Experimental implementation of a Wiener filter in a hybrid digital–optical correlator

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We present the implementation of a clutter-tolerant filter in a hybrid correlator system. Wiener filters were mapped with a complex encoding technique onto a smectic A^* liquid-crystal spatial light modulator (SLM). The technique overcomes the problem of representing high-dynamic-range data on SLM's that have limited modulation capabilities. It also provides a compact image recognition system that is robust enough for many real-world applications. Experimental results are presented.

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Optical correlators offer powerful image recognition capabilities. These correlators have many applications in the area of image recognition, from target tracking and identification to optical character reading. Optical correlators take advantage of the inherent parallel processing capabilities of the optical Fourier transform. Conventional systems are commonly based on the VanderLugt 4-f design, in which the input signal, s, is recorded by a CCD camera and displayed on a spatial light modulator (SLM). This signal is then coherently illuminated and optically Fourier transformed to S and optically mixed with a filter, F, in the Fourier plane. F is commonly represented on a second SLM. The new signal is again optically Fourier transformed to yield the correlation signal between the reference and input images.

However, the 4-f system suffers from several engineering problems that must be overcome: The system is alignment critical, and so optomechanical mounting needs to be robust; the input SLM suffers from low dynamic range and can introduce noise into the system; a complex optical design solution is needed to reduce the physical size of the system.

A hybrid digital–optical correlator offers a solution to these problems.[1–4] As in the conventional correlator, a CCD grabs the input signal, but instead of being placed in an input SLM, the data are digitally fast Fourier transformed. The complex data are then mixed digitally with predesigned filters and displayed on a SLM. The SLM is illuminated with a coherent collimated laser, and the wave front is optically Fourier transformed to the correlation plane. By use of modern digital processors, a 512×512 pixel fast Fourier transform can be performed in less than 40 ms.[2] This time is perfectly adequate for processing of the input signal for many applications; however, it is often necessary to search a large number of filters per input. Digital fast Fourier transforms are therefore too slow to perform the second Fourier transform, and so it is done optically. This method has several advantages over conventional systems.[1,4] Only one optical Fourier transform is required, so the whole system is physically smaller; the input SLM is removed so that there is a much higher dynamic range (e.g., 8-bit or 32-bit, depending on the processor architecture) and little noise; there are no difficult optomechanical alignment problems, and the system is physically more robust.

The Wiener filter was used to perform image detection in this experimental demonstration. This filter is robust to clutter and gives a sharp correlation peak. The input signal, $s(x, y)$, in the correlator system consists of two parts, the target, $t(x, y)$, and the background clutter, $b(x, y)$.

The background clutter can disrupt the correlation response. The Wiener filter incorporates the background clutter or a model of it, thus reducing the clutter's effect. The light amplitude just after the filter is given by

$$F(u, v) = \left[\frac{T(u, v)^*}{|T(u, v)|^2 + |B(u, v)|^2} \right] S(u, v) , \qquad (1)$$

where $T(u, v)$ and $B(u, v)$ are the Fourier transforms of $t(x, y)$ and $b(x, y)$, respectively. The bracketed term is the Wiener filter that is applied to the filter-plane SLM in conventional correlators. Since in the hybrid arrangement the mixing is performed electronically, $F(u, v)$ is applied to the SLM. This approach requires considerably less dynamic range from the SLM. If we consider a perfect correlation, i.e., $T(u, v) = S(u, v)$ with no background clutter, then $F(u, v)$ will become constant, which will simply focus a plane wave to a localized correlation spot.

Since the filters are generated offline, a static value for all images is required for $B(u, v)$. A complex division requires a large number of computer cycles and so is too slow to be calculated in real time. A clutter model was generated by use of an approximated term derived from the mean power spectrum of a set of training images.[5]

The encoding technique used is a two-pixel phase-detour technique.[6,7] The SLM used is an analog ferroelectric liquid-crystal device. Each pixel can be considered to be equivalent to a half-wave plate with an

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Fig. 1. Input image. The armored personnel carrier is the target.

electronically rotatable optical axis. The input light is linearly polarized at an angle that bisects the two extremes of the optical axis, and an output polarizer is placed orthogonal to this. In this configuration the device can modulate along the real axis, in both a positive and a negative direction, with 256 gray levels. Since negative modulation can be achieved, a two-element macropixel can be used to represent a complex number. One element represents the real data and one the imaginary. Full complex modulation is achieved off axis, in a direction in which there is a $\pi/2$ phase lag between the two pixels. In addition, every second macropixel must be negated for removal of the π phase lag that would otherwise occur between the adjacent real components.

The input scene spectrum was calculated digitally in real time and mixed with precomputed template data. These data were then written to the SLM and optically Fourier transformed to produce a correlation signal. A polarizing beam splitter ensured that the correct input and output polarization states were selected to give real axis modulation. The resultant correlation signal was captured by a CCD camera.

