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Adaptive Remote-Sensing Techniques Implementing Swarms of Mobile Agents

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ABSTRACT

Measurement and signal intelligence (MASINT) of the battlespace has created new requirements in information management, communication and interoperability as they effect surveillance and situational awareness. In many situations, stand-off remote sensing and hazard-interdiction techniques over realistic operational areas are often impractical and difficult to characterize. An alternative approach is to implement adaptive remote-sensing techniques with swarms of mobile agents employing collective behavior for optimization of mapping signatures and positional orientation (registration). We have expanded intelligent control theory using physics-based collective behavior models and genetic algorithms to produce a uniquely powerful implementation of distributed ground-based measurement incorporating both local collective behavior, and inter-operative global optimization for sensor fusion and mission oversight. By using a layered hierarchical control architecture to orchestrate adaptive reconfiguration of semi-autonomous robotic agents, we can improve overall robustness and functionality in dynamic tactical environments without information bottlenecking. In our concept, each sensor is equipped with a miniaturized optical reflectance modulator which is interactively monitored as a remote transponder using a laser communication protocol from a remote mothership or operative. Robot data-sharing at the ground level can be leveraged with global evaluation criteria, including terrain overlays and remote imaging data. Information sharing and distributed intelligence opens up a new class of remote sensing applications in which small single-function autonomous observers at the local level can collectively optimize and measure large scale ground-level signatures. As the need for coverage and the number of agents grows to improve spatial resolution, cooperative behavior orchestrated by a global situational awareness umbrella will be an essential ingredient to offset increasing bandwidth requirements within the net. A system of this type is being developed which will be capable of sensitively detecting, tracking, and mapping spatial distributions of measurement signatures, which are nonstationary or obscured by clutter or interfering obstacles by virtue of adaptive reconfiguration. This methodology is being used to field an adaptive ground-penetrating impulse radar from a superposition of small radiating dipoles for detection of underground structures and to detect/remediate hazardous biological or chemical species in migrating plumes.

This paper focuses on our recent work at Sandia National Laboratories toward engineering a physics-based swarm of mobile vehicles for distributed sensing applications. Our goal is to coordinate a sensor array that optimizes sensor coverage and multivariate signal analysis by implementing artificial intelligence and evolutionary computational techniques. These intelligent control systems integrate both globally operating decision-making systems and locally cooperative information-sharing modes using genetically-trained neural networks. Once trained, neural networks have the ability to enhance real-time operational responses to dynamical environments, such as obstacle avoidance, responding to prevailing wind patterns, and overcoming other natural obscurants or interferences (jammers). The swarm realizes a collective set of sensor neurons with simple properties incorporating interactions based on basic community rules (potential fields) and complex interconnecting functions based on various neural network architectures. Therefore, the swarm is capable of redundant heterogeneous measurements which furnishes an additional degree of robustness and fault tolerance not afforded by conventional systems, while accomplishing such cognitive tasks as generalization, error correction, pattern recognition, and sensor fusion. The robotic platforms could be equipped with specialized sensor devices including transmit/receive dipole antennas, chemical or biological "sniffers" in combination with recognition analysis tools, communication modulators, and laser diodes. Our group has been studying the collective behavior of an autonomous, multi-agent system applied to emerging threat applications. To accomplish such tasks, research in the fields of robotics, sensor technology, and swarms are being conducted within an integrated program. Mission scenarios under consideration include ground penetrating impulse radar (GPR) for detection of under-ground structures, airborne systems, and plume detection/remediation. We will describe our research in these areas and give a status report on our progress, including simulations and laboratory-based sensor experiments.

Keywords: Emerging threats, bio/chemical hazards, ground-penetrating radar, physics based swarm model, neural networks, genetic algorithms.

1. INTRODUCTION

United States strategic doctrine is predicated on a technologically superior intelligence apparatus to protect global interests and aggressively preempt emerging challenges to national security. Maintaining a decisive information advantage in the face of an uncertain, ambiguous threat environment will require innovative surveillance methods which can covertly extract and geo-spatially resolve multiple analytic sensor signatures (eg., thermal, acoustic, seismic, chemical, electromagnetic) over broad operational areas. As selective concealment of illicit NBC weapons capability is increasingly employed by adversaries in the aftermath of the Gulf War to deny direct observation by satellite or airborne reconnaissance overflight assets, strong motivation exists to deploy semi-autonomous ground-based sensing networks in combination with secure theatre communication nodes for data exfiltration. In the scenario proposed here, mesoscopic-scale mobile robotic warfighters carrying specialized sensor packages equipped with miniaturized optical reflectance modulators could be infiltrated to suspected proliferation sites or tripwire locations (interdiction chokepoints or ceasefire boundaries), positionally registered, and interactively monitored as remote transponders using a wide-bandwidth, atmospherically compensated laser communication protocol from a distant mothership or human operative. Such a deployment would follow initial discrimination and classification of a possible threat by a remote monitoring system employing spectral imagery and laser vibrometry. To improve the robustness of the intelligence gathering process, the robotic agents themselves could be endowed with rudimentary learning ability for collaborative and organized collective behaviors including local remote sensing coordination (search, evasion, navigation), self-compensation (optimization), and adaptive reconfiguration for global optimization of a mapping signature. Comprehensive representation of the tactical environment in denied areas using an inter-netted architecture of unmanned modular warfighters which possess redundant overlapping mission capabilities and a degree of decision-making autonomy will significantly enhance operational functionality in dynamic scenarios subject to hazard uncertainties, imprecise information or competing constraints. By creating fault tolerance and improving response time to active or passive threats without information bottlenecking, an intelligent control system which tasks low-level behaviors in a coordinated cooperative fashion can improve the performance of distributed surveillance systems; particularly in complex, information-dense clutter backgrounds such as hostile urban battlespace. When combined with next-generation enabling technologies for ground-based measurement and a communication protocol to support multi-robot connectivity and sensor data-sharing, this approach will form the basis for ***a new paradigm to remotely exfiltrate critical data with high spatial resolution and situational awareness from previously undetectable targets such as underground structures and migrating effluent or CBW plumes.*** Areas of specific concern to be addressed by this approach would likely include suspected NBC proliferation sites, underground WMD storage/production facilities in violation of arms-control agreements, terrorist staging and training centers, and clandestine deployment sites for impending military incursions. The resulting access when fused with other advanced RSTA systems and collective coherent change imagery would provide the requisite knowledge for planning precision air strikes and ground interdiction (see figure 1).

