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SIMG-503
Senior Research

Automatic Optical Matched Filtering

An evaluation of Reflexite and Transitions Lenses in an optical matched filtering role

Final Report

Timothy J. Hattenberger
Center for Imaging Science
Rochester Institute of Technology
May 2000

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Abstract

Automatic Optical Matched Filtering

Timothy J. Hattenberger

A matched filter is a device used to detect the presence and position of known objects in a scene. The ability to create an optical matched filter has been around for many years. The current filters have some aspects that are troublesome. The problems encountered by these filters include quantization error, and complexity in generating the matched filters. The optical matched filter being studied eliminates these problems in an attempt to generate a better filter. There are also other potential implications of this research. One can envision such a system being used for real-time target detection. The primary advantage over conventional digital image processing is the ability to compute at "the speed of light."

The filter has two necessary components: one to compute the complex conjugate of the phase and the other to store the complement of the magnitude. Reflexite™, (an array of corner-cube retroreflectors), was studied for its potential use in the optical matched filter as a phase conjugator. Transitions Lenses™, (a photochromic optical window), was studied for its potential use to store the complement of the magnitude real-time.

Early on we determined that the Transitions Lenses™ would not be feasible for our optical set-up. We also concluded that the while Reflexite™ does approximately conjugate the phase it would not be adequate to perform optical matched filtering. It did however work well enough to be used in simple optical filtering experiments.

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This report is accepted in partial fulfillment of the requirements of the course SIMG-503 Senior Research.
Title: Automatic Optical Matched Filter
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Project Advisor: Roger L. Easton
SIMG 503 Instructor: Joseph P. Hornak

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Automatic Optical Matched Filter

Timothy J. Hattenberger

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I acknowledge the following people for their contributions:

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INTRODUCTION

The long-term objective of this research is to create an optical filtering system, which will be automatic and inexpensive.
The term "automatic" is used to mean that the filter will be implemented by exposure to the desired test object without user intervention. Thus, the entire system could be considered as "real-time," in that an input scene is passed into the system, the filter is made inline, and the cross correlation output is generated. The system may be useful in military surveillance and other remote sensing or target detection applications. The system could also be applied to "... such area correlation problems..." as "object motion analysis" [1]. A hybrid optical signal processing system in conjunction with a digital system is also a possibility. In this scenario, the optical system performs the filtering, and the digital system performs some real-time calculations. These could include analyzing the results for movement, or the relevance of the match.

The major task of the research is the proof of our hypothesis that such a system will work. In other words, the hypothesis is that an approximation of the appropriate optical matched filter can be constructed automatically using Reflexite™
and an optical window containing photochromic particles. The results of this system will be analyzed to determine if the matched filter works.

BACKGROUND and THEORY

A matched filter is a device used to detect the presence and position of known objects in a scene. The known objects have the form f[x,y]. In this situation, "...the purpose ... is not to recover or restore a signal, but merely to *detect the presence* of a signal" [2]. The signal is located at position [x_0,y_0]. The input is therefore f[x-x_0, y-y_0], plus additional noise n[x,y]. The input to the system then becomes the following.

$$f[x - x_0, y - y_0] + n[x, y] \qquad (1)$$

The ideal filter will correctly distinguish between the signal and noise and give an unmistakable output at location [x_0,y_0]. In other words, if the input described in (1) is convolved with a matched filter, m[x,y], the ideal result will be a Dirac delta function at the location of the signal, δ [x-x_0,y-y_0].

$$(f[x - x_0, y - y_0] + n[x, y]) * m[x, y] = \delta[x - x_0, y - y_0] \qquad (2)$$

The system described by (2) is represented in Figure 1.

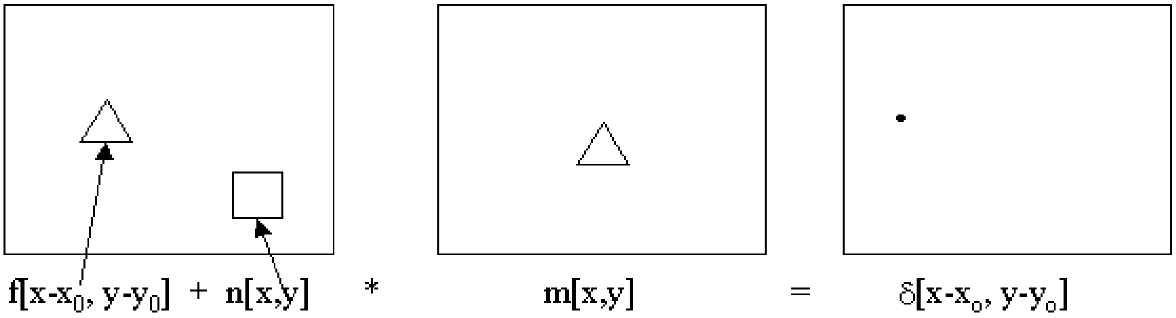

Figure 1. Rudimentary representation of matched filtering system

Typically, these calculations are performed in the frequency domain. The reason for this is that a convolution in the spatial domain becomes a multiplication in the frequency domain. This can easily be computed optically. In the Fourier domain, (2) then becomes:

