OPTICAL CALCULATION OF CORRELATION FILTERS FOR A ROBOTIC VISION SYSTEM

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ABSTRACT

A method is presented for designing optical correlation filters based on measuring three intensity patterns: the Fourier transform of a filter object, a reference wave and the interference pattern produced by the sum of the object transform and the reference. The method can produce a filter that is well matched to both the object, its transforming optical system and the spatial light modulator used in the correlator input plane. A computer simulation was presented to demonstrate the approach for the special case of a conventional binary phase-only filter. The simulation produced a workable filter with a sharp correlation peak.

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INTRODUCTION

The location and recognition of objects such as handtools drifting in space, boulders on the surface of Mars and the recognition and alignment of docking mechanisms using computer vision are typical of mission requirements in several NASA programs. These include the unmanned Mars mission, the EVA (Extra-Vehicular Activity) retriever and autonomous rendezvous and docking. In most of these cases the speed involved in the recognition process must exceed that of human vision. Even the fastest available digital computing systems cannot process data fast enough to compete with the eye-brain. An interesting alternative to using digital computation is a hybrid system that uses a combination of optical and digital computing. Among several promising schemes being studied by NASA for implementation is an optical computer that uses a "matched filtering" technique[1] for the recognition tasks. The key element in this approach is the design of a correlation filter; a new approach to designing filters is described.

MATCHED FILTERING

Matched filtering is based on computing the optical Fourier transform using a lens and then multiplying the transform by a filter that approximates the conjugate of the object transform under match conditions. This product is then inverse Fourier transformed using another lens. If the filter and the object are matched to each other then a strong correlation peak (an intense point of light) can be detected at the output of the optical system. An object is identified by testing it against a bank of previously calculated filters for an intense correlation peak. This testing can be carried out at extraordinary speeds using a special optical-digital chip designed for NASA by Texas Instruments in Dallas known as the Deformable Mirror Device (DMD). The DMD consists of an array of more than 16,000 microscopic mirror elements arranged in a square array only one quarter of an inch on a side. This array is mounted on an integrated circuit chip and is controlled by a small computer (an IBM clone). During the past 4 years, NASA has been working on a robotic vision system that uses the DMD to sequence through a set of test filters. The filters are stored and written to the DMD by the computer. One of the problems using this approach is the precise design of the test filters. At present the filter designs are based on computer models or digitized television camera images of the objects of interest. Unfortunately in a real system what an object will "look like" to the optical computer depends on the precise details of the spatial light modulator (SLM)[2] used in the input plane of the optical correlator. There are many different types of candidate SLM's available. These include liquid crystal light valves, modified liquid crystal televisions and even the DMD. It is exceedingly difficult to accurately model the image these devices would produce. An alternative to computer modeling is a more direct optical approach that uses the input SLM as well as the correlator optical system to make a precise in situ calculation of a correlating filter.

OPTICAL FILTER CALCULATION: GENERAL APPROACH

The ideal filter is one computed directly from images presented by the input SLM. This would provide precisely the filter needed based on the correct image rather than an approximate model. This can be done using an optical approach that collects the information directly using the same lens system that is used in the optical filtering operation. This approach has the additional advantages that it can account for certain shift invariant aberrations in the optical system as well as provide data quickly enough for real-time filter design. The latter

property is of use in building tracking systems that can lock onto arbitrary targets.

In order to explain the optical approach, a one dimensional model will be analyzed for convenience. First consider the intensity pattern produced $I(x)$ by the sum of the fields of the Fourier transform of an object $t(x)$ and a reference field $R(x) \exp[j\Theta(x)]$:

$$I(v) = \{F\{t(x)\} + R(v) \exp[j\Theta(v)] \}\{F\{t(x)\} + R(v) \exp[j\Theta(v)]\}^*$$

Here $F\{ \}$ represents the Fourier transform operator, $\exp( )$ represents exponentiation and the asterisk superscript represents conjugation. Letting

