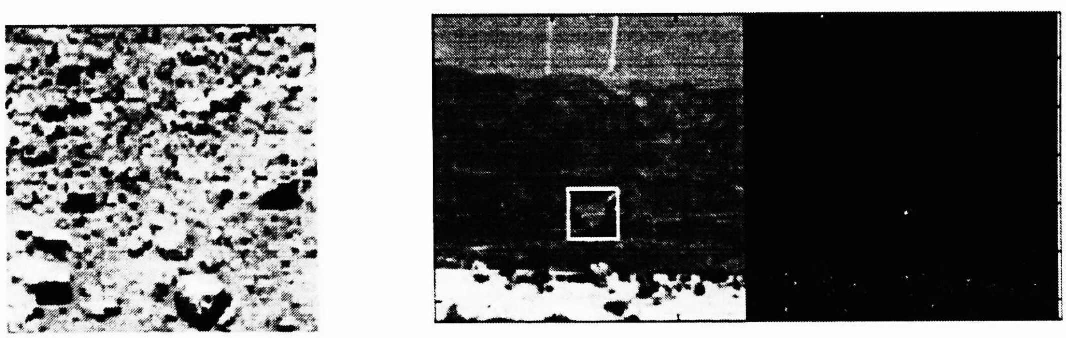

Figure 3a. Simulated noise background to substitute white noise in filter design.
3b. Input image.
3c. Correlation output using $\alpha=\beta=0.01$, $\gamma=1$ and the simulated noise image in 3a. in filter design

Of course the choice of what kind noise/clutter image should be used in the filter design will be application dependent. It thus requires some minimum *a prior* info about the potential noise/clutter environment. Although one may never foresee all potential input noise types, it is possible in many applications that one can at least know the typical or the most likely noise/clutter environment which poses the main difficulty in target detection.

III. FILTER PROJECTION TO GRAY-SCALE BIPOLAR-AMPLITUDE SLM

The optimal-tradeoff MACH filter as described above is optimized and well-balanced with regard to three major correlation performance criteria, i.e., the peak sharpness, the distortion tolerance, and the clutter/noise suppression. Such a powerful filter, which is complex in nature, however, has never been able to be implemented on optical

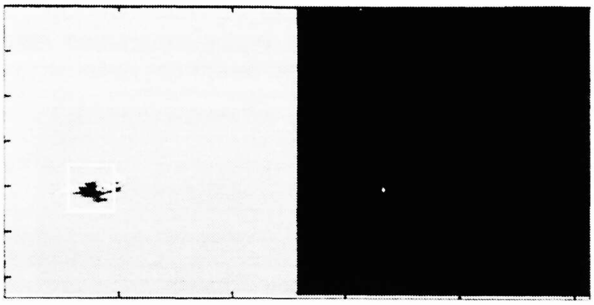

Figure 4a. Input image.
4b. Correlation output using $\alpha=\gamma=0.01, \beta=1$, and the simulated noise as in Fig.2a in filter design.

correlators due to limited SLM modulation capability. Two currently operable optical correlators, developed by Liton Data System and Lockheed Martin, both accommodating binary code (phase or amplitude) only, can not satisfactorily implement an optimal filter such as optimal-tradeoff MACH filter. Although there are other types of SLM modulation available, e.g., coupled phase and magnitude[11], no real demonstration has been reported so far.

We have recently developed the first compact grayscale optical correlator and demonstrated real-time target recognition and tracking.[3, 4, 5] The correlator's unique gray-scale (real-valued) filter modulation ability has made possible the direct implementation of near "theoretical" optimal MACH filter on an optical correlator. In fact, recent analysis[7, 8] has suggested that the performance loss of real filters is at most 3dB in SNR compared to their ideal complex counterpart, while at least a 10dB degradation in SNR has been observed for a binary phase-only filter.

To implement the above described MACH filter with the gray-scale optical correlator, we follow the Minimum Euclidean Distance principle[2, 9] to map the complex value to the bipolar-amplitude SLM coding domain. That is, we minimize the following energy function:

$$E_{\varphi}(\mathbf{h}) = \sum \left|\mathbf{h}^{P} - \mathbf{h}\exp(i\varphi)\right|^2$$

where $\mathbf{h}^P$=Re[$\mathbf{h}\exp(i\varphi)$] is the projected optimal filter constrained by the gray-scale SLM coding domain, and the summation is over all frequency components (the filter pixels). The phase factor φ arises from quadratic detection of the correlation function, i.e., the coding domain can be arbitrarily rotated in the complex plane. However the projection operation is not linear with this rotation; therefore the best rotation angle has to be chosen. For our bipolar-amplitude modulated SLM, the optimal phase rotation can be analytically found as

$$\varphi = \frac{\pi}{4} - \frac{1}{2}\tan^{-1}\left(\frac{-\sum 2h_r h_i}{\sum h_r^2 - h_i^2}\right)$$

where h_r, h_i denote the real and the imaginary parts of h, respectively. Figure 5 shows the correlation result using the projected real-valued filter version. Compared with the correlation result using the original complex filter version (see Fig. 3c) it has a negligible difference. This suggests that the real-valued bipolar-amplitude SLMs should be capable to implement near theoretical optimal filters such as OT-MACH filters with good performance.

Figure 5. As Fig. 3a, but use projected real-valued filter version

To confirm the ability of the gray-scale optical correlator to implement the close-to-theoretical-optimal filter, we have recently conducted a field demo. Figure6 shows a typical correlation result from the gray-scale optical correlator. Details about the experiment and more experiment results can be found in Ref. 5.

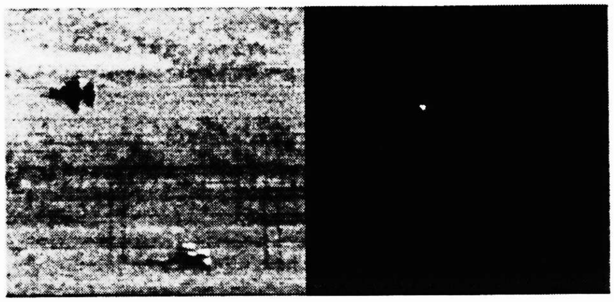

Fig. 6 Gray-scale optical correlator result. a) Input. b) Output.

IV. SUMMARY

By using an appropriate simulated noise/cluttered image in the MACH filter synthesizing procedure, we have improved MACH filter's performance in a severely cluttered environment. The unique real-valued modulation ability of gray-scale optical correlator enables us to implement the near theoretical optimum MACH filter. The combination of the powerful MACH-based filter algorithm and the powerful gray-scale optical implementation thus advances optical correlator to be more robust in noise/cluttered environment and thus a more practical tool in real-time target detection applications.

V. ACKNOWLEDGMENTS

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, and was jointly sponsored by the Ballistic Missile Defense Organization, the Naval Surface Warfare Center/Dahlgren Division and the National Aeronautics and Space Administration/Office of Space Science. The original digital MACH filter files used in this paper was provided by RMSC. The authors wish to express their sincere thanks to Mr. L. Kinsey, Drs. A. Mohalonobis, D. Carlson, and A. Takessian (of RMSC) for helpful technical discussions.

VI. REFERENCES

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