$$\left(F[\xi,\eta]e^{-2\pi i(\xi x_0+\eta y_0)} + N[\xi,\eta]\right)\bullet M[\xi,\eta] = 1[\xi,\eta]e^{-2\pi i(\xi x_0+\eta y_0)} \qquad (3)$$

From (3), it follows that two simultaneous constraints must be satisfied. First, the product of the Fourier Transform of the input and of the matched filter will result in a Dirac delta function at each location of the desired input signal. The other constraint is that the product of the Fourier transform of the noise and the Fourier transform of the matched filter will yield nothing. These constraints are described in (4) and (5) respectively.

$$F[\xi,\eta]\bullet M[\xi,\eta] = 1[\xi,\eta] \qquad (4)$$

$$N[\xi,\eta]\bullet M[\xi,\eta] = 0 \qquad (5)$$

In real applications, the constraints cannot be satisfied simultaneously in any situation. Therefore, the ideal filter does not exist. The matched filter is calculated to maximize the detection of the signal.

$$M[\xi,\eta] = \frac{1}{F[\xi,\eta]} = \frac{F^{*}[\xi,\eta]}{|F[\xi,\eta]|^{2}} \qquad (6)$$

This is what is known as an "inverse filter," and is so called this because it is the reciprocal of the FT of the input. Equation 4 is satisfied when the matched filter is defined as in equation 6. This filter has been constructed to perform matched filtering. However, from equation 6 it is noticed that this function becomes very large for small values of $F[\xi ,\eta]$, and is undefined if $F[\xi ,\eta] = 0$. The proposed filter addresses this weakness.

A discussion of the system needed to perform the necessary data processing is required before discussing the details of the proposed filter. The optical system is referred to as a ‘4F’ optical correlator. The ‘4F’ implies that the optical system requires four focal lengths to make the computation of the cross correlation. The light source in the system needs to be coherent because the optical phase is used in the calculation. Typically, a laser (denoted by S in Figure 2) is used as the source. The lens, L_1, is used to collimate the light from the laser. The input to be filtered is inserted as a spatially varying amplitude transmittance at plane P_1. Lens L_2, is the first Fourier transform lens. The Fourier transform of the input is located at P_2 as an amplitude distribution, now in the frequency domain. The transfer function of the matched filter is also placed at P_2, where the output of equation 3 is calculated. The filtered signal then passes through the second Fourier lens, L_3, which transforms the signal back to the spatial domain. The filtered output is located at P_3, and is represented as an amplitude distribution in the spatial domain [3].

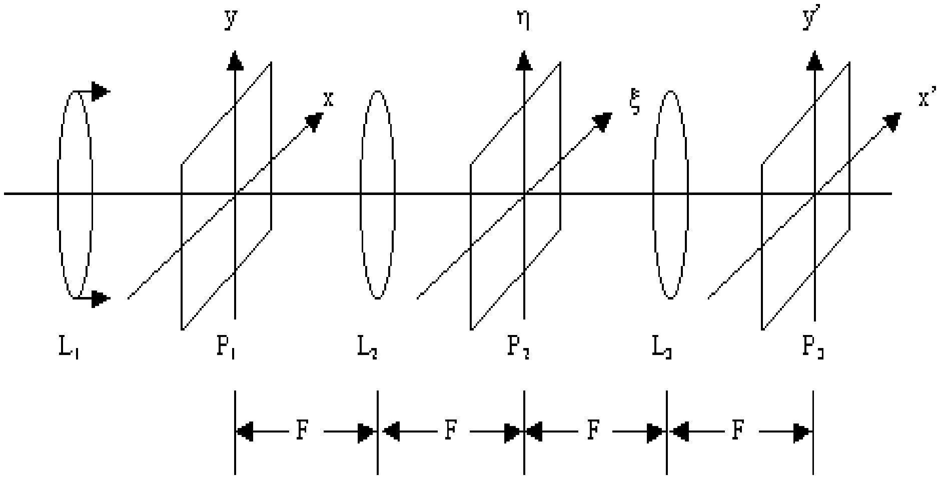

Figure 2. Configuration of coherent (4F) optical processing system [3].