$$T(v) \exp[j\psi(v)] = F\{t(x)\}$$

and carrying out the previous product gives

$$I(v) = R^2 + T^2 + 2RT \cos(\Theta - \psi) \qquad (1)$$

Equation (1) is the key to the filter design. Before discussing a general case, we will examine a simple case where Θ is constant. This implies the reference is locally a plane wave, although the amplitude is not necessarily a constant. If I, R^2 and T^2 are measured by separate intensity measurements it is possible to solve for the magnitude of the cosine term and hence the magnitude of the relative phase between the reference and the object transform. This is precisely the information needed to design a conventional binary phase-only filter. (A filter that will match provide the best match possible to a planar wavefront given the constraints that the filter will add either 0 or 180 degrees at given location v in the frequency plane.) If the relative phase magnitude is less than 90 degrees then the filter should add only 0 degrees of phase shift. Otherwise the filter should add 180 degrees of phase shift to provide the best match. To implement this approach the three intensity measurements can be made by using a camera with a frame-grabber to store the data in a computer. The processing is fairly simple and can be simplified further by avoiding the arccosine calculation of the relative angle. Since the only information that is needed is the phase range, it is only necessary to determine if

$$I(v) > T^2 + R^2 \qquad (2)$$

If this is true then it follows that the relative phase angle is less than 90 degrees and the filter will add no phase shift. If the inequality is false the filter should provide 180 degrees of phase shift. Inequality (2) provides a fast way to implement binary filter calculations using only three simple intensity measurements, addition and a simple compare operation. If a better matching than a binary filter is desired than more information than provided by inequality (2) is needed. This requires another intensity measurement.

The sign and magnitude of the relative phase can be found by making one additional measurement in which the reference wave is shifted by a known amount at every point and the intensities associated with the object wave and the reference wave are kept constant. If the reference shift is carefully chosen there are two equations for $I(v)$ at every point that can be solved for the relative phase. If the phase magnitude and sign are known at every point then an optimal phase filter can be designed that can produce the best correlation peak signal

possible within the phase constraints of the spatial light modulator (SLM) used to implement the filter design[3]. Furthermore a more arbitrary (nonplanar) reference can be used provided its shape is the desired output of the filter. For example, it may be desired to use the filter to provide quadratic phase compensation or perhaps provide the phase shift needed to produce its own inverse Fourier transform and thus save a lens in the correlation system.

One particularly easy method to implement the additional measurement occurs in the case of a plane wave reference. If the reference is shifted by 90 degrees then the additional equation replaces the cosine term in eq. (1) by a sine term. These equations can be solved uniquely.

SIMULATION RESULTS

It is interesting to demonstrate the method using a computer model for an arbitrary object. A one dimensional object was constructed using 64 random data points between 0 and 1 from a pseudo-random number generator that approximated a uniform distribution. A graph of the function generated is shown in Fig. 1.
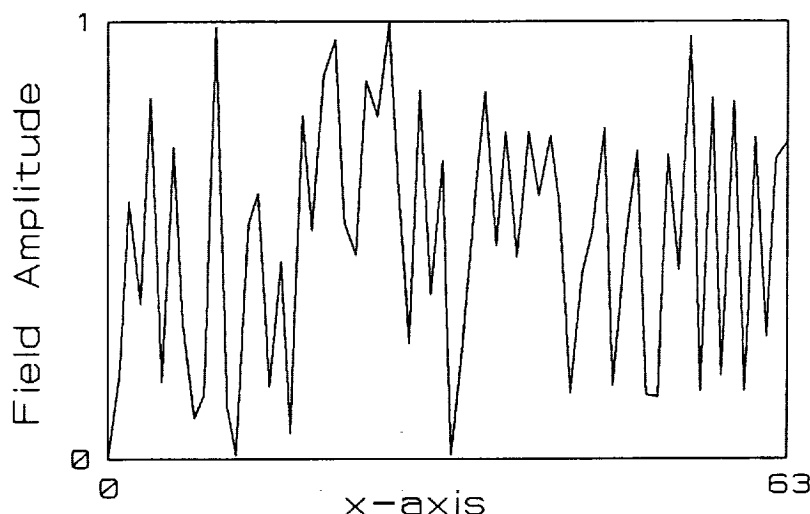

Fig. 1. Random object used for filter design.

