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ADAPTIVE SENSOR OPTIMIZATION AND COGNITIVE IMAGE PROCESSING USING AUTONOMOUS OPTICAL NEUROPROCESSORS

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Abstract

Measurement and signal intelligence demands has created new requirements for information management and interoperability as they affect surveillance and situational awareness. Integration of on-board autonomous learning and adaptive control structures within a remote sensing platform architecture would substantially improve the utility of intelligence collection by facilitating real-time optimization of measurement parameters for variable field conditions. A problem faced by conventional digital implementations of intelligent systems is the conflict between a distributed parallel structure on a sequential serial interface functionally degrading bandwidth and response time. In contrast, optically designed networks exhibit the massive parallelism and interconnect density needed to perform complex cognitive functions within a dynamic asynchronous environment. Recently, all-optical self-organizing neural networks exhibiting emergent collective behavior which mimic perception, recognition, association, and contemplative learning have been realized using photorefractive holography in combination with sensory systems for feature maps, threshold decomposition, image enhancement, and nonlinear matched filters. Such hybrid information processors depart from the classical computational paradigm based on analytic rules-based algorithms and instead utilize unsupervised generalization and perceptron-like exploratory or improvisational behaviors to evolve toward optimized solutions. These systems are robust to instrumental systematics or corrupting noise and can enrich knowledge structures by allowing competition between multiple hypotheses. This property enables them to rapidly adapt or self-compensate for dynamic or imprecise conditions which would be unstable using conventional linear control models. By incorporating an intelligent optical neuroprocessor in the back plane of an imaging sensor, a broad class of high-level cognitive image analysis problems including geometric change detection, pattern recognition, and correlated feature extraction can be realized in an inherently parallel fashion without information bottlenecking or external supervision, Using this approach, we believe that autonomous control systems embodied with basic adaptive decision-theoretic capabilities can be developed for imaging and surveillance sensors to improve discrimination in stressing operational environments.

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Adaptive Sensor Optimization and Cognitive Image Processing Using Autonomous Optical Neuroprocessors

I. Introduction

Information awareness is currently limited by sensory overload and bottlenecking in the analysis stage. Interpretation and integration of sensor data is not currently well matched to up-tempo operational demands and the perceptual bandwidth for decision-making. The ability of sensor systems to detect, filter, and process raw data to infer optimum decisions or pursue optimization strategies based on uncertain, non-stationary, or ambiguous information is in a rudimentary state. New autonomous preprocessing analysis tools which combine a level of on-board inferential reasoning function with automated processing are required to improve data-gathering effectiveness and more efficiently aggregate relevant knowledge. The study of autonomous neural control systems applied to surveillance-gathering sensors is a key enabling technology for future information management systems responding to complex measurement signatures in uncertain environments. A neo-cognitive inference paradigm is necessary when causal relationships defining the origin of signatures exhibit significant deviations from a rules-based or probabilistic antecedent-consequent knowledge structure.

Measurement and signal intelligence demands have created new mission requirements for information management and interoperability as they affect surveillance and situational awareness. Direct integration of on-board autonomous learning and adaptive control structures within a remote sensing architecture would substantially improve the utility of intelligence collection by merging an interpretive or inference layer capable of contextual/relational pattern analysis with internal self-optimization of measurement parameters. Such a sensor-processor system would then be potentially capable of performing both rudimentary cognitive interpretation and follow-on exploitation against ambiguous or complex signature representations under variable field conditions in near real-time during the same tasking cycle. A problem faced by conventional digital implementations of intelligent systems, however, is the inherent conflict between a distributed parallel structure and a sequential serial interface functionally degrading bandwidth and response time. In contrast, optically designed networks exhibit the massive parallelism and interconnect density needed to perform complex brain-like functions within a dynamic asynchronous host environment. The large overlap between requisite features of network models and natural domains of the optical regime such as parallel and distributed processing has enabled rapid progress in the marriage combining Fourier optical processing and intelligent algorithms. Optical resonators incorporating holographic elements are potential candidates for storing information that can be accessed through addressable or associative recall. To date, perceptron and phase-conjugate holographic interferometers employing photorefractive memories and spatial light modulators (SLM) have been demonstrated for correlated image processing, basic two-level pattern recognition, and optical image synthesis. Adaptive target classifiers for pattern recognition incorporating both conventional correlator and feature-based neural network approaches have been reported.

Recently, all-optical self-organizing neural nets exhibiting emergent collective behavior which mimic perception, recognition, association, and contemplative learning have been realized in combination with sensory subsystems for feature maps, threshold decomposition, image enhancement, and distortion-tolerant nonlinear matched filters. Psaltis and Farhat (1985) were the first to show that neural net mapping, synaptic plasticity, and pattern retrieval for feature detection could be accomplished in a retinotopic topology employing optical interconnects and a holographic transformation. The auto-associative properties of a neural net can be used to map identifying characteristics of input source waveform or spectra, or detect novel patterns, complex signatures, edge or contour detection and are adaptive to missing boundary information or discontinuities. Unlike traditional correlator-based pattern recognition systems which are optimized for white Gaussian noise backgrounds and not effective in rejecting other types of noise or clutter, neural net systems can be configured as morphological or "smart" filters which can process weak intermittent signals in non-stationary backgrounds without distortion. These systems can be used in data compression, restoration of noisy incomplete or otherwise corrupted data, and in novelty filters.