Sandia National Laboratories is developing next-generation technologies that can be directly applied and extended to the development of mobile tactical robotic warfighters capable of cooperative remote sensing for specific high-value missions. As part of this current research effort, the basic concepts of layered distributed control within autonomous multi-agent systems, both decentralized cooperative and hierarchical, are being investigated for control effectiveness in combination with various integrated sensor and short-range communication packages. These collective behaviors introduce new flexibility in the command interface by allowing for cooperative sensing and adaptive sensor reconfiguration modes to refine performance. Statistical analysis has been used to evaluate maximum utilization strategies of a distributed robot swarm to achieve specific mission goals subject to real-world deployment restrictions concerning mobility, sensor density and limited detection range, reliability, noisy measurements, and level of cooperation in relation to overall asymptotic stability (reproducibility) and convergence (probability of success). Object-oriented simulation and computer animation testbeds have been constructed which are capable of depicting the evolving state of a multi-robot system, robots positions and orientations, on-board specialized sensor configuration, and a two-dimensional sensor-based map of identified targets and obstacles in the surrounding environment. Innovative landmark cooperative navigational network concepts and cognitive perception algorithms applicable to the general class of guidance problems found in urban tactical environments are also being examined.

Traditional areas of unattended ground sensors (UGS) now include hardware-tested loco-motor mesoscopic robotic platforms (in^3) that offer additional flexibility in tactical field operations, including intelligent or learned sensor optimization. These robo-bugs will form the basis of next-generation heterogeneous sensor arrays which can be inserted in hazardous territory and autonomously navigate structured environments while performing a range of distributed surveillance tasks and collaborative sensing tasks, perhaps covertly. As MEMs fabrication technology matures, mission-specialized microsensor package designs will encompass a full arsenal of pro-prioceptive, exteroceptive, and interoceptive measurement capabilities in the battlespace including multi-axis gyro /accelerometers, GPS, nonlethal anti-personnel weaponry, passive radar tags, and visual stealth. With these advances will come new requirements for improvements in information management, communication, and interoperability as they affect intelligence and battlefield situational awareness. The use of a layered hierarchical control architecture employing a wide-bandwidth, atmospherically compensated optical communication relay between a mothership and the distributed collective will allow efficient global optimization of area signatures by coordinating the requisite spatial reorganization and remotely recording the data stream. This linkage will also open up the possibility of sensor fusion with reference terrain overlays and laser radar data for image processing. By achieving a balance between cooperativeness and autonomy in the behavior of robotic agents, the warfighter interface can be made seamless in stressing conditions. In short, the resultant functionality is greater than the sum of its parts (see figure 2).

The objective of this program is build upon these precedents in classical and nonclassical distributed controls methodology by leveraging several recent scientific advances in ground-based measurement, pulsed-power antenna engineering, adaptive optics, and photonic devices to prototype/benchmark a uniquely powerful sensor implementation for collective interrogation of nonstationary or concealed threats. By integrating a local distributed robotic sensor network capable of cooperative learning with an interoperative expert system capable of competitive global optimization using a wide-bandwidth atmospherically-compensated optical communication link, it should be possible to create an autonomous system which can generalize, error correct, and pattern analyze in the presence of dynamic stressing environments. The ability to perform near real-time intelligent high-level multivariate processing and sensor fusion with other forms of external optical or radar imagery (LIDAR, SAR) from the remote platform will form the basis for a new type of organized and adaptively reconfigurative remote sensing, thereby considerably enlarging the mission space for detection of suspicious signatures and uncooperative targets. The following discussion will focus in detail on two representative operational scenarios requiring (adaptive) spatial organization and synchronization of individual single-function elements within the sensing grid as a prerequisite for useful diagnostic measurement, namely detection of deeply-buried underground structures and release of migrating chemical or biological agents. The roles of remote detection oversight, intelligent algorithms, and optical communication links will be discussed in the context of these applications.

2. REMOTE DETECTION OVERSIGHT

Preempting next-generation emerging threats in the face of efforts by adversaries to conceal illicit WMD capabilities underground will require a new measurement paradigm which integrates autonomous ground-based sensing networks with remote look-down interrogation and data exfiltration. Reconnaissance techniques such as laser vibrometry which have the potential to detect transient ground motion perturbations to surface topological relief over an imaged terrain scene must be fused with locally-measured mapping signatures acquired by robotic warfighters to unambiguously differentiate characteristic change features identifying potential buried structures from natural background patterns. By using intelligent swarms of adaptively-reconfigurable robot agents carrying specialized sensor packages (e.g., seismic, chemical, biological) equipped with corner cubes or optical reflectance modulators, specular guide stars, encoded beacons, and communication linkages can be established to enhance data acquisition, geo-spatial registration, and sensor grid coordination/optimization within the infiltrated proliferation site. Full-field modal vibrational analysis in conjunction with mapped terrain overlays of chemical or biological effluent, and joint time-frequency pattern recognition algorithms will facilitate the reconstruction of approximate source locations as a precursor to interdiction or remediation.

A new class of covert, long-range interferometric remote sensing modalities such as laser vibrometry which can sensitively detect artificial ground motion and nonstationary perturbations to natural topological relief is critical for gathering intelligence concerning underground structures. The remote acquisition of full-field ground flexural mosaics which are discernible from natural background patterns and which can be correlated with characteristic frequency, amplitude, and phase signatures will provide the basis for identifying buried structures previously undetected by reconnaissance overflight. The measurement paradigm must be relatively immune to the effects of turbulent atmospheric wavefront distortion and cloud scattering on effective receiver aperture and phase sensitivity, and be fusable with hyperspectral imagery to differentiate change features from inhomogeneous diffuse surface contours with a high degree of radiometric contrast. Modal vibration analysis of surface deformations in conjunction with geo-spatial registration (GPS), terrain overlays, coherent change detection, and joint time-frequency pattern recognition algorithms (e.g., wavelets, neural networks, genetic algorithms, clustering routines) will facilitate the reconstruction of approximate source locations as a precursor to deployment of ground-based sensors. The authors have developed a self-referencing laser shearing interferometer [] which measures the intensity distribution and spatial/temporal statistics of the moving speckle field produced by a vibrating diffuse object and can resolve micron-sized amplitude displacements for both piston (out-of-plane) and tilt (in-plane) motions. The secondary interference pattern produced by speckle correlation in the observation plane as a function of illumination geometry is a unique fingerprint of perturbations (tilt or piston) relative to the static surface relief background. By leveraging OPA technology in a type I NCPM collinear geometry at the wavelength/polarization degenerate point in combination with adaptive optics turbulence compensation, the receiver becomes a phase conjugate homodyne wavefront sensor with enhanced sensitivity to ground motion. The phase conjugate nature of the wavefront mixing process provides a matched filter for speckle tracking /autocorrelation and reduces the degradative effects of fade and environmental phase distortions on signal fidelity. Closely-spaced multiple beam geometries can be used in the interrogation aperture for common mode rejection of piston aberration effects due to turbulent atmosphere (see figure 3).

