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An Optical Adaptive Resonance Neural Network Utilizing Phase Conjugation

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Abstract

A novel adaptive resonance (ART) device has been conceived that is fully optical in the input-output processing path. This device is based on holographic information processing in a phase-conjugating crystal. This sets up an associative pattern retrieval in a resonating loop utilizing angle-multiplexed reference beams for pattern classification. A reset mechanism is used to reject any given beam, allowing an ART search strategy. The design is similar to an existing non-learning optical associative memory, but does allow learning and makes use of information the other device discards. This new device is expected to offer higher information storage density than alternative ART implementations.

The Optical Implementation

The design of the optical ART unit is shown in Figure 1. It is a modification of

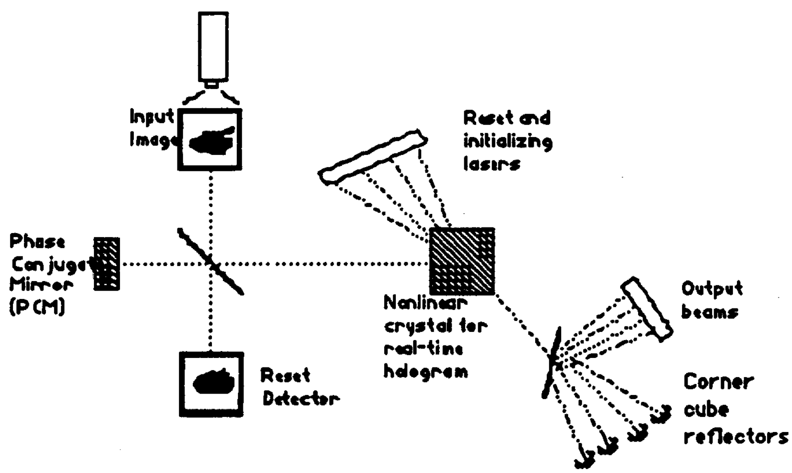

Figure 1. A phase-conjugating ART unit.

the resonating loop reported by Soffer et. al.[1] in 1987, and shown in Figure 2. The key element to notice in Figure 1 is the nonlinear crystal (such as barium titanate) in the center. This is a phase-conjugating device capable of recording a hologram in real-time.[2] It acts as part of a resonant cavity designed to converge on the correct images to make it behave as an ART unit. Contrast this with Figure 2, where a fixed hologram is used. The Soffer et. al. device in Figure 2 is capable of associative pattern retrieval, but is not capable of learning. Another difference to notice between Figures 1 and 2 is the replacement of PCM1 in Figure 2 by corner cube reflectors in Figure 1.

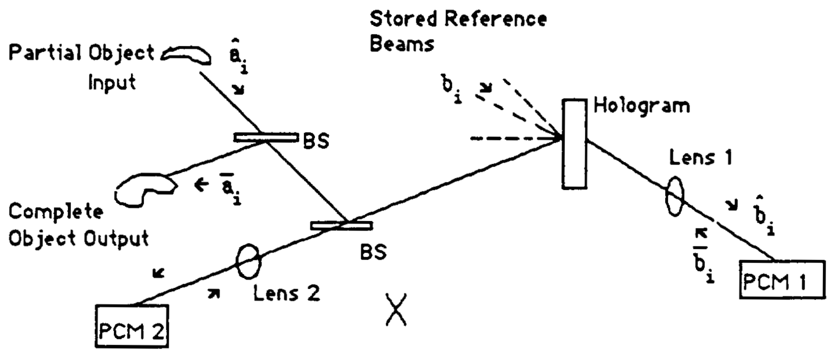

Figure 2. The holographic optical resonator

A brief review of the operation of the holographic resonator in Figure 2 will help to explain the optical ART unit in Figure 1. The holographic resonator is primed with a partial input pattern, $\hat{a}_i$, in the upper left of Figure 2. This is reflected off the second beamsplitter toward the fixed, previously recorded hologram, exciting several reference beams $\hat{b}_i$. These are retro-reflected by PCM1 back toward the hologram, setting up a resonant loop between PCM1 and PCM2. The loop is biased by the presence of the hologram and by the injected signal $\hat{a}_i$ and will suppress all stored patterns (and their reference beams) except for the one most closely matching $\hat{a}_i$. This will cause a readout of the stored image $\bar{a}_i$ closest to the input $\hat{a}_i$. Note also that the device can be considered as a pattern classifier by considering the output reference beam b_i to be an angularly multiplexed classification code. Finally, note that light containing information from both $\hat{a}_i$ and $\bar{a}_i$ will be present at the point marked X in Figure 2, but that this information is not used in any way.