Typically, optical matched filters record the complex-valued spectrum of the known object as magnitude and phase. The Fourier spectra of the known object and the unknown scene are used to compute the correlation of the two functions and a match if one exists. Research in this area is underway to determine the best means to quantify the magnitude and phase of the Fourier spectrum [4]. John Knapp and Roger Easton designed an optical matched filtering system that uses spatial light modulators and a 4F optical system. The spatial light modulators can display 128x128-pixel bitonal arrays. The magnitude and phase of the desired object spectrum were computed digitally, and then displayed on the filtering spatial light modulator. Though they obtained good results using this system, its limitations are sometimes troublesome. First, since the spatial light modulators are bitonal, significant quantization error in the representation of the Fourier spectrum is unavoidable [5]. To improve the rendering of the function, error-diffused quantization was used [6]. Also, the components of the system are expensive and the steps in the process are relatively complicated. A computer was required to pregenerate the magnitude and the phase of the transfer function of each object. These problems can be overcome by making some adjustments to the system. The hypothesis is that an approximation of the appropriate optical matched filter can be constructed automatically using

Reflexite™ and an optical window containing photochromic particles.

Reflexite™
is an array of small corner cube prisms (see Figure 3). A corner cube prism "has the property of being retrodirective; that is, it will reflect all incoming rays back along their original direction" [7].

Figure 3. Corner-cube prism as in Reflexite™ [8].

Barrett and Jacobs (1979) demonstrated that Reflexite™ acts as an approximate phase conjugator [9]. The phase of the outgoing waves is approximately the complex conjugate of the input phase. The experiment is shown in Figure 4. Light from a point source was passed through a beam splitter onto the retroreflective array. The reflected light retraced its path and was reflected by the beam splitter towards the image formation plane. At the image formation plane, a point source was formed. The next step was to repeat the experiment with a distorting medium in the path of the light. Barrett and Jacobs used deforming media such as clamshell-fractured glass and plastic-bubble packing material. They found that a point image was still formed at the image plane even with the distorting medium in place.

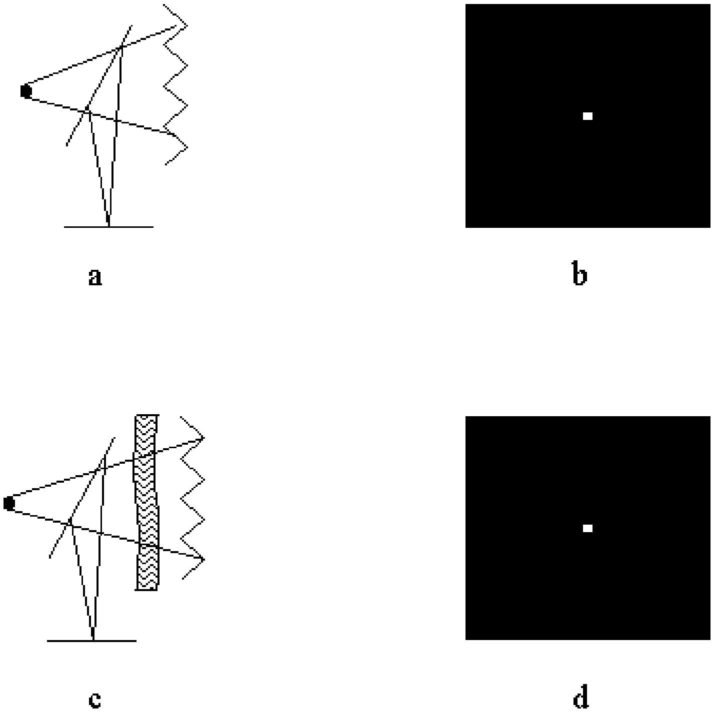

Figure 4. (a) Shows the experiment Barrett and Jacobs

ran with only the beam splitter and the retroreflective array in place. (b) The result was a bright spot at the image plane. (c) Shows the experiment with a distorting medium in place. (d) Again, the image shows there was still a point at the image plane. [9]

The use of Reflexite™ as a phase conjugator was demonstrated in this experiment, as well as its robustness to variation in the distorting medium. The Reflexite™ calculates the complex conjugate of the phase and therefore eliminates the need to use error diffusion to display the phase. Elimination of the quantization will reduce the error in the calculation. This is expected to yield improvements.