Such hybrid information processing devices depart from the classical computational paradigm based on analytic rule-based algorithms and instead utilize unsupervised fuzzy generalization, heuristic variables, and exploratory, experiential or improvisational learning behaviors to evolve toward optimized solutions. These systems are robust to instrumental faults (eg., camera pan or tilt errors) or corrupting environmental noise and can enrich knowledge structures by allowing parallel competition between multiple hypotheses. This feature allows them to rapidly adapt to dynamic or imprecise conditions which would be fundamentally unstable for conventional linear control models. By incorporating an intelligent optical neural processor in the back-plane of an imaging sensor, a broad class of high-level cognitive image analysis problems including geometric change detection, pattern recognition/classification, and correlated feature extraction can be realized in an inherently parallel fashion without information bottlenecking or external supervision. Self-compensating behaviors introduced through learned optimization orchestrated by an evolving fitness function would automatically adjust instrumental parameters including focus, angular magnification, light level, detection wavelength, and optical figure "on the fly" to actively enhance operational functionality and to improve image discrimination in dynamic environments. Using this approach, we believe that a new generation of closed-loop autonomous sensor control systems embodied with basic adaptive decision-theoretic capabilities for recognition/interpretation can be developed for imaging surveillance and reconnaissance sensors to improve both the quality and efficiency of the data-gathering process.

The basic objective of this exploratory LDRD project research was to lay the foundations to demonstrate an all-optical neuromorphic processor for visual sensing and pattern recognition that combines geometric change detection, correlation, photorefractive holographic memory, and a neural network-based learning control loop with an imaging sensor. Although the study specifically addressed real-time unsupervised optimization of a simple camera imager against calibrated test scenes, we believe that our conceptual approach is generally applicable to all classes of signature exploitation and remote sensing measurements, including spatial imagery and time-signal analysis. Fully optical implementations of reconfigurable associative memories for autonomous learning and intelligent feedback control of sensor systems are in their infancy and represent a level of complexity beyond contemporary two-state designs, but offer new opportunities for improving the quality of imperfect information acquired from pure data-based systems. This innovative approach builds upon state-of-the-art precedents in non-classical controls methodologies by leveraging recent scientific advances in cognitive image analysis using self-organizing distributed optical topologies implemented with angle-multiplexed photorefractive holograms. Incorporation of a robust, competitively optimized learning capability in an adaptive resonance neural net configuration using optical feedback will accelerate convergence for interpretation of mapping signatures and subsequent adaptations. Our approach will facilitate more flexible sensor tasking during the observation interval and the adjustment of instrumental transfer functions or stimulus curves for maximum contrast in spatially and spectrally dynamic scenes possessing structured backgrounds and variable illumination, or in the presence of noise or conflicting data. By virtue of multi-dimensional parallel processing and free-space connectivity, optical neural net architectures potentially satisfy the intensive computation requirements for real-time pattern classification and state vector tracking. The computational rendering of learning algorithms with fully parallel optical networks and adjustable neural weighting allows a unique compromise between distortion tolerance properties (sensitivity versus noise immunity) of a matched filter and the discrimination properties (selectivity) of an inverse filter. Feature-based cognitive neural nets operate morphologically on a collection of elementary shape parameters of the input pattern to associate the data structure into a more compact form represented as contextual objects or clusters. Extracted features recognized in the first layer can be recombined into higher-order associations and subsequently refined in deeper layers until the degree of recognition/classification is completed in the output layer.

Optical implementation of an embedded feature-based learning processor for unsupervised optimization is a revolutionary advance in sensor-based information processing capability which will enhance interpretation and integration of contextual data in complex information-dense cluttered backgrounds (such as urban areas). Using real-time adaptive cognition models based on layered association, both sensor fusion from cross-tasked multi-band discriminants and pixel-to-object morphological pattern classification from mixed image data based on spectral, topographic, and other point-form measurements can be integrated to produce compact prioritized pattern recognition data structures for efficient analysis and subsequent image performance optimization. By using situational awareness attributes to recognize contextual or naturalistic cues in the environment and learned experiential-based strategies regarding uncertainty (noise, clutter artifacts) to simultaneously sense, filter, and preprocess images, the resulting operations will dramatically reduce link budget and bandwidth requirements. The resulting data stream will more effectively match human analysis perceptual bandwidth with the tempo and precision of operational demands for decision-making by avoiding information saturation due to extraneous or ambiguous data overload which can exacerbate complexity of interpretation; relevant information rather than raw data would be exported. Development of automatic strategies to regulate and adapt image acquisition parameters ("active lens") to time-varying measurement environments will improve the reliability of subsequent image processing and exploitation phases against critical high-priority targets with reduced false alarm rates and enhanced probability of detection. Although standard pattern recognition problems typically involve image reduction to binary (digital) form for edge detection, segmentation, and feature extraction operations, classification of real-world imagery is often made more difficult by the lack of primitive or global shape features and flawed ground truth owing to partial occlusions and ground clutter. These artifacts can severely distort the relation between image signature and object classification during image processing in the absence of contextual information. In addition, the transition from pixel to contiguous object determination can also become problematic in the presence of bad data values due to saturation, drop-out, or masking by meterological obscurants such as clouds. We can significantly improve exploitation against targets in these instances using autonomous decision-theoretic classification algorithms where ***a priori*** probabilistic maximum likelihood estimators are not reliable or are poorly sampled. Synthetic scene generation and object-oriented simulation/visualization tools can be used to develop contextual training sets and discrimination algorithms to "tune" the sensing platform ahead of time to emphasize selected deterministic aspects of the target guidance or terrain registration characteristics in various mission scenarios, including battle damage assessment, multi-spectral signatures, Kalman filtering, atmospheric compensation, low-CNR statistics, moving target processing, or missile plume detection.