Physical sensors positioned on the ground in the vicinity of suspected underground facilities offer improved resolution over remote vibrometry for data exfiltration, but require advanced queuing or intelligence guidance for delineating deployment areas. Frequently, the facilities, which require monitoring, are in denied or unfriendly territory subject to the constraints of international law and substantial political or human (operative) risk is involved in sensor placement. For these reasons, space-based or airborne laser vibrometry will play a primary role in performing look-down surveillance over broad operational areas for initial discrimination of threats and areas of interest warranting further scrutiny. The laser platform will have multifunctional crossover benefit to active high-resolution spectral imagery and to optical communication down-links with distributed sensor arrays once infiltrated for data exfiltration. Robot-mounted corner cubes configured as cooperative guide star arrays can improve the robustness and registration accuracy of laser vibrometry measurements (and closely analogous optical communication links) in turbulent atmospheric conditions. The use of specular ground returns will allow isolation of turbulent atmospheric wavefront distortion and improve phase sensitivity to diffuse surface contours.

3. AN INTELLIGENT, ADAPTIVE MULTI-AGENT MODEL

Conventional linear control methods 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 nonlinearities, time delays, noise corruption, transient parameters, or saturation occur creating information uncertainties and an imprecise learning environment, which may exhibit undesirable instability characteristics. Nonclassical intelligent hybrid control represents a new field of artificial intelligence for constructing a multi-agent nonlinear controller using heuristic variables and exploratory problem-solving. These systems integrate globally operating expert (decision-making) systems and local cooperative learning neural nets to enhance real-time operational robustness to complex and potentially hostile environments, and to manage uncertainty. Intelligent hybrid control systems integrate globally operating expert (decision-making) systems and local cooperative learning neural nets to enhance real-time operational responses to dynamic environments. 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. One can view the neural net as a nonlinear network whose nonlinearity can be selectively tuned by changing weights, biases, and parameters of the activation function- a locally tuned reception field. Neural nets provide a greater degree of robustness and fault tolerance than conventional systems in that minor variations or imperfections do not impair performance. When combined in a two-tier control loop competitively trained for optimization, the ability of the neural net to learn (improvise) in imprecise situations enables the expert system to modify (adapt) and enrich knowledge structures autonomously without bottlenecking or diverging, and to allow competition between multiple hypotheses. Bidirectional transfer of knowledge between these components allows modification of existing rules and to infer new optimization configurations, which may not be intuitive. The expert system could be based on a physics-based genetic algorithm (GA) which mimics the principles of evolution and Darwinian natural selection to perform a parallel stochastic but directed search to the most fit population. Expert systems and neural networks represent complimentary approaches to knowledge representation:

the logical, cognitive, and mechanical nature of an expert system versus the numeric, associative, and self-organizing nature of a neural net.

We have developed a computational test bed that enables us to simulate and engineer heterogeneous systems of sensors exhibiting hierarchical self-organized competitive and collaborative behavior. This test bed, components of which are Sandia patent-pending, will make it possible to test a variety of system-design and mission scenario hypotheses. Rather than assume a particular sensor architecture and mode of usage, the intelligent test bed approach should allow us to generalize, evaluate performance, and solve for the optimal system based on multiple criteria including cost, complexity, search efficiency, reliability, resistance to countermeasure, and flexibility of application. We can investigate questions concerning the minimum number of required sensors, the appropriate heterogeneity of sensor types, the optimal communication protocols, as well as the organized behavior type and diversity. Our test bed includes genetic and evolutionary methods to competitively optimize system design for control and recognition, overlaid onto or combined with collaborative agent-like sensors that learn and share information. Conceptually similar to a conductor and his orchestra, competition can be used to select, coordinate, and analyze the players and their overall musical output, the players in turn can be a mixed assembly of focussed experts (strings, brass, woodwind, percussion) that must behave collaboratively for best results. In our concept of a sensor system, the conductor or expert might be a remote computer-assisted human observer or a large computational platform responsible for sensor fusion and high-level image processing. The coordinated players, or individual sensors would work collaboratively and redundantly at the local level to identify, document, and communicate information about sites, targets and threats. In the example shown, 64 identical mobile sensors are dropped randomly onto a site with an unknown target location. They randomly walk (each of their paths are plotted after selected elapsed times) and share information with nearest neighbors as they search for the target. Finite communication range complicates their behavior, but in the example we plot the important limiting cases corresponding to long-range (top) and very short-range (bottom) interconnectivity. For this example the only information shared is collective assessment of the best signal from a candidate target, and its location. After finding the target, their behavior changes (responding to instruction from the remote expert), and they redistribute as a sparse array to optimize signal resolution and target outline. More interesting cases we will investigate include heterogeneous sensor mixtures and a constellation of individually specific chem-bio sensors, as well as more realistic behavioral and communication protocols (see figure 4).

The decision-making process of our multi-agent model is an intertwined model implementing evolutionary computational techniques, hybrid neural topologies, and physics-based models. At the center of this model is the many-body particle physics model which realizes the robots' kinetic motion. Additional forces formed by neural and fuzzy-neural network structures respond to environmental conditions and measured signature events. Genetic algorithms globally optimize model parameters providing autonomous and complex collective behaviors, in addition to the swarms make-up (e.g., sensor heterogeneity and positioning), allowing it to fulfill a variety of mission specific goals.

3.1. Physics-Based Models

The macroscopic, dynamical state of the many-particle ensemble can be linked through various statistical methods to the microscopic single-particle inter-actions []. Sensor or pseudo-forces, a potential or force associated with sensor measurements (sensor fusion) and realized by artificial neural topologies, formed (or trained) correctly provides the necessary intelligence and adaptability to accomplish a variety of tasks. Realizing these forces within the constructs of a physical model and incorporating them into the genetic algorithm's objective function, a level of surety can be maintained. Two models best suited to simulate multi-agent behaviors include lattice gases (Lattice Gas Automata, LGA) and plasmas (Particle-in-cell or PIC codes).

3.1.1. Lattice Gas Methods

Lattice gas cellular automata (LGA) models incompressible or "weakly" compressible hydrodynamic fluid (or gas) at low Mach numbers. Theoretical work links simple microscopic nearest-neighbor particle interactions to the macroscopic dynamical thermodynamic variables of the equation of state, such as density and viscosity. Leveraging this framework, colli-sion rules are reinterpreted by the superposition of forces and pseudo-forces (as well as neural networks and fuzzy logic). At any instant in time, the particle system evolves by applying a propagation operator, the motion of a robot along a single lattice edge, and the collision operator, the total directional force on that robot by its neighbors and environmental influences. Initial simulations implement a very simple functional form of the force acting on a robot :

(formula here) ,

where nn is the number of line-of-sight nearest neighbors, Frepul (r) = r^{-2}, Fattract (r) = r, and The pseudo-force represents the sensor measurements of the signature events, chemical or biological agents and transient, vibrational signals. Incorporation of theoretical global dynamics of lattice gases and plasmas (indirectly) imprints the desired collective behaviors into the robots actions during evolution, thus confining the robotic ensemble (it dynamics) within a stable phase-space.

