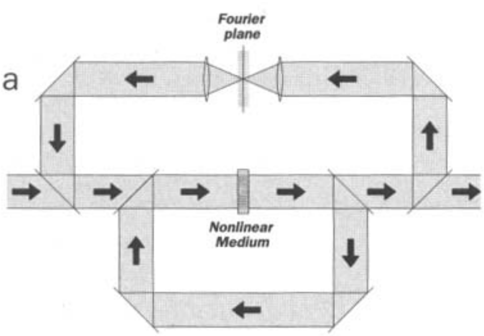
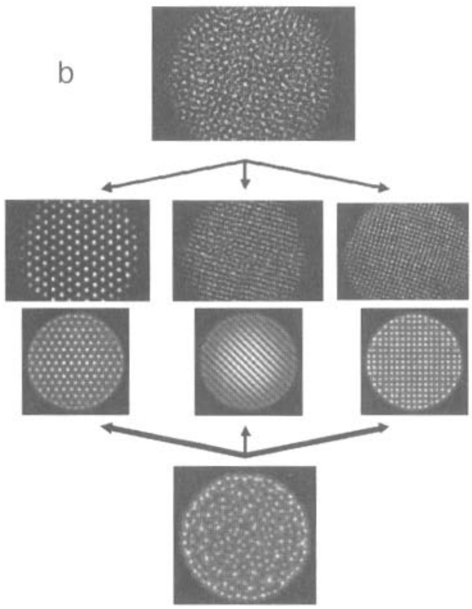
a


b


c


Harkness Figure 1. (a) A diagram of the feedback control scheme, based on Fourier-space filtering, which our group proposed recently. (b) Experiments (top)—courtesy of R. Neubecker—and numerical simulations (bottom) showing how the technique can be used to stabilize turbulent output to give hexagonal, stripe, and square patterns. (c) A combination of near- and far-field filters can stabilize images more complicated than periodic patterns. (See color image, page 15).

hexagons, and squares. Typically only the most stable of all the patterns available to the system will be generated. When no stable pattern exists the output may show spatio-temporal disorder, termed "optical turbulence." Our group recently proposed a feedback control technique, based on Fourier-space filtering (see Fig. 1a), which can be used to select between output patterns, even unstable ones[4,5] and even during optical turbulence[3,4] (see Fig. 1b). The desired pattern is a solution of the system both with and without feedback. The feedback's effect on the pattern is only to alter its stability, making it the preferred one. As the system approaches this desired state, the energy in the feedback loop decreases, in principle to zero, but in practice to a floor determined by noise. The control method is thus non-invasive.

The above-cited experiments, based variously on liquid crystals, photorefractives, and alkali vapors, fully confirm the efficacy of Fourier-space control. Two of them[2,3] conform closely to our scheme, using a special feedback loop containing a Fourier filter. The other one[1] simply placed a Fourier filter in a pre-existing feedback loop, which is functionally quite similar. The separate loop is more widely applicable, and is necessary for some functions, such as the stabilization of images more complicated than periodic patterns.

A simple and amusing first example of image stabilization is shown in Figure 1c, where the use of both near- and far-field filters allows an aperiodic pattern to be generated. Note the qualitative distinction between "generating" and "imprinting" an image: Our model system is not fed an image of Old Glory, as is a slide projector, but rather is configured so that Figure 1c is its preferred output state. Might the brain's visual memory work in this way?

Acknowledgments

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Three-dimensional Spatial Electro-optical Correlator

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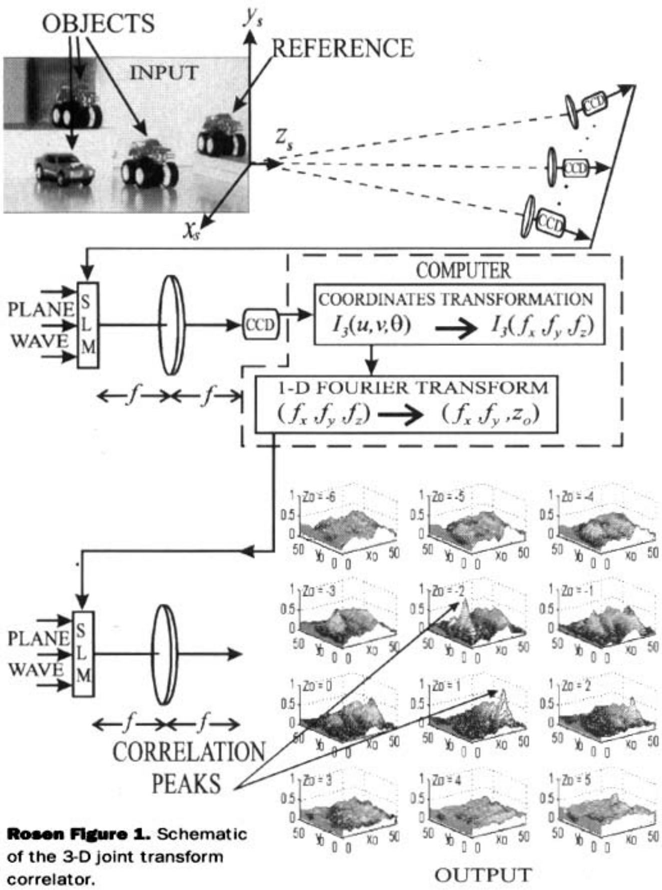
Correlation is essential in signal processing in general, and in optical image processing in particular. A spatial correlation is used extensively in various schemes of edge enhancement, pattern recognition, target tracking, and more. In most of these schemes the functions involved are at most 2-D. However, our real world is 3-D, and in some applications one needs to process 3-D objects in their natural 3-D environment. Pattern recognition and target tracking are examples of applications that can benefit from the use of 3-D correlation. In these applications one uses the information obtained from the 3-D shape of the target and learns its location in the 3-D space.