II. Intelligent Controls:

Conventional linear control models work best when an accurate state representative model describing the dynamic system exists for decision-making but breakdown for classes of problems which are inherently under-defined. Difficulties arise when non-linearities, time delays, noise corruption, transient background parameters, or saturation occur creating information uncertainties and an imprecise learning environment which may exhibit undesirable instability characteristics for optimization. Non-classical intelligent hybrid control represents a new field of artificial intelligence for constructing a nonlinear controller using heuristic variables and exploratory problem-solving. These systems integrate expert decision-making systems and cooperative learning neural nets to enhance real-time operational robustness to complex environments and to manage uncertainty.

Neural nets are biologically motivated models for solving high entropy problems in which the underlying algorithm and state model describing the system is unknown or imprecisely defined, and the required transformation must be learned from example. The neural structure is trained to produce an appropriate response to a class of inputs being presented with examples (references) during the learning (evolutionary) phase. One can view the neural net as a nonlinear network whose non-linearity can be selectively tuned by changing weights, biases and parameters of its activation function; basically a reconfigurable reception field of interconnected elementary parallel processing nodes which stores information distributively. Intermediate nodes (hidden layers) between the input and output interact with cooperative or competitive feedback of competing hypotheses to force generalization of a decision filter. Collectively, sensor neurons with simple properties, interacting according to basic community rules, can accomplish complex interconnecting functions such as generalization, error correction, pattern recognition, and localization. Interconnect density creates decision space redundancy and multiple routing to overcome link failures and improve fault tolerance in the presence of noise or conflicting data. This feature allows them to rapidly adapt to changeable measurement conditions and to recognize/classify unknown object patterns or orientations with reduced false alarm rate and a minimum subset of precursory information. The neural net architecture is defined by the network topology, node characteristics, learning rules, and discrimination capability. Many neural network architectures have been designed for learned pattern recognition problems including adaptive resonance, backward propagation, Kohonen-style self-organizing maps, and simulated annealing. By incorporating an intelligent optical neural processor with internal associative memory capability in the back-plane of an imaging sensor, a broad class of high-level cognitive image discrimination analysis problems including geometric change detection, registration, pattern recognition and taxonomy, and correlated feature extraction can be automatically realized from complex contextual scenes in an inherently parallel fashion without information bottlenecking or external intervention.

When combined in a control loop competitively trained for performance optimization, the ability of neural nets to learn (improvise) in imprecise environments enables the expert system to modify (adapt) and enrich knowledge structures autonomously without bottlenecking or diverging. The transfer of knowledge between these levels, allows modifications of existing rules and to infer new optimization configurations for identifying feature correlations which may not be intuitive to the human observer. Findings to date strongly suggest that visual awareness is not simply the end product of a hierarchial series of linear processing stages, but instead involves expert cognitive processing with feedback, a form of neuromorphic processing embodied by perception. The expert system in this case could be based on a physics-based genetic algorithm which mimics the principles of evolution and Darwinian natural selection to perform a parallel stochastic but directed search to the most fit population even in the presence of uncertainty. Such an approach is more powerful than standard statistical techniques because a larger range of solutions can be represented by parallel manipulation of a whole population in the absence of an assumptive model for the fitness function. Efficient neural training methods for updating generalized multilayer network models using back-projection and genetic programming have recently been used at Sandia National Laboratories to speed up the learning process and to coordinate emergent cognitive behavior and naturalistic decision-making in situ. Genetic sequences of interconnect weights and response functions from the neural net which describe multiple variable-sized regions or pixels in the image scene can be optimized by evolutionary competition under unsupervised genetic algorithm control for specific applications including remote spectral sensing. Expert systems and neural networks represent complimentary approaches to knowledge representation; the logical, cognitive, and mechanical nature of the expert system versus the associative and self-assembling nature of the neural net.

Although standard pattern recognition problems typically involve image reduction to binary (digital) form for edge detection, segmentation, and feature extraction operations, classification of real-world imagery is often made more difficult by the lack of primitive or global shape features and flawed ground truth owing to partial occlusions and ground clutter. These artifacts can severely distort the relation between image signature and object classification during image processing in the absence of contextual information. In addition, the transition from pixel to contiguous object determination can also become problematic in the presence of bad data values due to saturation, drop-out, or masking by meterological obscurants such as clouds which can confuse spectral algorithms. Automated image analysis procedures must use screening procedures relying on decision rules, clustering algorithms and a priori knowledge of the expected distribution of valid data. In practice this is usually accomplished with designated training sets of signatures or pattern classes to establish decision parameter boundaries, or so-called Bayesian maximum likelihood classifiers which are statistically based on their mean vector and variance-covariance matrix. Unfortunately, in many cases such as small or sparse sub-pixel static targets imaged from high-altitude orbits or non-stationary time-critical scenes with unknown background characteristics or weather interference on threshold levels, it is not always possible to get sufficient sampling to estimate maximum likelihood models or to verify the underlying statistical assumptions made in derivation of the classification method used. For these types of imaging problems, a degree of autonomous decision-theoretic capability that can yield a required operational decision function directly by rapid iterative training without assumptions regarding underlying probabilistic information during the measurement event is a better option. Neural vision schemes of ATR provide boundary completion of occluded targets, normalization of spatial discontinuities for varying luminescence values, segmentation based on textural information (adaptive to missing boundary information)- a distortion tolerant classifier.