The photochromic optical window computes an approximation of the complement filter. Briefly, photochromism is a two-part process. First, the photochromic molecule changes form in response to a particular ultraviolet wavelength of electromagnetic radiation. In the new form, the molecules absorb visible EM radiation. Thus the lens becomes dark wherever it had been exposed to the wavelength of sensitivity. When the wavelength of electromagnetic radiation is removed, the molecules revert to their original form, and the optical window becomes transparent in the visible region of the spectrum. These photochromic materials are "transferred into the front surface of the lens to a depth of 0.15mm" [10]. It is potentially important to realize that the photochromic materials do not just reside on the surface of the lens. The photochromic particles are sensitive to "climate," including both the wavelength of sensitivity, and the ambient temperature. The higher the intensity of the UV illumination, the darker the lenses become. Increased temperature results in faster bleaching (return to the transparent state). The lenses also get darker at colder temperatures [10].

The optical analogue of the complement filter can be stored by exposing the photochromic optical window to the wavelength of sensitivity. This can then be used in the matched filtering system.

As shown in equation 6, the inverse filter is undefined where F[ξ ,η] = 0. The complement filter can eliminate this problem by being scaled within a desired range. In other words, where the inverse filter is defined as in (7), the complement is defined as in (8).

$$I[\xi,\eta] = \frac{1}{F[\xi,\eta]} \tag{7}$$

$$C[\xi,\eta] = 1 - \left(\frac{|F[\xi,\eta]|}{F[0,0]} \right) \tag{8}$$

F[0,0] is the largest value in the spectrum. Thus the value in parentheses becomes normalized.

An optical matched filter can be constructed using the complement filter in conjunction with the phase conjugator. Using these materials in a matched filter context should overcome the problem of quantization error, as well as robustness to noise. In addition, the use of these materials can yield an automatic system, where the filter is constructed in real time. The overall system is less complex than previous matched filtering systems and could be an inexpensive automatic system.

METHODS

Proof of Concept Computer Simulation

The first task in this research was to simulate the optical matched filter on the computer. This was accomplished by using Images, a program written by Roger Easton that performs 2-D arithmetic on images. First, an object (Figure 5) was created. The object was a white "E" on a black background. Two calculations were then performed. The first calculation performed was the autocorrelation of the object. The output was saved to a file. The next calculation was to perform the complement correlation of this object. The object was correlated with the complement filter. The output of this was also saved to a file. The results of the two calculations were compared and confirmed that the complement correlation filter would result in sharper, more distinguishable peaks, thus making it easier to identify a match. The output of this simulation is presented in the Results section.

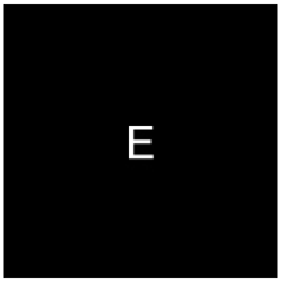

Figure 5. Object used in computer simulation

Transitions Lenses™

The computer simulation described above proved the theory behind the experiment. Therefore the next step was to examine the materials we were going to use in the optical matched filter. The first material that was examined was the Transitions Lenses™. The Transitions Lenses™ was immediately eliminated from the optical set up. The optical system consisted of a HE-NE Laser as the illumination source. However, the Transitions Lenses™ changes its properties only when exposed to UV illumination. Therefore, the system would have been extremely cumbersome in order to accommodate the Transitions Lenses™. In addition, the Transitions Lenses™ was exposed to sunlight, in order to see the reaction to UV radiation. The change in the Transitions Lenses™ was negligible. Therefore Transitions Lenses™ would not have been feasible in constructing the optical matched filter.

The Optical System

The next major goal of the research was to evaluate the Reflexite™ as the approximate phase conjugator in the optical matched filtering role. The optical system needed to be set up in order to continue the research. The optical

system was set up based on the theory behind a 4-f optical correlator. The source used was a HE-NE Laser. A 60x-microscope objective was used to expand the Laser. The object was placed either between lens and the Reflexite™
as in figure 6, or before the first lens. The light passed through the first lens and was focused at the plane of the mirror or Reflexite™ . The Fourier Transform of the object was located at the Reflexite™ plane. The complement of the magnitude filter was placed at the Reflexite™
plane and filtered the Fourier Spectrum of the object. The filtered signal was then sent back through the beamsplitter, and focused using a second lens at the image formation plane. A digital camera was placed at the image formation plane in order to capture the results. (*Insert Line Drawing of Setup*)

