OPTIMIZING A CONTINUOUSLY VARIABLE FILTER IN A HYBRID OPTICAL CORRELATOR

Richard D. Juday
Tracking and Communications Division
NASA Johnson Space Center
Houston, TX 77058

SUMMARY

In contrast to binary filters, continuously variable optical filters offer an ability to compensate for certain imperfections in the optics of a hybrid correlator. We introduce arbitrary static phase errors in a model of a phase-only filtering hybrid correlator, and we simulate a method of discovering a correction for them. By a recursive technique a first approximation to the impulse's matched filter is adjusted (allowed to relax) so as to produce successively more localized distribution of the output in the correlation plane. The method is motivated by the development of continuously-variable phase-only spatial light modulators, but it is applicable to amplitude modulators and -- with appropriate modification -- to binary modulators as well. The technique is robust against the form of the system's departure from ideal behavior.

INTRODUCTION

In a coherent optical correlator the image controlling the input spatial light modulator (SLM) causes a disturbance of the coherent reading wavefront. A lens places the optical transform of the disturbance at the location of a second SLM, the filter plane. In classical matched filtering, the filter has a multiplicative effect proportional to the complex Fourier transform of a reference object whose correlation with the input pattern is desired. The complex conjugate comprises two parameters, phase and amplitude, but a one-parameter combination of phase and amplitude is all that is usually induced with ordinary devices. The challenge is to optimize a filter within the constraint of controlling only the one-parameter combination of phase and amplitude.

Modeling of the POF (phase-only filter) has not yet addressed the sensitivity of the POF correlator to random phase deviations of the order easily introduced by real optics. Bartelt and Horner [1] indicate an iterative scheme which optimizes a POF derived from a classical matched filter. However, their technique operates entirely in simulation of ideal abilities and limitations of the POF, as opposed to iterating on the basis of physical observations. In contrast, the technique reported here is intended precisely to compensate for unknown, indirectly observable departures from physical ideality. The one-parameter form of the method is not dependent on the type of SLM since its relaxation is driven by only the input-output relationship and is blind to physical details of intervening interactions.

PRACTICAL CONSIDERATIONS

The pattern brought to the filter plane of a linear space-invariant (LSI) optical correlator system is not exactly the mathematical Fourier transform of the original input image. At the filter plane we find the mathematical Fourier transform convolved with the diffraction pattern of a single pixel of the input spatial light modulator, so the optical transform of the LSI system will differ from the mathematical Fourier transform even without consideration of the non-ideal characteristic of the optics. In performing matched filtering or other correlator functions, though, we clearly may need to take into account the transform that the system actually does on the input image. In addition to the diffraction pattern convolution, which does not impair the LSI nature of the correlator, non-ideal optical properties of real components and setups arise. Undesirable but real effects that do change the LSI properties of a correlator include non-planarity of surfaces, scattering centers such as dust or inclusions, and imperfect optical alignment. With respect to phase, realistically sized imperfections in a high-index transmitting element can cause appreciable departure from what perfect optics would give. A beamsplitting cube might have a tenth-wavelength non-planarity per surface. The number of surface interactions is configuration dependent, but three to six interactions and a typical refractive index give the potential of several radians of phase distortion. For a phase-sensitive correlator there is clearly the possibility of significant unexpected distortion.

(NASA-TM-89279) OPTIMIZING A CONTINUOUSLY VARIABLE FILTER IN A HYBRID OPTICAL CORRELATOR (NASA) 4 p CSCL 20F
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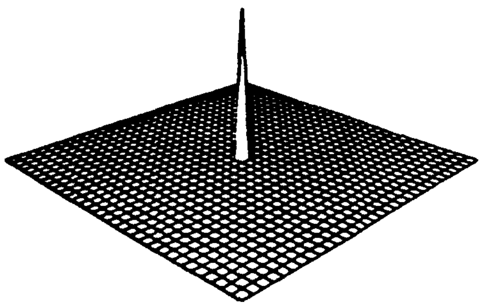
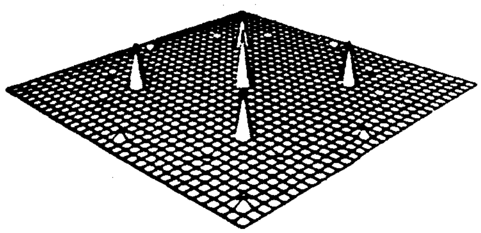
Figure 1 shows the amplitude pattern in the correlation plane of an idealized optical correlator. A centered impulse is filtered with the phase part of its MF (matched filter). In Figure 2 we see the effect of adding a two-dimensional seven-cycle sine-wave disturbance to the filter, the disturbance of the phase being only 1.5 radians at its maximum. The departure from the ideal matched filter is clearly evident. The correlation peak becomes hardly distinguishable from the sidelobes induced by the sinusoidal disturbance.



1. Correlation plane, undisturbed filter.



2. Correlation plane, disturbed filter.

The filtering SLM is asked to make those adjustments to a complex wavefront that will cause the wave corresponding to the reference image to converge at the center of the correlation plane. It has to accommodate for both the transforming and retransforming optics in order to do that. Modeling of phase-only matched filtering [2,3] shows that the POF has the possibility of producing very sharp correlation peaks; concomitantly one expects that phase-only correlation will be very sensitive to phase errors at the filter plane.