The optical ART unit of Figure 1 was inspired by the Soffer et. al. device, but uses a barium titanate crystal instead of the hologram to allow learning. This simple change is the key to making the device behave as an ART unit, but two problems arise: 1. It is difficult to control the resonant behavior of three phase-conjugating crystals, and 2. It is necessary to provide a reset mechanism to correctly implement ART. These problems are both solved by replacing PCM1 of Figure 2 with the corner cube reflectors of Figure 1. This clearly solves problem 1, since there are now only two crystals. The solution of problem 2 hinges on placing a detector in a position to record the overlap of the input pattern and the recorded template. This is precisely the information that is discarded in location X of Figure 2. The reset detector of Figure 1 is an integrating photodetector, and the path lengths and pump beam angles are adjusted so as to cause constructive interference between the input pattern $\hat{a}_i$ and the stored template $\bar{a}_i$. If this detector's measurement is too small, reset is indicated, and the corner cube reflector corresponding to the most active reference beam angle is deflected. This gives the other memories of the system a competitive advantage for the duration of the search cycle. If reset is not triggered, the system will be allowed to resonate in its preferred mode, causing learning of the new pattern. In any event, the output of the device is the classification provided by the reference beam angle, which can be read off by use of a beamsplitter as shown in Figure 1. It is also possible to read out the stored template information in a similar manner to the "Complete Object Output" shown in Figure 2. In other words, the device can be used as either a heteroassociative or autoassociative ART-based memory.

The optical layout schematic of the device is shown in Figure 3. For experimental verification of the design, human observation of the reset signal and deflection of the corner cube reflectors is acceptable. This role could ultimately be played by piezoelectric motors or optoelectronically. The beamsplitters that allow the reference beams should be of increasing reflectivities, i.e. 33% and 50% for this configuration.

Experimental Setup

Two photorefractive (Barium Titanate) crystals are called for in the optical ART demonstrator implementation illustrated in Figure 3. The first is the memory crystal, used to record object templates against which input patterns are classified. The second is used for phase-conjugate feedback of laser light within the ART resonator.

For the memory crystal, there are two operational modes, template storage and readout. The template storage mode calls for the use of relatively intense waves in the reference beams and in the object input wave (through the SLM) in order to quickly create long-lived phase gratings within the photorefractive. The readout mode involves much lower intensity waves in order to maximize the time at resonance before over-writing of the stored holograms occurs. In other words, the competitive pattern matching mechanism of ART can be realized at low power levels to minimize erasure of previously recorded templates. Once the system has made a classification, a higher power level is used to quickly write the new updated template. Over time, both the high power writing of new templates and the integrated effects of low power readout can degrade previously learned templates. This can be circumvented by re-referencing the storage crystal with the template image(s). This could be compared to the refresh cycles necessary in a dynamic random access memory. Such re-referencing could take place each time a new template is written after a classification search has terminated. However, such frequent re-referencing may not be necessary. It is possible to stagger power levels [6], anticipating template erasure by writing earlier templates at higher power and gradually decreasing the power.

For the phase conjugate feedback crystal, we will employ a four-wave mixing geometry with controllable pump wave power so that (1) adequate effective gain is established to overcome transmission and holographic efficiency losses within the resonator, and (2) the effective gain of the phase conjugator increases with increasing input power for the relevant range of input power levels. The need for the latter objective is that it allows competition between the modes of the system, allowing a nonlinear selection to be made.

The feedback retroreflector / reference beam pair used to record a particular template must be configured so that the reference beam size (when it arrives at the retroreflector beyond the memory crystal) is matched to the retroreflector aperture size, and so that the location of the retroreflector along the reference beam is much less than one rayleigh range away from a focal waist in the reference beam. This is not difficult, since the rayleigh range for our design is be on the order of a meter.

The electric field amplitude of the seed wave (input pattern) immediately after its reflection by the beamsplitter into the resonator is defined as E_O over a total area of A_O, assuming constant electric field amplitude over the input area. This assumption is justified in the case of ART1, since the input patterns for ART1 are binary. Removing the assumption is a straightforward extension of the expression that follows. The input light attempts to resonate with each of the stored template objects, i. Each of the template objects couples with the object seed through scattering in the memory crystal. It can be shown that, after many round-trips through the resonator, the electric field amplitude associated with the i^{th} stored template (within the resonator as it emerges from the input beamsplitter) is given by

$$E_i = (K_1^{oi} A_o / A_i)^{1/2} (K_2^i)^{1/2} K_t^{1/2} G_i^{1/2} \times \exp(K_2^i K_t^{1/2} G_i^{1/2}) E_o \exp(j \phi_{oi}) \quad . \qquad (1)$$

In the above equation, K_1^{oi} is defined as the fraction of the power in an object wave, o (which may or may not correspond to a stored template), which is scattered by the memory crystal into a virtual image of the reference beam used to store the i^{th} template. This template is defined as having total area A_i. The variable K_t is defined as the round-trip transmission power losses in the resonator, including two passes through the resonator-input beamsplitter. G_i is the effective gain of the phase conjugate mirror in response to resonance with the i^{th} stored template, and ϕ_{oi} is the overall residual phase due to one round-trip pass through the resonator when the object wave is scattered from the i^{th} template's grating. We have assumed that the position of each of the feedback retroreflectors along its reference beam has been adjusted so that there is zero residual phase due to one round-trip pass through the resonator when the i^{th} template wave is scattered from the corresponding template grating.