The SLM used was a Boulder Nonlinear Systems 128×128 analog ferroelectric liquid crystal. Since a 2×1 macropixel encoding technique was used, the

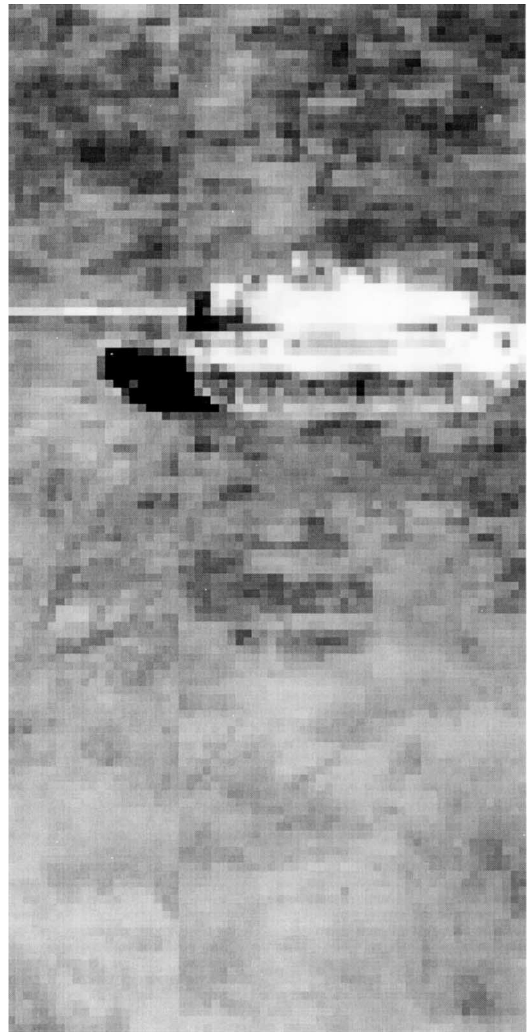

Fig. 2. False-target input scene.

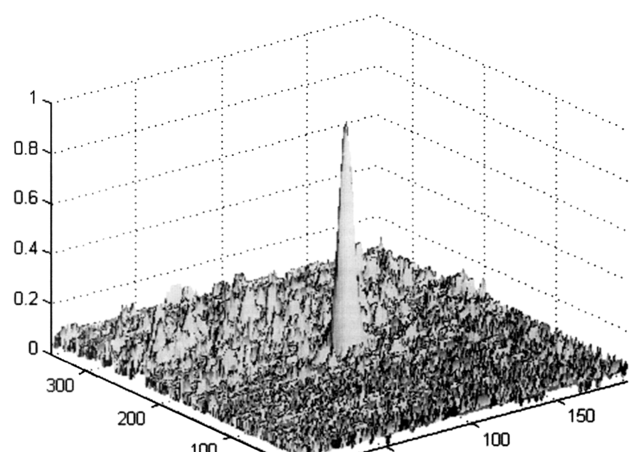

Fig. 3. Correlation peak result for the true target.

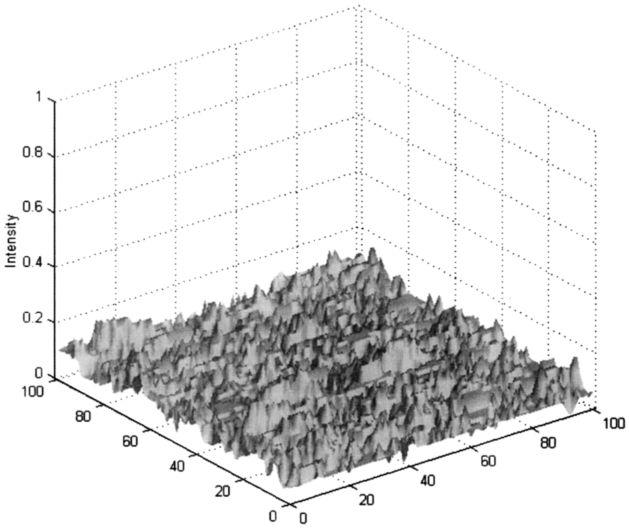

Fig. 4. Correlation-peak result for the false target.

resolution was reduced to 64 × 128, giving a rectangular output field. The SLM is suitable for high-speed digital–optical correlation, since it has a frame load time of 102 μs and a high-speed data input port.

The input signal (an image of an armored personnel carrier with clutter) to the correlator is shown in Fig. 1. Realistic clutter scenes are used to give a more accurate representation of real correlator performance. A false target (a tank) was placed in the clutter background and used to test the correlator (see Fig. 2).

A plot of the region of interest near the correlation peak is shown in Fig. 3. The correlation of the false target is shown in Fig. 4. The Wiener filter successfully identified the correct image in the midst of a large amount of clutter. The false image of the tank was completely rejected.

A Wiener filter has been demonstrated in a hybrid digital–optical correlator system. The method uses a complex phase detour method to encode the data on an analog liquid-crystal spatial light modulator. The SLM was not required to have a large dynamic range for successful demonstration of the filter.

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