3.1.2. Plasma Physics Methods

Plasma physics models collective effects of particles influenced and electromagnetic fields. Particle dynamics within a conducting liquid or gas occurs when charged particles are set in motion under the action of applied fields which can be represented by sensed environmental conditions. Due to the complexity in which the macroscopic motion of the particles influence the applied fields and vice versa, PIC codes calculates the average charge densities approximated by Poisson's equations through the mesh realizing these correlated long-range forces. Many biological systems also show such an effect, a "flocking-" force; a flock of interacting individuals (birds) not only communicate among other members but also account for the aerodynamic wake of the others. Additional nearest neighbor forces prevent collisions while maintaining cohesive properties, repulsive and attractive interactions, and. global center-of-mass potentials allow the to cluster, possibly breaking into two separate groups or gravitate back into a single unit. PIC methods take advantage of the linear nature of the forces, r^{-1} and r^{-2}, which can easily be incorporated into the current theoretical dynamics framework, providing a stable and robust behavior during training, and of the reduced number of calculations required by simulations from $O(N^2)$ down to O(N), where N is the number of particles or robots, providing real-time movements and decisions. As with LGAs the multi-robotic system evolves under the influence of the mesh or flocking-force incorporating the stability analysis afforded by the immense theoretical prowess in this field.

3.2. Artificial Intelligence

Artificial intellegent algorithms enhance the particle attributes or robot's ability to think by analyzing and interpreting a variety of sensor values (sensor fusion) through the use of neural networks, fuzzy logic, and neuro-fuzzy hybrids. Neural structure consists of a stoma or base, called a neurode, and many interconnecting synapses, or connections, through its dentrites an axon. Artificial neural or hybrid net-work architectures models neural structure and functionality by forming and weighting (synapses) the interconnections (dentrites, axon) between neurodes (stoma). Associated with each neurode is an activation function, a nonlinear threshold (squashing) function or a set of fuzzy inferences. The input into a neurode is the superposition of the weighted inputs from other nodes. The functionality (and dynamics) of the neural network depends on the immense structural interconnectivity between its neurodes. By exposing the neural network to many input-output pairs of events, the interconnects and weights can be globally optimized by genetic algorithms to perform various, such as determine directional information of a moving target by interpreting nearest-neighbor sensor information, extract chemical/biological signature concentration levels by analyzing sensor spectral images, and classify physical features within bitmap.

3.3. Global Optimization

The ability to produce desirable macroscopic or collective swarm behaviors from local or nearest-neighbor interactions (via robotic artificial intelligent methods) is a complex multivariate analysis problem. Optimization techniques that employ stochastic non-derivative calculations are thus less likely to get caught in local minima and not requiring the target system to be described by a smooth or continuous function are termed global. Different types of algorithms include stochastic, simplex, and evolutionary based programming; the latter of which, in the form of genetic algorithms, have been implemented.

A genetic algorithm performs three operations -- selection, crossover (mating), and mutation -- onto the elements of a population, a population of neural networks or a population of swarms. Selection preferentially chooses those high fitness individuals from which to produce offspring, where an individual's fitness contains information on how well it performed a task such as following a moving target, pattern recognition, or optimal signal measurement. Crossover or mating share sequences of genetic material to their offspring enhancing previously successful performance onto the next generation. Mutation maintains diversity by infusing a steady level of new genetic material into the population, allowing the GA to search the entire parameter phase-space in search of a global optimal solution. By exposing the system to the environment, represented by many input-output pairs or sequences, the population learns (or trains) how to perform various tasks as well as how to adaptive such as avoiding obstacles while tracking a plume. Current work will incorporate additional pseudo-potentials enhancing the swarm's adaptability and performance.

4. OPTICAL COMMUNICATIONS

Successful realization of a heterogeneous cooperative robotic system will require an efficient communication architecture and protocol. Several hierarchical network modes are envisioned: short-range (local) messaging and relay between robots, strategic (global) command and dissemination, surveillance and mapping bursts (obstacle avoidance, hazard detection, navigation), and secure encrypted links. Proximity or short-range local communication functions for coordinated maneuvers and reconnaissance are assumed to use conventional low-power infrared, acoustic or swept frequency microwave interconnecting architectures inherent to the robot mission package. For longer-range interactions with the mothership (source), a two-way transponder ("modem") mechanism for data transferal will be adopted using a sensor-integrated E/O reflectance modulator based on an adaptation of the asymmetric Fabry-Perot cavity concept internal to a strained layer quantum well structure. The photovoltaic amplitude modulator responds to activation by an external designating laser pulse ("pinger") originating from the source and encodes digital signal outputs derived from the sensor buffer onto the broadcast or floodlighting optical carrier. Detection and processing of the reflected waveform is subsequently conducted at a time-gated imaging transceiver to complete the data up-link; global optimization instruction sets can be down-linked to dedicated smart nodes in the sensor array by reversing the process. Laser optical communication potentially offers significant advantages for remote coordination and data exfiltration from covert distributed ground-sensing networks. Because the optical link can be designed to operate at eye-safe infrared wavelengths above the short-wavelength cut-off for passive FLIR detection and is strongly directional (low probability of intercept), it is largely immune to countermeasures and jamming. The spatial coherence of a laser transmitter offers favorable antenna gain with small payload dimension and precise angular tracking characteristics for synchronization, and the relative temporal coherence associated with optical carrier frequencies can support tremendous information bandwidth without baseband interference or frequency allocation problems (see figure 5).

A major weakness limiting the operational utility of unguided optical communication channels propagating in atmosphere, however, has been adverse effects of extinction (loss), scattering (dispersion), turbulence (degraded coherency), and fade which degrade realizable transmission bandwidth and gain aperture for acceptable bit error rate. We have investigated the use of a previously developed active reflectance imaging technique based on an optical parametric amplifier (OPA) receiver to enhance detector sensitivity, signal fidelity, reception distance, and error rate performance for unguided digital communication links affected by cloud-like conditions. Using a kilohertz repetition rate femtosecond laser system operating at eyesafe wavelengths, we have evaluated the role of signal-spontaneous OPA beat noise (s-ASE) on amplified signal, noise figure, and channel sampling capacity for various binary modulation formats in both direct and coherent detection modes to establish fundamental response limitations as a function of turbidity, laser power, and modulator aperture. Time- and frequency-multiplexing techniques can be selectively employed to achieve a burst communication mode or to combine multiple modulator channels into a composite spectrum. Given the compact size versus gain scaling relationship, improved data capacity, and directionally-specific nature, such an approach when combined with global navigational references (GPS) or terrain overlays appears to be ideally suited for transmitting instructions and receiving undistorted data streams from a large number of distributed "smart" sensors which can be remotely coordinated for multivariate signal optimization and coverage. To improve the robustness of the intelligence collection process, the local sensor array could be endowed with adaptive learning capacity for cooperative and self-compensating behaviors including search and evasive actions.