The use of imbedded feature-based inference capability merged with adaptive contextual decision-theoretic capability will improve our ability to gain understanding in ambiguous environments. By adapting to both somatic and synaptic influences, procedural knowledge paths in the decision tree can reconfigure for new outcomes. The resulting flexibility will expand the solution space to include causal influences beyond conditional probabilistic outcome which are not currently accounted for by conventional statistical analysis. Because the nodes in the governing decision tree can respond to evolving information from a variety of sources, new synergistic interactions are possible including various target representations: statistical model, syntactic model, relational model, projective geometry model, and physical models. The concept of dynamic fitness places a premium on flexibility and adaptability of embedded information structures in response to a changing environment.

As the number of discriminators and complexity of categorization increases, the number of connections and decision units will grow nonlinearly and rapidly with problem size. The overall dimensionality will increase approximately as the square of the number of spectral bands and will require better interconnect density and processing speed to keep the image processing problem manageable in real time. This prerequisite can be met with a fully parallel network implementation for fast computational rendering of algorithms with adjustable weighting that allows a compromise between distortion tolerance properties (sensitivity versus noise immunity) of a matched filter and the discrimination properties (selectivity) of an inverse filter. Feature-based cognitive neural nets operate morphologically on a collection of elementary shape parameters of the input pattern to associate the data structure into a more compact form represented as contextual objects or clusters. Extracted features recognized in the first layer can be recombined into higher-order associations and subsequently refined in deeper layers until the degree of recognition/classification is completed in the output layer. In the time domain, spatio-temporal image filtering with cellular neural networks is a promising arena for image motion analysis. Conventional digital processing of time-varying images requires high frame rates (latency) to avoid the deleterious effects of temporal aliasing, but the higher frame rates establish extraordinary performance requirements for the processing stages. Cellular nets operate in continuous time so that temporal aliasing is not an operational limitation and facilitates applications involving pulse compression or dispersion compensation. Quantum neural networks use the unique information representations of quantum entanglement and the non-local properties of a linear superposition to invoke exponential memory capacity and faster computational convergence for incomplete or combinatorial explosive alternatives.

III. Optical Neuromorphic Processing

A. Biological Inspiration

A fundamental capacity of perceptual systems and the brain in general is to deal with the novel and unexpected. In vision, we can effortlessly recognize a familiar object under novel viewing conditions or recognize a new object as a member of a familiar class. The ability to generalize and deal effectively with novel stimuli using partial generalizations is based on experiential learning and assimilation. Animals at the phylogenetic level of amphibia do not have a fully developed cortex, but instead select behavioral output from a limited number of alternatives by evaluating a small number of trigger events from their local environment. A network that models this behavior would be a sensory layer plus a decision layer or basal ganglia. Feed-forward networks that model this type of behavior use a similar strategy using *a priori* knowledge to limit alternatives. The advent of a cortex is linked to emerging capability of increasingly deeper analysis of sensory input, combining the expert database of the hippocampus with mood or emotional factors which shape perception; i.e., adding an expert layer. Similar antecedents apply to the development of intelligent computing architectures. In early studies, biological neurons were modeled as decision elements described by two-value state variables which were then organized into logical networks employing simple Boolean functions. Later studies with perceptrons (analogous to the basal ganglia) solved simple pattern recognition problems with logic networks using feed-forward synaptic connectivity and simple learning algorithms. More recent studies have used model neurons exhibiting less contrived properties (fuzzy neurons with modifiable soma or weights aggregations) in conjunction with continuous valued nonlinear models in networks to implement associative memory tasks and graded responses. Programmable optical neurons and adaptive matched filters have been implemented using real-time photorefractive holography and spatial light modulators to provide self-organization and leaning attributes. Optical architectures offer speed and bandwidth to signature discrimination.

Motion detection is a common element in the early stages of visual processing by many organisms and is a useful starting point in artificial vision systems. Adaptive processing and interpretation of a scene by removal of previously recognized or stationary parts from the input to produce a differential active residual can reduce subsequent processing load and bandwidth. Motion detection and tracking operations combined with learned movement prediction can be implemented as an analog front-end instead of first-layer processing employed by traditional imaging devices. This proposal describes a hardware prototype of an intelligent neuromorphic processing system for visual pattern recognition which combines cascaded elements of an optical novelty filter, joint transform cot-relator, internal associative memory function, and an adaptive control interface as shown in figure 2. Structural elements keyed toward signature recognition combine an optical preprocessor subsystem for change detection and correlated feature extraction of images in the Fourier domain with an optical neural processor or associative memory matched filter module for sensor optimization and pattern classification. Analysis, matrix-vector multiplication, and optimization processes are driven optically *without external computer intervention.* The basic design incorporates optically addressable spatial light modulators (SLM), lenslet arrays, and a holographic photorefractive crystal to represent the nonlinear activation function (neuron), interconnect topology (axon), weight distribution, and read/write memory (synapse) respectively of the neural net classifier. A thresholding detector measures the output signal accumulated as a nonlinear function of the weighted summation received through the holographic interconnections. By placing an SLM in the back focal plane of the input lens to implement weights in the form of a transmission coefficient, the incident sensor image can illuminate the real-time volume holographic structure and learning optimization will ensue as the result of parallel optically encoded weight adjustments in response to an updating reference beam.