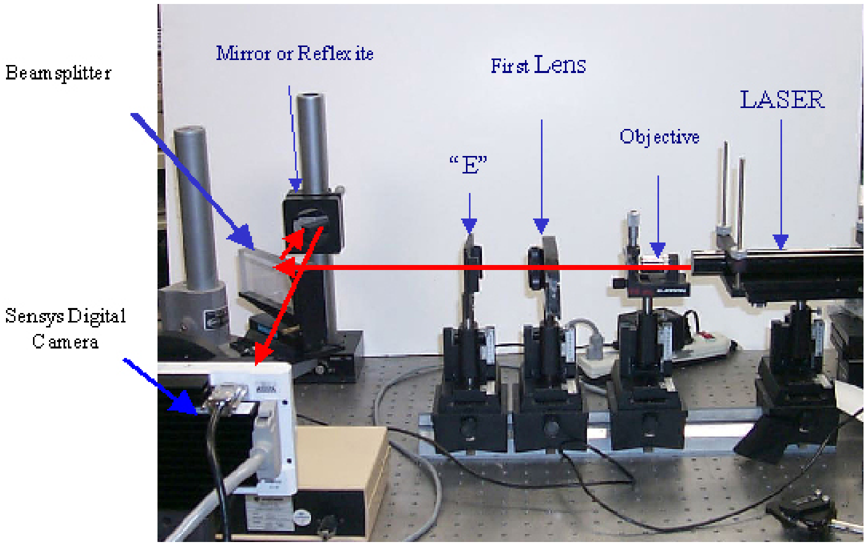

Figure 6. Photograph of the optical system used in the research.

Reflexite™ as an Approximate Phase Conjugator

According to the theory behind the optical matched filter, the phase of the filter must be conjugated. This was the purpose of the Reflexite™. Other research [9] had been done to see if Reflexite™ does indeed conjugate the phase. Experiments were performed using the optical system above to verify if Reflexite™ as a phase conjugator. Figure 6 shows the system used in our research. An "E" that was carved out of an index card was used as the object. Two different images were captured. First, an image using the mirror as the reflector was captured. Next, the Reflexite™ was put in place of the mirror. Another image was taken. The idea behind this experiment is simple. If the Reflexite™
was conjugating the phase, the output "E" should be the flipped copy of the image obtained when the mirror was used. This experiment also began to show the performance of the Reflexite™ in terms of its "resolution."

Optical Matched Filtering

The Object "E"

As stated above, the Transitions Lenses ™ was eliminated from the experimental design. Therefore, another means to store the complement of the magnitude was necessary. We decided to use transparencies. The first step was to decide how large the object should be. It was necessary to have an object that was small enough so a large enough Fourier Spectrum was obtained, but also large enough so the output would be recognizable. Trial and error was used to determine an appropriate size for the object. First, in Adobe PhotoShop, several "E's" were printed on a piece of transparency film so the transparent portion was the "E," and the surrounding background was black. The optical system described above was used, with the Reflexite™ in place. Then, the different sized "E's" were put in place as the object, until a recognizable output image was obtained, while maximizing the size of the Fourier Spectra. The "E" chosen was a 24 point Helvetica font "E."

The Scaling of the Optical System and Printer

Again, since the Transitions Lenses™ was not going to be used to automatically generate the complement of the magnitude filter, it would have to be generated manually. The size of the object was chosen as explained above, which results in a specifically sized Fourier Spectrum. The scale between the object and the Fourier Spectrum needed to be determined in order to make the filter the correct size. A diffraction grating with a known, constant spatial frequency of 100 cycles per millimeter was placed in the system as the object. The Fourier spectrum was large enough so a measurement could be easily made. The measurement from the center of the spectrum to the first order was 17mm. This says that 100 cycles/mm in the spatial domain results in 17mm in the frequency domain, or 1 cycle/mm in the spatial domain results in .17mm in the frequency domain. The scale of the optical system was determined, now the scale of the printer needed to be determined.

First, the "E" image that was generated in PhotoShop was opened again. A rectangle was drawn over the "E" and filled in white. The new object was a rectangle that was the same size as the "E." The Fourier Transform of the rectangle image is taken using the programming language IDL. The reason for doing this is because it is known that the Fourier Transform of a Rect[x,y] is Sinc[ξ ,η]. There is now enough information to compute the scale of the printer. The image of the rectangle is printed. Then, the Fourier transform of the image, a sinc, is printed. The width and height of the rectangle are measured. These measurements directly relate to the zero crossings in the image of the sinc. For example, the width of the rectangle is proportional to one half of the distance between the first horizontal zero crossings in the sinc image. Computing these numbers gives the scale of the printer. The scale of the printer and the scale of the optical system need to be related. The scale of the system divided by the scale of the printer yields the demagnification factor.