Our baseline system architecture incorporates a remote monostatic laser transceiver or mothership, a local sensor array with miniaturized measurement modules, and a sensor-integrated reflectance modulator transponder mechanism for two-way optical communication. The transponder (or modem) encodes high-level signal outputs from the sensing buffer onto the broadcast optical carrier which is then detected and processed in the all-weather imaging receiver up-link; global instruction sets can be down-linked to dedicated smart nodes (distinguishing modulation frequency) within the array for subsequent local short-range interpretation. Prerequisite technology building blocks for hardware implementation are summarized below.

(i) Sensor Module: Local environmental measurements can be accomplished in application-specific MEMs-based transducers and preprocessed in an on-board signal conditioning buffer with nonvolatile memory and programmable tasking (EPROM). A laser-activated photovoltaic switch triggers the transition from passive archival data logger to active data retrieval thereby minimizing emission signature and power loading.

(ii) Reflectance Modulator: Sandia's experience with vertical cavity surface-emitting microlasers has provided the research base for the design and fabrication of surface-normal reflection optical modulator assemblies. At present, the technology exists to build hermetically packaged E/O modulators operating at eye-safe wavelengths (l~1.3 mm) in retroreflection configurations. These low-voltage photonic devices are an adaptation of the asymmetric Fabry-Perot cavity concept implemented internal to a strained layer quantum well structure, and rely on the red shift of a semiconductor absorption edge through the quantum Stark effect to introduce loss. The current design consisting of a nominal 2 mm diameter transmission modulator and PIN detector in strain-relaxed InGaAs exhibits rf bandwidths > 10 MHz, 60% double-pass reflectivity, and an acceptance angle of approximately 30 degrees.

(iii) Broadcast Laser: Compact high-brightness pulsed sources can be constructed using diode-pumped microchip laser designs or low inductance PCSS (photoconductive semiconductor switch) gain-switched laser diode arrays at MHz pulse repetition rates. The peak power in these devices is sufficient to drive nonlinear devices for frequency conversion and range-gating applications.

(iv) Atmospheric propagation: Adaptive systems designed to overcome the adverse effects of clouds have achieved minimum BER by compromising data transmission rates to unacceptably low levels. We propose to address these shortcomings by adopting nonlinear optical methods based on parametric amplification which we previously developed for active compensated imaging through extended turbid media (reference). Phase sensitive variations of the OPA concept demonstrated elsewhere are expected to have cross-functional benefit to remote laser vibrometry (a precurser to sensor deployment) and optical preamplification of nonideal communication channels given the close analogy between spatial imaging and amplification of time-modulated signals. By working in a type II phasematching geometry at the degenerate point, both incoherent and coherent detection modes of operation are possible by adjusting the polarization, in some cases achieving noiseless amplification by destructive interference of the noise component in the measurement quadrature. Future work will incorporate multiplexing in the time-frequency domain to access larger bandwidths. An increased bandwidth in combination with fast optical filter techniques allows for pseudo-random encryption methodologies securing communication channels (see figure 6).

5. APPLICATIONS

Building upon precedents in collective robotic behavior, optical imaging, and sensor engineering, this paper will investigate two operational concepts fundamental to the emerging threats mission: (1) spatial mapping and remediation of a migrating (wind-driven) chemical or biological plume with a collectively orchestrated mixture of mobile point sensors exhibiting selective reactivity and (2) formation of a phased-array, ground-penetrating impulse radar for detection and characterization of underground structures by electromagnetic superposition of a distributed aperture of discrete dipole antennae (optically triggered pulsers).

5.1. Plume Characterization and Remediation Using Autonomous Mobile Sentinel-Destroyers

Existing tactical countermeasures against dispersed biological or chemical weapons suffer from inadequate baseline detection capability, adverse operational impact to the battlespace, and limited coverage boundaries. Characteristic spectral signatures from biological toxins are typically transient in nature due to prevailing wind currents and variable environmental factors, and exhibit wide wavelength diversity. Discriminating spectra features can be easily disguised by natural obscurants or artificial interferences, which make recognition analysis by conventional optical measurement techniques problematic in interpretation. The limited field-of-view of laser sources makes stand-off detection and hazard-interdiction impractical for countermeasures over realistic deployment areas. An alternative approach, which does not require wavelength diversity and high-power broadcast lasers, is to spatially map the migrating plume using an intelligent constellation of mobile robots deployed with chemically-specific point sensors. By using an autonomous interoperative measurement network capable of organized collective behaviors, such as adaptive reconfiguration, improved in situ response to dynamic hazard uncertainties (wind, terrain obstacles, atmospherics) associated with migrating plumes can be accomplished. Endowing the robotic warfighters with rudimentary learning ability governed by intelligent controls for remote sensing coordination, self-compensation, and optimization of characteristic mapping signatures will enhance performance and fault tolerance without information bottlenecking.

In this operational scenario we envision a distributed sensing architecture in which forward-deployed autonomous chem/bio sensors act initially as an advanced warning tripwire and then act collectively under a coordinating situational awareness umbrella to optimize interrogation and remediation of the sampling space. We envision two types of robots, ignitor robots and remote-sensing robots, both of which must be carefully positioned to monitor and initiate combustion. Using physics based models, the robot positions will be controlled by applying two inter-connected potential fields. One field is highly-attractive near the edges of the plume, thus attracting the ignitor-flavored robots; and, the second combines a flat and inverse-radial field, thus distributing remote-sensing-flavored robots evenly beneath or inside the plume and sparsely beyond the plume's perimeter. Remote-sensing robots will image the spectral dynamics of combustion within the plume's region and beyond its perimeter. Short-range laser absorption/fluorescence detection techniques will be implemented to measure the physical and dynamical macroscopic properties of the plume. Using advanced intelligent controls to coordinate the distributed swarm, first to characterize the plume composition, and then to tailor their behavior to insure destruction of the hazard by controlled inward-directed combustion (controlled flash/flare thermal energy) from the plume boundary, indiscriminate dispersal by convection and radial shock waves can be avoided. By manipulating the control state vector, it may be possible to actively orchestrate convective flow mechanics and local combustion kinetics so as to permit segregation of the hazardous agent into a prescribed spatial region or to define optimal placement for fuel-air explosives. In combination with landmark navigational concepts and cognitive perception algorithms applicable to guidance problems in complex environments, this concept, namely a cooperative remote sensing measurement network is unique in its ability to both diagnose and actively interdict dispersed biological or chemical agents in migrating plumes. We are currently expanding our intelligent algorithm testbed to better control the swarm's physical state by evaluating various fitness functions for optimization and self-awareness. The robots will measure and encircle the plume's perimeter by sampling and communicating information at the local level and then perform pattern recognition utilizing the entire sensor array and applying neural networks for global (macroscopic) information. Local potentials governing swarm dynamics and density of state for both collective sensing and ignition functions will be constructed which leverage physics-based plasma particle-in-cell codes or lattice gas statistic models, and will be implemented in conjunction with GA and neural net training algorithms for enhanced spectral analysis and pattern recognition capability. To control such behavior, successful local implementation of recurrent neural networks to decipher a sequence of events (images or patterns) will be expanded to extract global information (see figure 7).