B. Novelty Filter

A novelty filter detects what is new in a scene and may be likened to temporal high pass filter. The novelty filter will track time-dependent features of the scene from one frame to the next and will aid clutter reduction and image differentiation. A background updating procedure can be used to adapt the stationary background to scene change and moving objects. The novelty filter effect can be best achieved by a representation mapping the loaded data stream onto a three-layer (one hidden) feed-forward associative memory. A neural net learning architecture will allow the filter to selectively' suppress noise and increase detection probability of weak transient signals without distortion. Presentation of familiar patterns and successive realizations of ambient noise will tend to evoke a null response in the novelty filter. When a weak intermittent signal is injected to the background, the adaptive network will ignore it reproducing only the signal as output without distortion for subsequent signal processing and discrimination analysis but rejecting the underlying noise component. Detection of a completely known additive signal in a high level of channel noise is typically performed using a matched filter. The matched filter cross-correlates its input with a stored replica of a known signal type requiring a uniquely matched filter for each class of transient signal. Adaptive novelty filters eliminate the need for a large bank of filters with inflexible noise and spectral characteristics for analyzing broad classes of waveforms. Over the last decade, optical novelty filters have been developed and tested using nonlinear optical resonator feedback and interferometric phase conjugation techniques, notably by J. Feinberg (USC) and D.Z. Anderson (JJLA). Software implementations of neural network based novelty filters have been used in change detection and video processing.

C. Optical Correlation:

Correlation is a basic building block in pattern recognition because Fourier optics descriptors are one of the most versatile data structures for scale-invariant object description and are compatible with wavelet analysis. Optical correlation has historically been accomplished in either Fourier domain complex matched filtering or spatial domain filtering; correlators that use the Fourier domain are of van der Lugt type (VLC) and those that use the spatial domain are of joint transform type (JTC). The basic distinction between these techniques is that the VLC depends on Fourier domain spatial filtering whereas the JTC depends on spatial domain impulse response. In the former, the Fourier plane mask for recognition performs the correlation between two functions based on the autocorrelation theorem and the Fourier transform property of a lens. Using a weighted neural holographic filter in the transform plane allows matched spatial filtering between the input scene and selected characteristic features to be performed through the correlation operation. Reference templates or synthetic scene simulation data can be stored in the optical memory crystal placed at the input plane of the correlator for adaptive learning. A transform lens array placed at the focal distance from the Fourier hologram produces correlation peaks in the output plane and the central light intensity of each correlation peak signal is proportional to the inner product of the input with the neural net filter. Feature groupings and centroid location can be detected in the output plane with a photodiode array and optimized using a genetic algorithm control loop to adjust the transfer function of the adaptive correlator.

In this approach, the interconnect weights or learning state vector are input with an optically addressable spatial light modulator SLM mask in the back focal plane illuminating the volume holographic medium which both records weighting and performs nonlinear thresholding response by the photorefraction mechanism. The photorefraction effect is a reversible mechanism for formation of a spatially modulated index pattern (phase hologram) in a material due to optically induced charge distribution. Two-beam coupling has been characterized as a function of electric field and fringe spacing for the elementary grating formed by intersecting polarized plane waves. The photorefractive crystal records and updates connecting weights in the form of two-beam phase gratings where the modulation depth or diffraction efficiency defines the strength of a neural interconnect weight and is proportional to the outer product with the writing beam. Each grating represents the physical realization of a separate node in the volume hologram and can be simultaneously multiplexed angularly and spatially in a 3-D hologram to preserve full parallelism of the neural weight filter synthesis thereby facilitating rapid convergence of complex training set decisions for optimization. The updating process is accomplished in the distributed hologram through superposition of many exposures of the nonlinear crystal in which individual gratings are strengthen or weakened. Learning is accomplished by perturbing the stored grating with an interference pattern that is the desired outer product of input and training signals. Alternatively, by making the memory crystal part of a phase conjugate resonant cavity we can use mode competitive gain feedback for pattern retrieval and reset. The evolving bipolar weights, both exhibitor-y and inhibitory, are of critical importance to discrimination capability of the neural net which are reconfigurable temporally and spatially. In time domain processing of communication or impulse signals, holographic optical delay lines for time-signal recognition can be developed by properly distributing time delays over the network to dispersively precompensate for temporal propagational offsets. Multichannel correlators permit parallel processing of a large number of selected features and can be adapted from the basic configuration described above. In this case, a 2-D binary optic grating is cascaded with a Fourier transform lens to generate a NxN array of spatially replicated Fourier spectra of the input object; i.e., a scene multiplexer with the scale of the resulting diffraction pattern proportional to laser wavelength. Note that if specific mapping relationships are required for feature extraction that custom lenslet arrays can be used. High-fidelity reference templates or synthetic scene simulation data can be stored in the phase conjugate optical memory placed at the input plane of the correlator for adaptive learning.