In other words, in order to generate the complement of the magnitude of the "E," the magnitude of the Fourier transform must be computed. This must then be scaled by this demagnification factor before it is printed. This will result in the correctly scaled complement filter. The complement filter can then be placed in the system at the Fourier plane, in order to perform the matched filtering.

Other Simple Spatial Filtering

We also performed some simpler filtering. First, the nature of the complement filter is that it is primarily a high pass filter. Therefore we decided to place an opaque dot over the center of the Fourier transform in the optical system. Essentially the constant term, along with some of the low frequencies were blocked. Also, some low pass filtering was performed. This time, a pin hole filter was used which allowed the low frequencies to pass, but blocked the high frequencies. The results were documented. Several different sized low and high pass filters were used in a trial and error fashion.

RESULTS and DISCUSSION

Computer Simulation

Figures 7 and 8 show the computer-simulated output of both the autocorrelation and complement correlation of the "E" object. Figure 7 shows the ideal output of the optical correlator with the object as in figure 5. The input is represented in frequency space as $|F[\xi]|e^{i\varphi(\xi)}$. The filter is represented as $|F[\xi]|e^{-i\varphi(\xi)}$. The optical correlator multiplies these two together and then takes the invese transform. The result is the same as the autocorrelation of the input "E." There is a sharp peak at the center, but there are also peaks with less amplitude on either side of the central peak. The next step was to simulate the optical correlator with the same input object, but this time the complement filter would be used represented by $1-|F[\xi]|e^{-i\varphi(\xi)}$.

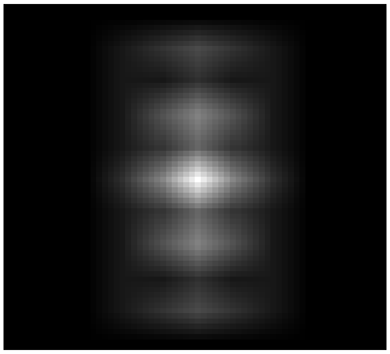

Figure 7. Computer output of Autocorrelation of "E"

Figure 8 shows what the filtered output would be if a complement filter had been used. The peak resulting from the complement filter is much sharper than the peak in figure 7. Also, the adjacent peaks are less pronounced. This would make it easier to determine if there was a match a specific location. In the ideal case, one would want to obtain a Dirac Delta. That is not possible in a real system. However, figure 8 more closely represents a Dirac Delta than the output in figure 7. After examining the results of both filters, it was determined that the complement filter does indeed give a result that makes a match easier to locate.

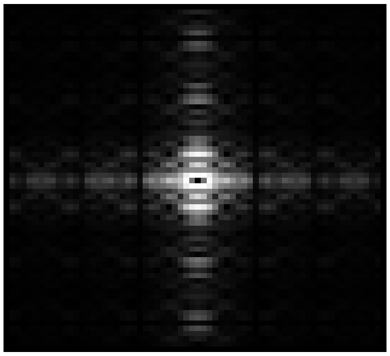

Figure 8. Computer output of Complement Correlation of "E"

Reflexite™ as a phase conjugator

The optical matched complement filter was proved at a theoretical level by the computer experiment described above. Therefore the next step was to try implementing the filter in the optical system. The first experiment was to determine if the Reflexite™ would conjugate the phase. The optical system described in the Methods section above was used. The input to the system was an "E" carved out of an index card. First, the mirror was used as the reflector. Figure 9 shows the output from this experiment. The "E" is visible. Figure 10 shows the output of the system when the Reflexite™ was put in place of the mirror. This is the result that one expects to obtain if the Reflexite™ is acting as an approximate phase conjugator. The image in figure 10 is the flipped copy of the image in figure 9.

The explanation is given in the following two examples. A ray incident on a mirror at an angle θ will bounce off of the mirror at the same angle. Reflexite™ however is composed of an array of corner-cube retroreflectors. Therefore, a ray incident on the Reflexite™ will be directed back along the incident path, having the effect of "pseudo" phase conjugation.

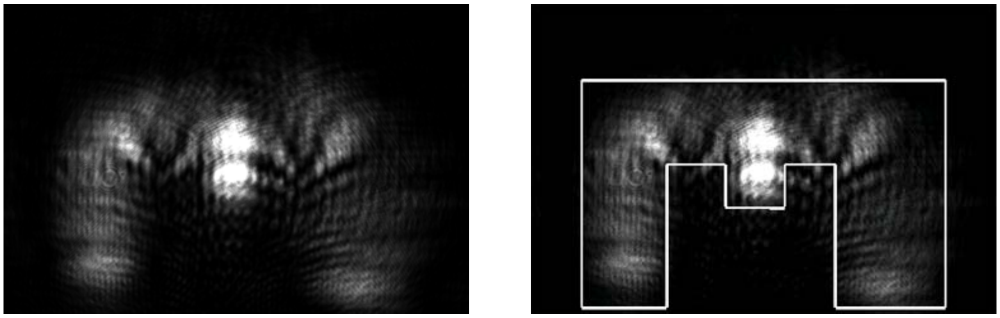

Figure 9. The image on the left is the output obtained when the mirror was used in the system. The image on the right is the same image, but with an outline of the "E" superimposed.