The robotic platforms will be equipped with previously developed optical-receptor tags which integrate specific molecular recognition sensors using engineered enzymatic or monoclonal antibody transduction, surface-enhanced Raman spectroscopy (SERS), and multivariate chemical analysis tools based on genetic and neural net algorithms to achieve 1 cfu sensitivity levels with minimal cross-reactivity. This compact point sensor has the advantage of using antibodies for specific detection and bioconcentration for very high specificity and sensitivity. Antibodies are available for most pathogens, toxins, chemical agents, and explosives. The spectral signature of unbound bioconcentrator guarantees simple system self-monitoring, and the intelligent algorithms eliminate false alarming from cross-reactive interferences. The high-gain resonant Raman process interrogates the immobilized receptor site which acts as a concentrator, and generates a unique fingerprint of the agent complex with modest laser requirements (< 1 mW) amenable to miniaturization. Our sensor architecture will use on-board ruggedized microchip lasers or diode arrays to both excite the Raman process during the detection phase and to locally stimulate optical ignition/implosion of a munition-deployable chemical energy source (magnesium or titanium dust) which is remotely targeted into the plume for remediation. The remediation process requires the disbursement of chemical energy source (magnesium or titanium dust) and the optical ignition of this chemical. The properties of the ignitor material used as a chemical energy source should be that it is essentially inert, easily dispersed, and capable of releasing an amount of energy necessary to destroy hazardous toxins or biologicals. Magnesium and/or titanium dust fulfills these criteria and can be locally stimulated to ignite at low laser power thresholds. Robot beacons in the swarm itself can be utilized to optimize delivery of the ignitor to the target plume. By leveraging Sandia's modeling and simulation capability, Monte Carlo (MC) analysis is being used to simulate combustion dynamics and convective flow, such as turbulence, flares, and shock-waves, and to establish correlation/response time parameters. Basic optical phenomenology of laser flash ignition and SERS with miniaturized lasers will be verified in future planned experiments.

5.2. Ground-Penetrating Radar

As another example of the new type of cooperative remote sensing and synchronization which can be addressed with a distributed collective operating synergistically at local/expert levels, the authors have conducted a preliminary evaluation of this methodology in the context of simulating a phased array ground-penetrating impulse radar antenna structure formed from the superposition of small mobile radiating dipoles for detection of sub-terrain structures in cluttered or propagationally dispersive backgrounds with unknown dielectric characteristics. Basic simulations and experiments of the spatially distributed aperture approximated by a finite number of elements were performed to study electromagnetic superposition, and target detection as a function of range (depth) and aspect (obliqueness). Short-pulse UWB waveforms were used in the time-domain impulse mode because of the potential advantages associated with resonance feature extraction in the backscattered echo for target recognition, and improved clutter suppression and imaging discrimination owing to temporal gating. By properly assembling the array in phase (time delay) amplitude, and spatial orientation, a directive illumination pattern with adjustable transfer function can be created to match the local measurement environment, including terrain obstacles and soil layer attenuation, and to locate optimal imaging pathways. Feasibility studies using iterative intelligent optimization algorithms for design variables of the radiating structure including sensor density, gain, directivity, and sidelobe characteristics in relation to detection criteria and variable simplistic geological models were reviewed. The general synthesis problem of a sparse array of active electromagnetic elements subject to a fitness function which optimizes a matched filter for the scattering topology of plane waves was examined in the context of joint finite difference time-domain, frequency domain transformation analysis (JTFA). The new theory of physical wavelets makes it possible to perform radar and sonar analysis directly in the space-time domain based on fundamental principles underlying emission, reflection and reception of electromagnetic and acoustic waves to pinpoint source locations. Recursive search algorithms based on the mechanics of natural selection and genetics were developed in this modeling work which can abstractly represent the inverse scattering problem as an optical potential in direct analogy with reflective tomography, passive sonar, and ultrasound image reconstruction. Because the GA conducts a global search of the solution space, its convergence is not limited by lack of a priori knowledge about the imaging environment as would be the case for gradient descent methods which are localized.

Detection of deeply buried underground structures in cluttered terrain or urban environments with unknown geological strata is very difficult to accomplish without recourse to indirect remote detection methods such as laser vibrometry [] and differential absorption or fluorescence lidars which rely on secondary signatures related to perturbative ground motion and ventilation effluent detection. Although such an approach is a precursor to selective deployment of ground-based sensors and offers some intelligence guidance, its results can be subject to misinterpretation and false alarm given the complexity of analysis. More direct sensing methods such as ground-penetrating backscatter or synthetic aperture radars have offered limited utility for covert applications against sub-surface targets because of conflicting practical requirements concerning antenna size scaling versus broadcast frequency content to offset attenuation and dispersion of the electromagnetic pulse in penetrating layered soil media. Because of range losses to the ground surface and impedance mismatch in air, large waveguide antenna geometries with easily detectable microwave emission signatures are required from airborne platforms. An alternative approach is to deploy an array of physical sensors which can adaptively reconfigure spatially and temporally as a distributed N-element phased antenna array. Such an array when endowed with intelligent collective optimization for the transmit/receive process can modify itself iteratively to enhance underground imaging capability, and reduce dispersive or clutter backgrounds as a function of sampling interrogation. By combining time and frequency domain analysis for structure identification with the ability to spatially redistribute, optimal penetration pathways for image quality can be selected. A self-organizing impulse radar aperture constructed by superposition of remotely activated rf pulsers and manipulated by a robust intelligent control loop can process many degrees of freedom without the accompanying problem of long convergence times (see figure 8).