D. Holographic Learning

Addition of optical feedback to self-pumped holographic memories using phase conjugate resonators has resulted in a new class of nonlinear associative memory. These systems perform associations between input patterns and stored patterns as in classical holography; however, unlike the case of classical holography external nonlinearities are used to make decisions and select between competing alternatives, perform error correction, and increase storage capacity. The nonlinear thresholding function and input-output processing path of these devices is fully optical. Associative pattern retrieval in a resonating loop governed by transverse modal gain competition can enhance or reduce state fluctuations thereby producing a mechanism for learning and classification via adaptive resonance theory (ART). Eigenmode competition in a resonant cavity with phase conjugate feedback from an externally pumped photorefractive memory crystal creates a context for a general dynamical process which can be reconciled with the nonlinear equations that describe the iterative procedures for neural learning algorithms and self-organization. The photorefractive mechanism establishes pair-wise interactions (holograms) which can be reinforced by optical feedback and nonlinearly amplified (gain) if their activation patterns are correlated to a reference pattern. Feedback and gain competition biases the resonating cavity and suppresses injected patterns except for those close to the desired reference state. Resonator chaos can produce a stochastic dream-like state. Note that adaptability is not the same as learning in these systems. A system that learns must be adaptive by virtue of adjusting the interconnect weights, but non-learning systems can also vary their outputs in a way that reflects changing input conditions. A non-learning adaptive system will adapt the same way to a given situation each time except for noise; a learning system may adapt differently the next time. The main difference of classical holographic memory and neural associative memory is that the holographic case is one step and its SNR is adversely affected by incompleteness of the input pattern, network-based memory evolves from an iterative process involving a nonlinear thresholding operation in which the SNR of a recalled pattern can be gradually improved.

Photokinetics of the holographic grating read-write process will impact information storage and decay. The reduction in efficiency that accompanies the increase in number of exposures ultimately limits the number of associations that can be superimposed on a single photorefractive hologram-the limit is reached when the strength of reconstruction of an individual association becomes comparable to the thermal noise level. One way to increase the number of available training cycles is to use two photorefractive crystals, one as short-term and one as long-term memory. Holographic exposures are accumulated in short term memory and its contents periodically copied to long-term; long term is also periodically rejuvenated by copying its contents into short-term memory and back again. This continuous exchange of information results in a non-decaying hologram for arbitrarily long training sequences.

IV. Optical Storage Capacity

A key advantage of this technology is the extraordinary information theoretical limits potentially obtainable for storage capacity measured by diffraction-resolvable gratings and modulation transfer function in the crystal momentum space (k). For an active crystal ~mm^3 and reasonable optical parameters it should be possible to imprint 10^10-12 gratings which is sufficient to form a fully interconnected network of 10^5-6 neurons. Using a single crystal of lithium niobate, a sequence of 5000 holograms of high-resolution images (320x220 pixels) was successfully stored in experiments. Issues and mitigation strategies associated with intensity noise, grating formation dynamics, photorefractive kinetics, and beam coupling ("cross-talk") on resolution on storage, learning, and memory erasure have been experimentally investigated by several authors.

V. Differentiation from Conventional Optical Computing:

All-optical implementations of multilayer learning neural net architectures are uniquely promising because the inherent bandwidth of free-space optical signal paths offer the fastest possible parallel communication channels without requiring physical limiting conductors with reduced overhead. Improved compact system interconnectivity is derived from vector-matrix multiplication image quantization, thesholding, and recall functions being performed optically in the third dimension with grating holograms while preserving immunity to interference effects in the intersecting beams which can further limit interconnect bandwidth in conventional electro-optical systems. Parallel access to volume optical memory offers an attractive combination of storage capacity, rapid learning, and high aggregate data rates which is ideally suited to solving time-critical complex imaging sensor optimization problems from automated platforms. The scalability of this approach is further enhanced by recent technology breakthroughs in the area of high frame rate addressing structures (ferroelectrics and microchannel SLMs) exhibiting improved spatial resolution, dynamic gray-scale range, and space-bandwidth product, and in the area of high-density binary optics manufacturing capability for image data projection. This situation is differentiable from electrical hardware realizations of monolithic neural networks using VLSI quantum well devices (microprocessors, field programmable gate arrays) which have been shown to be limited in applicability by fan-in/fan-out interconnection density, susceptibility to interference and charge build-up, poor speed-bandwidth product, and low fabrication dimensionality (2-D). Electra-optic processors suffer performance limitations because of bottlenecks associated with planar interconnect technology. Optical integration has the potential to resolve these inadequacies by providing the higher dimensionality to achieve the density of connections necessary for efficient image analysis and fusion, together with sensor optimization on the same parallel platform. This approach not only accelerates through-put rates, but incorporates the adaptive reconfigurable structure of intelligent algorithms and evolutionary programming techniques directly in a compact receiver geometry. Further progress will take advantage of new free-space optical interconnect devices and smart pixel technology. The speed of the learning process may be substantially increased with next-generation holographic materials based on electronic $\chi^{(3)}$ instantaneous nonlinearities and recent developments in semiconductor multiple quantum well photorefractives using the quantum confined Stark effect.

VI. Experimental Results:

The goal of this project was to demonstrate a basic laboratory prototype of an optical learning structure for autonomous visual pattern recognition and sensor optimization. Based on our experience in intelligent algorithms and optical systems engineering, we attempted to construct a simple preprocessor based on an optical novelty filter cascaded with an adaptive holographic cot-relator in the transform plane to baseline applications to geometric change detection and defocussing (blur) compensation for representative imaging scenarios. Real-time correlation and novelty filtering of test images was demonstrated using degenerate four-wave mixing in barium titanate in a joint transform geometry.

The experimental arrangement of the JTC is shown in Figure 3. An Ar' laser at λ = 488 nm is used as the source for the three input beams to the four-wave mixing process. A combination of polarizing beam splitters (PBS) and half-wave (h/2) plates allows us to vary both the polarization and the relative intensity of each of the three beams. Test and reference beams are created by placing transmission masks in the front focal plane of identical f = 35 cm lenses (L_1 and L_2) and illuminating them with coherent plane waves. A zero-degree cut $BaTiO_3$ crystal is placed in the back focal plane of L_1 and L_2, where the Fourier transforms of the reference and test images cross.