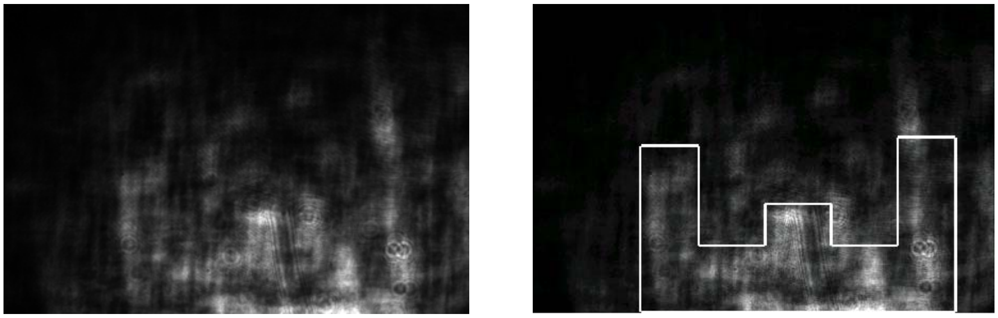

Figure 10. The image on the left is the output obtained when the Reflexite™ was used in the system. The image on the right is the same image as the left, but with an outline of the "E" superimposed.

There is another important observation that was made from these images. The image obtained when the mirror was used is noticeably clearer than the image that was obtained with the Reflexite™ . This is where the limitations of the Reflexite™ had begun to be noticed. The Reflexite™ is composed of a discrete number of the corner-cube retroreflectors of a discrete size, unlike the mirror that has a continuous surface. In addition, the surface of the Reflexite™ is not completely covered with the corner-cubes. The only explanation as to why it was not completely covered was that it was a result of the manufacturing process of the Reflexite™ . This had the effect of reducing the "resolution" of the Reflexite™ .

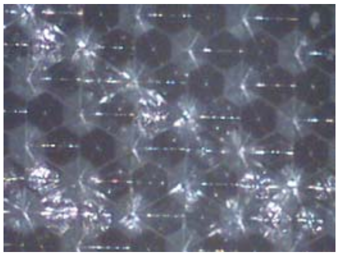

Figure 11. Reflexite™ AP imaged at 200x with the Mattel QX3 microscope. The dark areas are areas where surface is not retroreflective.

The research continued, keeping these limitations in mind. The next step was to store the complement of the magnitude of the object on a transparency. The complement of the magnitude of the object was generated and then saved in tiff format using IDL. This image dimensions needed to be scaled. The scale factors of the system and the printer were determined as described above in the Methods section.

Scale of Printer	1cy/mm spatial = 13.37 mm frequency domain
Scale of System	1cy/mm spatial = 0.17 mm frequency domain

In order to determine the demagnification factor, the scale of the printer divides the scale of the system. The result is a demagnification factor of 0.01259. Therefore the dimensions of the image must be multiplied by this factor. The image was printed after it was scaled. However, the image was .639mm by .639mm. The detail in this image was too small for the printer to render. The next approach was to take a photograph of the complement of the magnitude, scaling the system optically. However, a more simple experiment was performed before this was done.

The complement of the magnitude can be represented by 1-F[ξ ,η]. F[ξ ,η] is the Fourier transform of the object, and is dominated by low frequencies. Therefore, 1- F[ξ ,η] will be composed of high frequencies. If the complement of the magnitude is constructed in this manner, it will essentially be a high pass filter. Therefore, a high pass filter was used in conjunction with the Reflexite™ . Different high pass filters were used. Basically, the high pass filters were slides with different sized dots printed on them. These slides were placed so that the dot blocked the low frequencies. When the Reflexite™
was used with these filters, no meaningful results were obtained. Therefore it made no sense to continue constructing the complement filter knowing that it would not work.

The next step was to try low pass filters in conjunction with the Reflexite™ . The low pass filters were essentially pin holes that blocked the high frequencies and allowed the low frequencies to pass. The image in figure 12 was chosen as the object for the low pass filtering experiments. Results were obtained from this experiment.