Probing for sub-terrain structures using GPR techniques can be thought of as an inverse scattering problem in which the goal is to develop an efficient search technique that can unambiguously identify structural geometries such as triangular or conical shapes of man-made origin in an unknown dielectric medium and geological profile. For a typical mission scenario, initial remote surveillance or the autonomous activity of a mobile robotic swarm will lead to a deployment area in the vicinity of suspicious activity. By controlling the position and phase of the antenna-flavored robots, an iterative technique is employed to map out the sub-terrain and subsequently optimize imaging of any artificial underground structures. To initiate the operational sequence, each robot transmits a pulse and receives signal. From analysis of the time-of-flight and the strength of measured signal, preliminary depth and attenuation can be determined. Next, the data is up-linked to a host (global NN or GA) which processes an image of the terrain beneath the swarms, from which the beginnings of a potential field is formed. Terrain overlay information or corroborative remote sensing data from other sources is fused during this step. Embedded image processing by trained neural nets searches for possible targets. The resulting potential field is then incorporated into the fitness function for a hierarchical GA, which converges to an optimum imaging configuration by changing its state variables- timing, spatial distribution, etc. This overall process is repeated to evolve toward establishing a matched filter for the scattering and dispersive properties of the underground substrata. We will describe the details of this iterative optimization process in the discussion of simulations below. By implementing intelligent algorithms, such as GAs and ANNs, optimal signal transmission and swarm distribution can be taught to quickly converge to optimal pathways, which can enhance structural GPR imagery.

The sequence of events for underground probing of unknown structures by an intelligently-coordinated adaptive phased can be broadly categorized into three steps: (1) coalescing toward a targeted region, (2) successive range-gated probing of the sub-terrain map, and (3) performing a detailed imagery analysis of anomalous features. In order to target a region for interrogation, intelligence information obtained from either internal swarm diagnostics in the course of roving or external remote sensing measurements is needed as a precursor for deployment. Keying on areas of seismic activity, the swarm can then determine the point of origin by combining trained recurrent neural network analysis with multi-sensor spatial distribution data to accomplish systematic triangulation. Combining joint-time frequency spectra with relative positional data will provide improved signal quality and calibrate for dispersion. Probing large sub-surface depths will require a detailed knowledge of the intervening geological profile to correctly optimize phase and pulse-shape of the radar broadcast. However, accurate knowledge of the sub-terrain is not expected to be available in uncooperative situations and must be measured in situ by progressive measurements. For this purpose, an iterative neural net procedure first forms phased array subgroups in the swarm; secondly, inverse scattering data is used to map the contours of terrain up to a maximum depth determined by subgroup size; then, a GA leverages off these spectra to establish the low potential (least loss) imaging pathways through the geology and re-optimization techniques determine the best regrouping scheme. The process is repeated until an optimal depth is reached (the limit of the superposition) or a structure is identified. Following identification, the potential field is developed for improved spatial resolution using antenna phase control, modulation, and directionality in the transfer function. Work is in progress toward developing intelligent algorithms for shape detection and feature extraction.

Hardware implementation of the adaptive radar array consists of the radiating elements, a communication link, and a remote mothership or global decision-making operative for overall image processing of the point-wise measurements and sensor fusion. Each basic radiating element of the distributed grid will consist of an omni-directional dipole antenna (50-100MHz) combined with a compact optically triggered photoconductive semiconductor switch (PCSS), transmission line, and time-delay circuit or phase-shifter module. A time-delay or phase-shifter module controls the relative phases of these antennas. Optical modulators transfer data or receive commands from an outside platform. Detection will be accomplished using the same receivers in a time-gated cooperative listening mode following the initial impulse to eliminate multi-path dispersion and clutter echoes. Using intelligent algorithms operating synergistically at both the local (repositions, internal timing) and expert level (image quality, resolution), the assembled array can be iteratively optimized in individual phase (synchronization with broadcast laser pulse), amplitude, and spatial orientation (l/2 spacing to avoid grating sidelobes) relative to other nearby sensors to create by electromagnetic superposition an adaptable illumination pattern which can respond to local environmental factors such as soil type, dispersion, and anomalous reflections. Since antenna characteristics are determined primarily by the geometric position of the radiators and their relative amplitude and phase excitation, the outgoing radiation pattern would exhibit controllable sidelobe reduction for minimizing clutter and jamming by external noise sources. Active beam steering and the creation of shaped transfer functions as part of an adaptive control loop to maximize signal-to-noise ratio (SNR) could be used to correct for sensing errors, cross-talk, and accommodate building shadowing or constrained search modes. In a layered control architecture, global decisions at the mothership would determine radar function prioritization and resource allocation, while beam manipulation (waveform, chirp, PRF, etc) and signal management would be orchestrated locally by a sub-array. This design concept has the advantage of being amenable to covert infiltration and compact packaging, and can be overlaid with other autonomous ground sensor measurements including co-registered range-resolved optical imagery and passive extoreceptive signatures.

The ability of gallium arsenide PCSS to deliver high peak power, fast risetime pulses when triggered with small laser diode arrays makes them exceptionally suitable for fast impulse radars. This type of direct time domain radar is uniquely suited for observation of large structures underground because it can operate at low frequencies and high average power; low center frequencies offer better penetration and short duration pulses increase the available power on target. By using a properly configured extended synthetic aperture of such devices with the operative PRF (~ 1 KHz burst mode) adjusted to avoid angle ambiguities and image fold-over, the overall achievable spatial resolution can be improved at the expense of coverage assuming synchronization can be maintained. The practical significance of high field operation > 4 KeV/cm in the high-gain nonlinear switching mode of a lateral PCSS is that the carrier multiplication factor (x105) allows for activation with very low energy optical pulses and the corresponding temporal response is characterized by fast subnanosecond risetimes < 200 ps. Experiments have shown that a 90 nJ optical pulse can trigger a switch that delivers 48 MW in a 30-50W system. A combination of these switches can produce either monopulse or monocycle impulse signals. These attributes facilitate compact source design with low intrinsic timing jitter, which have been tested for applications in UWB transmitters, firing sets for munitions, E/O modulators, and active optical sensors.