The third beam is a plane wave illuminating the crystal from the opposite side, counter propagating with the test beam. Interference from either the reference or test beam and the plane wave would give rise to a reflective holographic grating via the photorefractive effect. However, in order to optimize the diffraction efficiency and minimize grating competition, this third beam is orthogonally polarized relative to the reference and test beams and, therefore, incoherent. This beam is then used to read out the volume hologram formed by the interference of the test and reference beams. To utilize the largest electro-optical coefficient in the photorefractive crystal, r_{42}, the test and reference beams are extraordinarily polarized and the crystal is oriented with the c-axis parallel to the input face, as shown in the figure. Diffraction of the read beam from the transmission hologram obeys Bragg's law and scatters a fourth beam in the opposite direction of the reference beam. L_2 then Fourier transforms this scattered wave, creating a correlation signal in the back focal-plane of L_2 proportional to $(u_2^* \$ u_1) * U_3$, where u_2^* is the complex conjugate of the reference image, u_1 is the test image, U_3 is the inverse Fourier transform of the plane wave u_3, \$ denotes the correlation integration, and * denotes the convolution integral. Since the inverse Fourier transform of a plane wave is a delta function, this signal is simply the correlation between u_2^* and u_1. A beamsplitter redirects this signal beam, and L_3 reimages the correlation signal onto the camera.

In order to look at correlation signals, we placed two USAF resolution bar charts in the test image and reference image planes. The power of the test and reference beams was about 500 μW at the crystal, and the read out beam was 4.9 mW. By illuminating different patterns on the charts, we saw the intensity of the correlation signal change. The residual signal is due to the overlap of the dc component of each Fourier spectrum; even with different patterns, the correlation integral is nonzero. The key to target recognition is setting the threshold of the detector such that the system can differentiate between similar and different patterns. The correlation signal is significantly reduced when the test pattern does not match the reference.

Quasi real-time target recognition can be accomplished by integrating a liquid crystal spatial light modulator (SLM) into the experimental setup. By replacing our USAF bar charts with an SLM, both the test and reference patterns can be written by computer, or the test pattern can be directly relayed from a camera. In a next generation system, the optimization interface and associative memory functions will be implemented using trained neural net patterns realized with optically-addressable structural elements and multiplexed holograms. Initial images will be programmed in a 128x128 element SLM array to implement the weights in the form of a transmission coefficient. Correlated output states formed from the nonlinear holographic transfer function with a reference state vector will be integrated with a lenslet array and registered on a CCD camera for analysis. The volume holographic process itself will be implemented with a barium titanate photorefractive crystal and the learning control loop will adjust optical magnification and focussing distance to the object scene. A hill-climbing genetic algorithm will orchestrate convergence of the fitness function for camera control. Various hybrid artificial network formats will be investigated and in each of these cases, the learning and taxonomy capability will be evaluated for convergence, latency, and noise tolerance with a range of unsupervised learning parameters.

VII. Conclusions, Impact, Future Work

This proposal describes design for a hybrid E/O sensor system embodied with self-optimizing behavior introduced though a two-tier expert-neural control loop which can cognitively respond to contextual data. The control protocol could be orchestrated by a physics-based genetic hill-climbing algorithm which would optimize instrumental parameters including focus, angular magnification, light levels, detection wavelength, and optical figure “on the fly” to actively enhance operational functionality against high-priority objects and to improve image discrimination for dynamic environments suffering from noise or nonstationary structured backgrounds during the overflight period. Active lens, agile phased arrays, and roving fovea concepts could be implemented with control algorithms to evaluate PSF and correction of imaging properties for frame jitter, aberration, and misalignment. Applications to Kalman filtering, atmospheric compensation, autonomous target recognition and guidance, subpixel centroid localization, microscan resolution enhancement, low-light level spatial imagery, are possible with this novel approach to adaptive nonlinear optical image processing using appropriately optimized optical synthetic discriminant filters.

Autonomous cognitive image processing and sensor optimization using optical neuro-processors is a revolutionary advance. Knowledge-based decision models will act as enablers for future data-gathering technology implementations in uncertain ambiguous environments. Next-generation sensor information management structures will use adaptive decision-theoretic and contextual methods to compress data streams to relevant perceptual bandwidths for interpretation. Future decision-making methods will merge human cognitive functions with automated intelligent computational processing layers to increase response tempo and reliability- information saturation is additive to fog of war. Current efforts largely focus on sensor technology advances from a machine-based perspective and are incompatible with fuzzy or incomplete knowledge representations (or influences of human factors). New analytical strategies which integrate semantic and relational inference engines with data-based systems will reduce uncertainty by improving the quality of imperfect information for extrapolation and prediction using experiential or associative memory to fill in gaps, suppress noise, or establish useful correlations. The use of imbedded feature-based inference capability merged with adaptive contextual decision-theoretic capability will improve our ability to gain understanding in ambiguous environments with the following outcomes:

- On-board autonomous learning and adaptive control structures could be integrated with a sensor platform to improve intelligence collection in dynamic or uncertain environments

- All-optical feature-based cognitive processors incorporating neural networks which exhibit associative memory and self-compensating or contemplative learning behaviors could be developed

- Massive parallelism and interconnect density inherent to optical computing architectures would preserve rapid image processing/optimization capability without serial bottlenecking

- Neuromorphic holographic memory with optically recontigurable weighting would achieve an agile compromise between distortion tolerance, signal fidelity, and discrimination