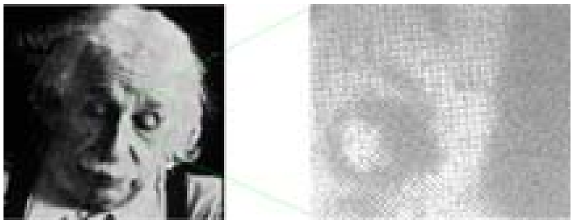

Figure 12. Metrologic Slide with half-toned image of Einstein used in the low pass filter experiments. The image on the right is the section that was used in the experiment. (Click on image to open larger image)

The results from the low pass filtering are shown in figure 13. Since the high frequencies were all blocked, it is difficult to recognize features. In other words the frequencies that once formed the sharp edges of Einstein's eyes and nose were blocked. Thus what is left is the large or low spatial frequency structures.

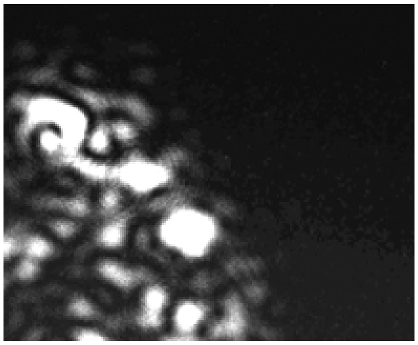

Figure 13. Output of the low pass filtering experiments

Several important results were obtained from these simple filtering experiments. First, the Reflexite™ did not perform well in a high pass filtering role, therefore it would not work in the optical matched filter. However, the Reflexite™ did give some results when used in conjunction with a low pass filter. One possible explanation is that most images have large low frequency content, which translates to a bright area in the optical system. Therefore, the spectrum was bright enough, over a large enough area of the Reflexite™ in order to achieve some retroreflection. Another important result was the reinforcement of the Reflexite™ as a phase conjugator. The Reflexite™ did not need to be placed directly behind the low pass filter in order to obtain results. The Reflexite™ was moved varying distances and results were still obtained. The rays that passed through the pinhole were retroreflected back through the pinhole and onto the image formation plane. If a mirror had been used, the rays that passed through the pinhole would have reflected and never be directed towards the image formation plane. Therefore the Reflexite™ could be used in some of these filtering experiments.

CONCLUSION

The hypothesis of this research was that an approximation of the appropriate optical matched filter could be constructed automatically using Reflexite™ and an optical window containing photochromic particles. The conclusion based on the discussion above is that this hypothesis is incorrect. However, many important results were obtained through this research. First, a better matched filter can be constructed using the complement of the magnitude rather than the magnitude itself. This was seen through the computer simulation results. The term better refers to the fact that the output from the complement filter is a sharper peak, more closely resembling the Dirac Delta that one would obtain if an ideal system could be created. Practically speaking, if a sharper peak that is more distinguishable from the surrounding noise can be obtained, then there is less chance for a false alarm, or a missed detection. The question is not whether the complement will yield better results, but how can it be implemented. John Knapp and Roger Easton implemented the complement filter using the spatial light modulators attached to a computer. The goal of this research was to attempt to simplify the system by using common materials that could automatically generate the filter based on the object to be detected. The materials that were studied were the Transitions Lenses™ and the Reflexite™ . Again, the Transitions Lenses™ were not feasible for two reasons. First, they only changed their properties when exposed to UV radiation. This would have made the system more complicated and cumbersome than desired. In addition, preliminary results demonstrated that the Transition Lenses™ would not have gotten dark enough to produce a useful filter. The Reflexite™ was the other material under investigation as an approximate phase conjugator. The experiments performed above did confirm that Reflexite™ did indeed conjugate the phase. However, Reflexite™ turned out to be the primary limiting factor in constructing the optical matched filter. There were two reasons for this, which directly relate to the "resolution" of the Reflexite™ . The surface of the Reflexite™ was not completely covered with the corner-cube retroreflectors. Also, the individual corner-cubes were too large. This is a very important point especially when considering the size of the Fourier spectrum that was incident on the Reflexite™ . The Reflexite™ did produce results when it was used with a low pass filter. In addition it added an added degree of freedom due to its nature as an approximate phase conjugator. The Reflexite™ could be placed a variable distance behind the filter, and would still retroreflect the rays back through the filter and onto the image formation plane. Therefore, the optical matched filter could not be produced with the two materials that were proposed. The next step in the research would be to continue trying different materials in place of the Transitions Lenses™ and the Reflexite™ . Materials that could store the complement of the magnitude automatically and conjugate the phase would produce an automatic optical matched filter.

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