The efficiency K_2^j is defined as the fraction of the power in a conjugate (retro-propagating) version of the j^{th} template's reference beam which is scattered, by the memory crystal, into a conjugate version of the j^{th} template image. Here we assume that $K_1^{ij} = 0$ if i and j are template waves and $i \neq j$, based on the fact that the multiple templates stored in the memory crystal employ reference beams with sufficient angular separation that there is negligible cross-talk between stored templates. We have demonstrated this lack of cross-talk experimentally with as many as six coplanar reference beams, so cross-talk will not be a problem for our optical ART demonstration. Note that, by reciprocity, $K_1^{ii} = K_2^i$, when "i" denotes one of the templates.

Discrimination in the competition between modes due to different templates takes place through a dependence of G_i on the power in the i^{th} mode. The pump waves input to the four-wave phase conjugator will be adjusted so that the effective gain of the PCM increases with increasing input power. Under this condition, the interactions within the ART resonator will preferentially select a closest "match" to the input object from among the available stored templates. After a reset decision is reached by the optical ART system, the dominant mode can be extinguished by blocking access to it's feedback retroreflector, leaving the ART system to choose a closest match among the remaining templates. The equation for E_i also shows that unbiased competition between templates will require that the recorded holograms in the memory crystal be produced consistently so that K_2^i is essentially the same for each stored template.

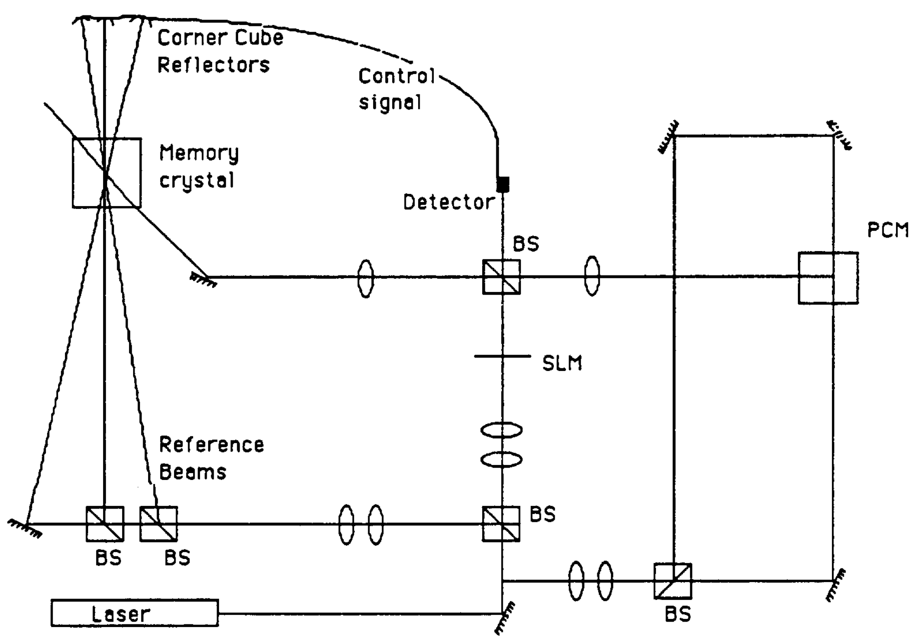

Figure 3. Optical layout of the optical ART unit.

The fully optical ART unit is capable of processing large patterns and has a large template capacity. The device's capacity should ultimately approach the capacity of holographic storage systems, which have the potential to greatly exceed electronic capabilities.[3,4] Furthermore, the device is all-optical in the information processing path--the reset detector's electronics are never used when an input pattern has already been learned or matches an existing template sufficiently. ART has been shown to be useful with extremely large input fields, such as may be expected in high-resolution images.[5] The high storage density of this device should make it outperform alternative ART implementations[7-11] that do not offer the same potential to deal with the large number of pixels in a high-resolution image. (Those implementations are more likely to be used with applications in which speed is more important than the capability to handle large numbers of pixels.) See Carpenter and Grossberg [12] for the full operational description of the ART1 neural network.

Conclusion

A novel adaptive resonance device based on a phase-conjugate resonator has been proposed. It offers a fully optical information processing path and the information storage capacity of holographic media. As such, it is an attractive alternative to other ART implementations for applications requiring large input fields.

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