- Automatic decision-theoretic classification algorithms would improve exploitation against high-priority hard targets where maximum likelihood estimates are not reliable or poorly sampled

- Contextual morphological filters and layered association could produce compact prioritized pattern recognition data structures from mixed or cross-tasked image data

- Synthetic scene generation and object-oriented simulation could be used as training tools to "tune" the sensing platform and enhance situational awareness by anticipating signature features

- Preprocessing the data stream to a useful perceptual bandwidth would reduce link budget and TPED requirements for decision and analysis; reduce exported raw data to relevant information

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Figures:

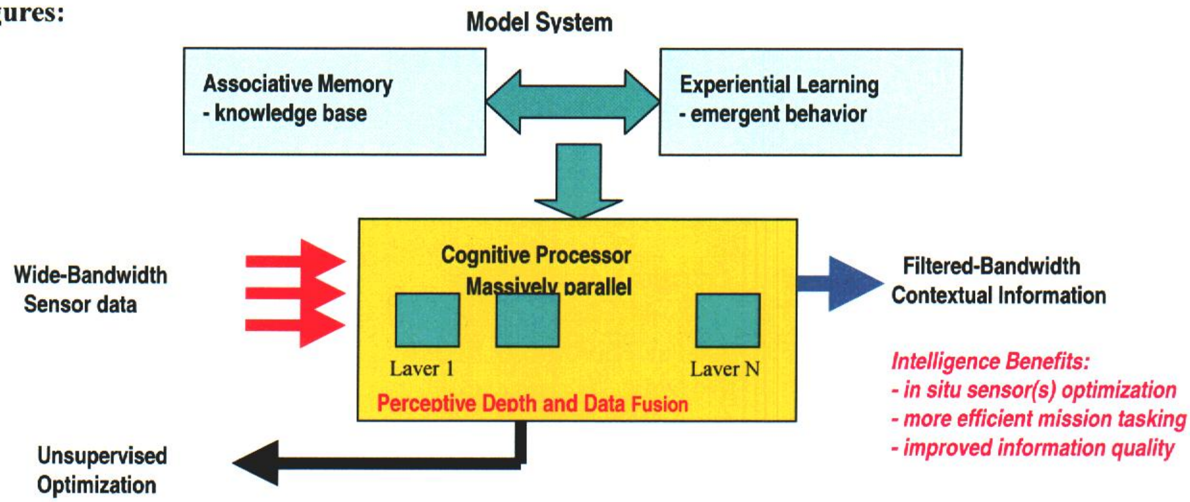

Figure 1: Sensor Processing and Optimization to Match Data Stream to Analysis Bandwidth

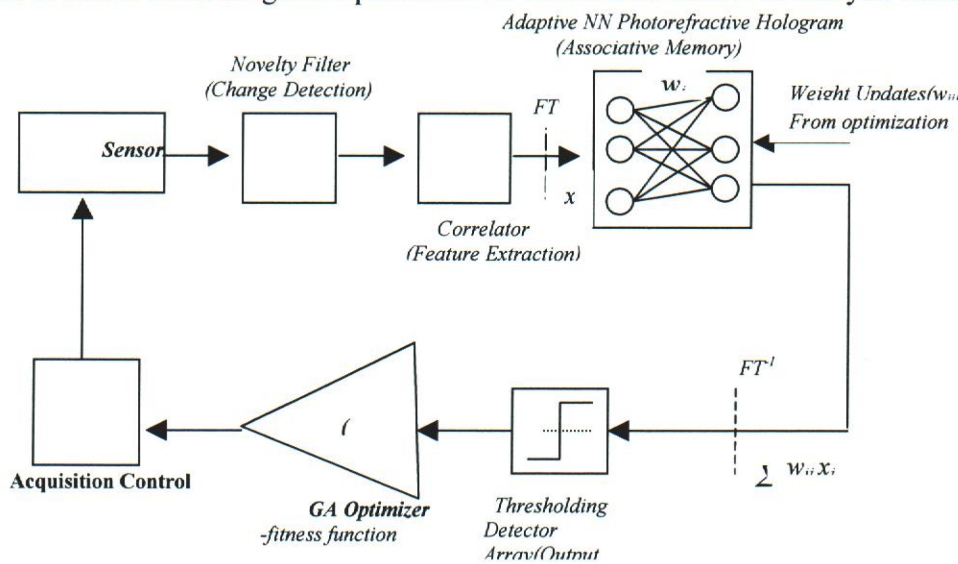

Figure 2: Notional Optical Preprocessor for Sensor Optimization

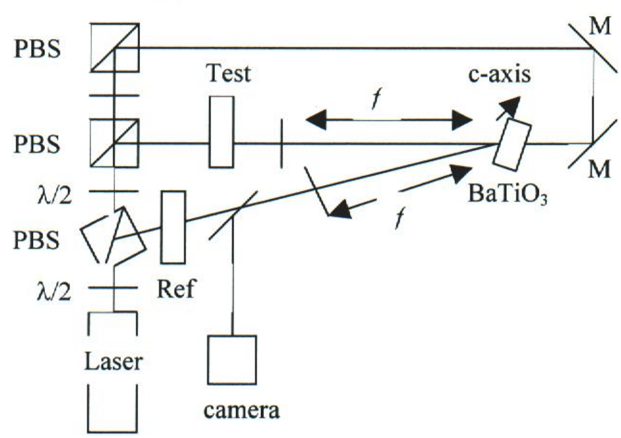

Figure 3: Experimental Schematic

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