An AOF produces broader correlations than the POF [3]; the hypothetical tenth-wave flat beamsplitter affects the transformed wavefront's amplitude less strongly than its phase; and measurements of amplitude (intensity) are easier than measurements of phase. Consequently, producing a near-optimum continuously-variable filter is expected to be more difficult for the POF than for the AOF. However, the promise of the POF's strong signal-to-noise ratio justifies attempts to realize its potential, and the easier AOF can also benefit from the method.

RELAXATION BY GRADIENT SEARCH

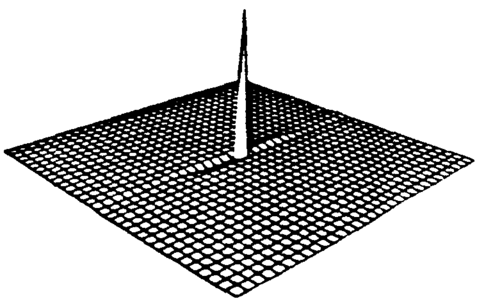
Suppose that the input is the desired reference image. Then we expressly wish to have the filter that produces a tightly confined bright spot in the correlation plane. We adjust a starting filter so as to confine the correlation spot more and more tightly, until there is no adjustment of the filter that further confines the correlation pattern. We thus achieve the filter that is best matched to the reference image _in the context of the individual correlator_, including its blemishes. (If the correlator is not LSI, the correlation process is space-variant and the adaptively determined filter is optimized only for the given position of the input image during the relaxation.)

Central to the relaxation technique is a search among all possible variations from the current estimate of the optimal filter. We need two tools. The first is a scalar whose value is to be maximized, corresponding to moving correlation plane's light into a small correlation spot. In practice with real correlators we will use the amount of light falling within a small central area in the correlation plane, though in digital simulation we were able to use simply the amplitude of the light at the central correlation spot. The second tool is an appropriate representation of the filter, a space in which to take the gradient of the scalar. For the space in which to represent the filter, we can use any of several candidates. In laboratory work we will use the Hadamard basis, though in the simulation shown here the unitary basis was used. That is, we directly adjusted each pixel of the filter (subject to retaining POF characteristics), which was possible because of the relatively small size of the array and the 32-bit precision of the simulation. In the use of another basis such as the Hadamard or Fourier, the space in which the gradient is taken is the one in which the coefficients of the filter are the components.

In general the space in which the gradient of the scalar is taken will have very high dimensionality. For an exhaustive search in a space of high dimension, the scalar must be rapidly calculable, and we must also consider the possibility of capture by false (local) maxima. In the relatively simple case shown here we maximized the amplitude of the central correlation spot and, since we could evaluate the results directly, we did not algorithmically avoid capture by false maxima. In a later report we will show results of a simulation which includes the possibility of capture by false local maxima.

RESULTS

In Figure 3 we see the results of spending 10 cpu hours of a VAX 11/785 adjusting the disturbed POF that gave the correlation pattern of Figure 2. No



3. Relaxed filter's results in correlation plane.

a priori information was given the relaxation program regarding the form of the disturbance. The program repeatedly marched in order through all the coefficients; for each coefficient the value of the central correlation plane amplitude was maximized. The effect of the adjustment order is apparent in the asymmetry of the correlation plane shape. Iteration will generally be required in this sort of optimization program, but a practical implementation might seek a better order in which to adjust the coefficients, based on the differences between the ideal pattern and the current pattern. Optical correlators typically transform to amplitude but sense in intensity. Nonetheless, the gradient of the intensity of the correlation pattern, as measured in the representation space of the filter, can be expected to have a large component in the direction of the inverse transform of the difference between the observed correlation intensity pattern and the ideal pattern. This expectation should lead to an optimized gradient search pattern.

The non-optimal adjustment order wouldn't have been so nicely visible had we used the Hadamard or Fourier basis to represent the filter. It would also have been specious to use the Fourier basis, since the disturbance has a particularly simple representation in that basis and a single coefficient adjustment would have compensated for it.

There is a significant obstacle in laying out an equivalent of the gradient search for the discrete filter. The obvious approach is to use the continuous representation of the filter and threshold it, but thresholding will cause an insensitivity or lack of uniformity to the change in the representation that is at the heart of the gradient search. Convergence to the optimum discrete filter is not so straightforward as it is for the continuous filter as presented here.

FUTURE WORK

The work reported here was done with a simple low frequency form of phase disturbance; in the future the disturbance will be replaced by one with higher frequency (narrower autocorrelation). We will evaluate the approach to robustness to capture by local maxima in the more complicated environment, and the algorithm for speeding the gradient search will be implemented.

ACKNOWLEDGEMENTS

This research was done in association with a cooperative agreement between NASA Johnson Space Center and the

U. S. Army Missile Command at Redstone Arsenal. Helpful comments were received from Don A. Gregory of MICOM, H. John Caulfield of University of Alabama at Huntsville, and Stanley E. Monroe, Jr., of Lockheed EMSCO. Computations were done by Brian Daiuto.

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