The object was used to construct a binary correlation filter using inequality (2). The object function was zero padded with an additional 64 points and digitally Fourier transformed. An on-axis reference wave of amplitude 1 and 0 degrees phase shift was assumed. The binary filter shown in Fig. 2 was produced.
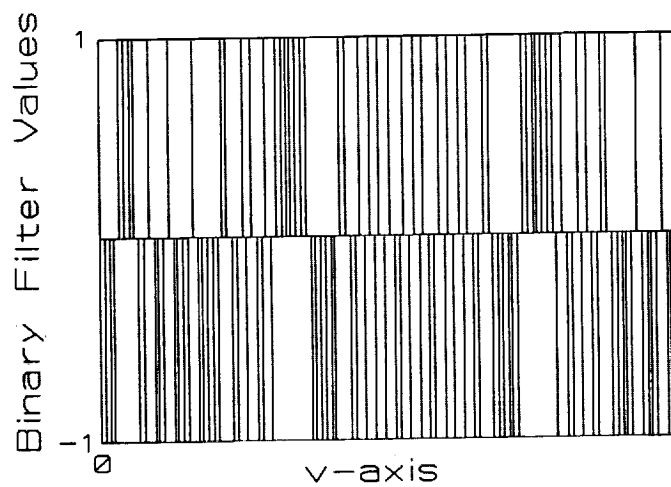
Fig. 2. The binary filter calculated from intensity measurements.

This filter was then applied to the Fourier transform of the random object and inverse transformed. The magnitude of the inverse transform was squared to produce the output correlation. The output is shown in Fig. 3 as a function of x', the output plane coordinates.
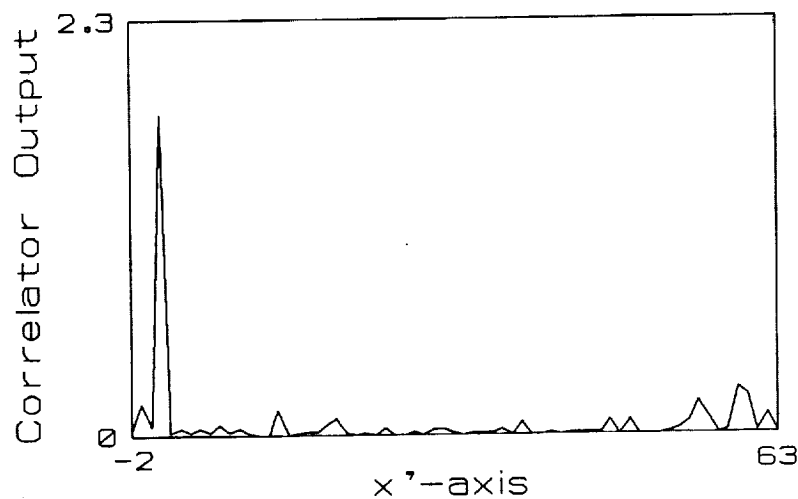

Fig. 3. Output plane correlation for binary filter.

This plot was slightly shifted using some frequency plane tilt and truncated to 66 points to show the region around the correlation peak clearly. This peak shows the typical sharpness expected from binary filters.

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CONCLUSIONS

A method has been presented for designing optical correlation filters based on measuring intensity patterns. A computer simulation was carried out for the special case of a binary phase-only filter using an on-axis uniform plane wave. The simulation produced a workable filter with a sharp correlation peak.

FUTURE WORK

Plans have already been made for laboratory demonstrations of the approach outlined. These plans include trials with the DMD and a liquid crystal television (LCTV). The DMD is phase-mostly SLM; it acts primarily on the phase with a small (usually insignificant) amount of amplitude modulation. It will be tried using phase-only filters. Previous experimentation with LCTVs at NASA has yielded fruit. A high contrast LCTV has been found that can be used both in the input plane and the filter plane. This device can be used for both amplitude and phase controlled binary filters. The amplitude only filter simply blocks the terms that normally require 180 degrees phase shift in a binary filter. This produces the same type correlation profile as a binary phase filter (i.e., All the phasors at the filter output are constrained to a 180 degree phase window.) but with a reduction in peak strength on the order of 4. In order to use the LCTV as a phase-only filter it is necessary to produce either 0 or 180 degrees phase shift at each pixel at the analyzing polarizer output. This can be done by putting the analyzer's polarization axis orthogonal to a polarization angle half way between the two angles associated with a maximally transmitting or blocking pixel. This method has low throughput unless an efficient (i.e. high contrast) LCTV is used.

In addition to the laboratory work, new schemes for optimizing the filters are being studied. Although it should be possible to digitally calculate an optimal filter using the intensity data, it would be interesting to consider optically methods to rapidly carry out these calculations. One simple scheme would be to vary the reference phase while monitoring the peak strength to search out an optimal design. This is reasonable using SLMs that are easy to write on via computer control. In the case of binary filters it makes sense to consider using optical subtraction and thresholding to calculate filters in real-time.

REFERENCES

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3. J. Knopp and R.T. Wingerter, "A Comparison of Binary and Continuous Phase-Only Filters With Restricted Range", Proc. of the SPIE, V1098 (1989).