Recently[1,2] we have developed a novel process of a 3-D electro-optical correlation between two 3-D real-world functions. This correlation was demonstrated on a 3-D joint transform correlator. In the proposed scheme, a reference and tested objects are observed from a single distant transverse plane. A few cameras, distributed on this observation plane, record 2-D projections of the 3-D input scene from various points of view. The correlation process contains a series of optical 2-D Fourier transforms applied jointly on the reference and tested objects. Then, the accumulated intensity distributions of the 2-D Fourier transforms are mapped on a 3-D spectral space. Finally, we obtain the correlation output using an additional 3-D Fourier transform. The output result of this process is a 3-D correlation between the reference and tested objects. This algorithm is composed by a series of automatic image processing operations. Part of them can be implemented optically, and together they yield the 3-D correlation between any two arbitrary functions. Implementing a 3-D Fourier transform in the first stage by electro-optical means is the key concept of the proposed system. Based on the convolution theorem, an additional 3-D Fourier transform yields the desired 3-D correlation result.

In our example, the input scene contains four vehicles as shown in Figure 1. One of them, the reference, is located in the right side of the scene and is identical to two cars from the left group of the three vehicles used here as the observed objects. Note that the two lower vehicles are located in front of the reference, whereas the upper vehicle is behind it. The system should recognize the two cars that are identical to the reference and ignore the other vehicle. In this experiment, a single camera was shifted along the x-axis to 24 equal displacements, 12 for each side. Each projection was recorded by the camera and Fourier transformed. The intensity of each 2-D Fourier transform was stored in the computer.

3-D plots of the output space are shown in the lower part of Figure 1. Each 3-D plot presents the transverse intensity distribution at some z_o along the longitudinal axis. The two strong correlation peaks on planes $z_o = -2$ and 1 indicate the locations of the two recognized vehicles, which are identical to the reference.

In conclusion, our (3-D) optical correlator opens opportunities to process 3-D images directly and rapidly. Therefore, targets distributed in 3-D space can be recognized or tracked by optical correlators in the same fast and parallel manner as the well-known 2-D correlators have always demonstrated for targets in the 2-D scene.



Rosen Figure 1. Schematic of the 3-D joint transform correlator.

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Diffraction Tomography of Strongly Scattering Objects Based on Homomorphic Filtering

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Inverse scattering from far-field data typically requires a solution of the integral equation

$$\psi_s(\vec{s}_s) = \int V(\vec{r}') \frac{\psi(\vec{r}')}{\psi_i(\vec{r}')} \exp\left[-ik_0\left(\vec{s}_i - \vec{s}_s\right)\vec{r}'\right] d^3r', \quad (1)$$

which relates the scattered field ψ_s to the unknown object V[1]. Here, $\psi_i = \exp[-ik_0 \vec{s}_i \vec{r}']$ is the incident field assumed to be a plane wave, ψ_s is the scattered far field, and ψ is total field. The unit vectors $\vec{s}_i$ and $\vec{s}_s$ describe the propagation direction of incident and scattered field components, respectively.

For very weak scattering objects the first Born approximation can be applied, which assumes $\psi \approx \psi_i$. Then Eq. 1 identifies ψ_s as the Fourier transform of the object V along a circle tangent to the origin in Fourier space. The superposition of data taken with different $\vec{s}_i$ yields the information about a low pass filtered image of V. To extend the range of objects that can be imaged, many attempts have been made to evaluate higher-order terms of the Born series approaching the solution of Eq. 1 by means of iterative numerical methods. However, without significant further sophistication, the convergence of the Born series, and hence the validity of reconstruction methods based on it, is still limited to objects with small k_0Va, with "a" being a measure of the physical extent of V.

To image objects with $k_0Va >> 1$, we chose a different approach based on homomorphic filtering.[1] As an initial step this involves back-propagation of the scattered field ψ_s for each view that yields an estimate of V multiplied with ψ/ψ_i. To remove the field component we take the logarithm to transform the product into a sum. In the cepstral domain, *i.e.*, the Fourier space of the signal's logarithm, we apply a filter. The inverse Fourier transform of the ceptrum is exponentiated. An enhanced estimate of the object is obtained from a superposition of all viewing angles. Cepstral filtering was introduced to remove multiplicative noise.[2] In fact, the only assumption we implicitly make is that the field component is not correlated with the object's structure and the spatial frequency content of both components are substantially different. Both assumptions are at least fulfilled to a certain degree.

Our method was successfully applied to real data problems. Figure 1 shows the reconstruction from data of the Ipswich experiment,[3] which provides the com-