To analyze the relative merits of different waveforms (monopulse versus monocycle) with varying frequency content and to estimate peak powers for detection of underground structures at fixed depth, we have developed a simple first-order frequency-dependent radar model that includes transmit and receive antenna Fourier response functions, attenuation and dispersion of the electromagnetic impulse by soil layers, transmission losses due to impedance mismatch at the air/soil boundary (upon entering and exiting), and target cross section. For this work we assumed direct soil contact with a matched (240W) bow-tie antenna geometry and examined the normal beam component to the ground which is assumed flat and featureless. A buried test target was approximately modeled as a 10 meter by 10 meter stainless steel slab at a depth of 10-20 meters in dry homogeneous clay and soil type; no volumetric moisture contribution in the bulk dielectric. Typical attenuations of the outgoing pulse following 10-20 m of penetration depth approach five orders of magnitude and the observed temporal dispersion broadens a nominal 500 ps Gaussian impulse to more than 5 ns because of the preferential attenuation of high frequencies combined with frequency dispersion during propagation. Antennae gain of a phased array formed by coherent field superposition, ignoring mutual coupling artifacts, is proportional to the number of individual radiating elements. We find that to achieve sufficient peak powers for this class of measurements that approximately 100-200 sensor elements would be required which should be balanced against coverage and desired spatial resolution. It would be possible to deploy multiple antennae on a single robo-bug. In the following sections, a GA controlled simulated phased-array antenna structure probes a various subterrain profiles. Basic experimental tests verifying superposition properties of pulsed array antennas will also be presented.

We have performed rudimentary experiments implementing a short-pulsed, phased-array of antennas. Thes experiments tested the superposition concept for increased gain and resolution under controlled laboratory conditions with pre-existing antenna hardware. By controlling the position and phase (or time delay) of the antennas for path-length correction, it was shown that the superposition of the reflected echoes at the receiver could be achieved for substantially larger returns ~O(N), where N is the number of antennaes. It is believed that these fundamental feasibility experiments will lay the groundwork for more substantial and realistic ground studies in the future. For the study, a finite number of transmit and receive channels (~x4) configured as simple dipoles (~ 250 MHz broadcast) viewed a 2-D static target suspended in air from multiple aspect angles. In these experiments, a fiber-coupled avalanche diode was used to trigger multiple UWB rf transceivers (Yagi-Uda) at various time/phase delays (simulating a distributed aperture of dipole pulsers optically triggered by photoconductive switches) to study electromagnetic superposition, and target detection as a function of range (depth) and aspect (obliqueness). The range to target was adjusted so that a single transmitter/receive channel was unable to measure a return echo. By firing multiple transmitters which can move with respect to each other and with respect to the target obliqueness, and sequentially recording the return echo at different times (equivalent to sweeping position) on a single wide-bandwidth digitizer channel, the goal is to show the distinguishing advantages of both higher gain (superposition) and resolution (reconfiguration) for the grid without the complications of a heterogeneous dielectric medium. The results can be compared with simulation, and the transfer function of the distributed array in relation to image quality or orientation evaluated (see figure 9).

6. CONCLUSIONS

We believe that an integrated hierarchical all-weather, competitively designed and coordinated group of heterogeneous sensors exhibiting collaborative and collective behavior is a unique and compelling solution to emerging security threats of the next century. In general, if the point sensor design(s) can be made simple, small, and cost-effective enough, adaptive optimization of multivariate remote sensing data from such an interoperative network will decisively enlarge the mission space for counter-proliferation. A system of this type would be capable of sensitively detecting ground-level environmentsl perturbations with high a degree of spatial resolution and situational awareness. The ability to maintain full communication functionality in adverse visibility conditions coupled with operational wavelength agility makes this a versatile technique applicable to both underwater (blue-green) and terrestrial intelligence monitoring.

Information sharing and distributed intelligence opens up a new class of remote sensing applications in which small single-function autonomous observers at the local level can collectively optimize and measure ground-level phenomena for subsequent data transferal to a remote expert processor. As the need for coverage and the number of agents grows to improve spatial resolution, cooperative behavior will be an essential ingredient to offset increasing bandwidth requirements within the net. Recently developed object-oriented simulation environments to visualize behavior will be an invaluable tool for iterating design parameters and evaluating convergence. A system of this type would be capable of sensitively detecting, tracking, and mapping spatial distributions of measurement signatures, which are nonstationary or obscured by clutter noise and interfering obstacles such as buildings. This methodology could be used, as we proposed, to field an adaptive ground-penetrating radar for detection of underground structures in urban environments and to detect chemical species concentrations in migrating plumes. The ability to field an optical communication down-link with minimal risk of detection would also benefit rapid maneuver and special operations forces in mountainous terrain where horizontal line-of-sight is limited, or early entry forces prior to the establishment of an adequate terrestrial communication link. An optical tripwire for advanced threat warning and automated situational awareness based on this technology in combination with sensitive acoustic or ground motion sensors could increase preparedness to interdict insurgents at tactical chokepoints or cease fire boundaries.

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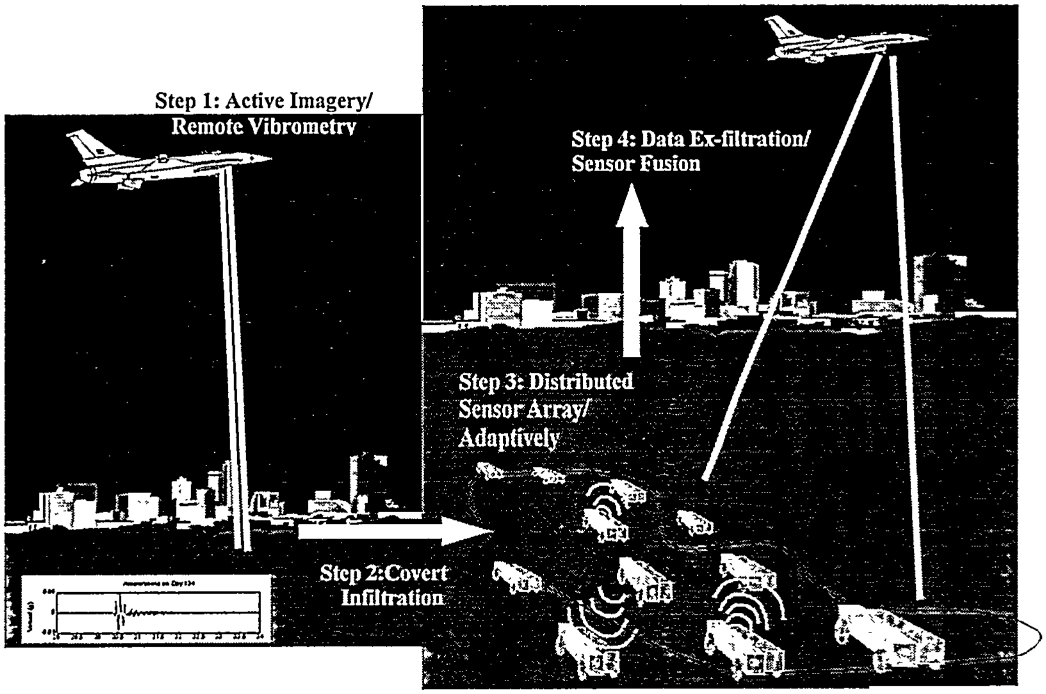


Figure 1. Mission Overview.

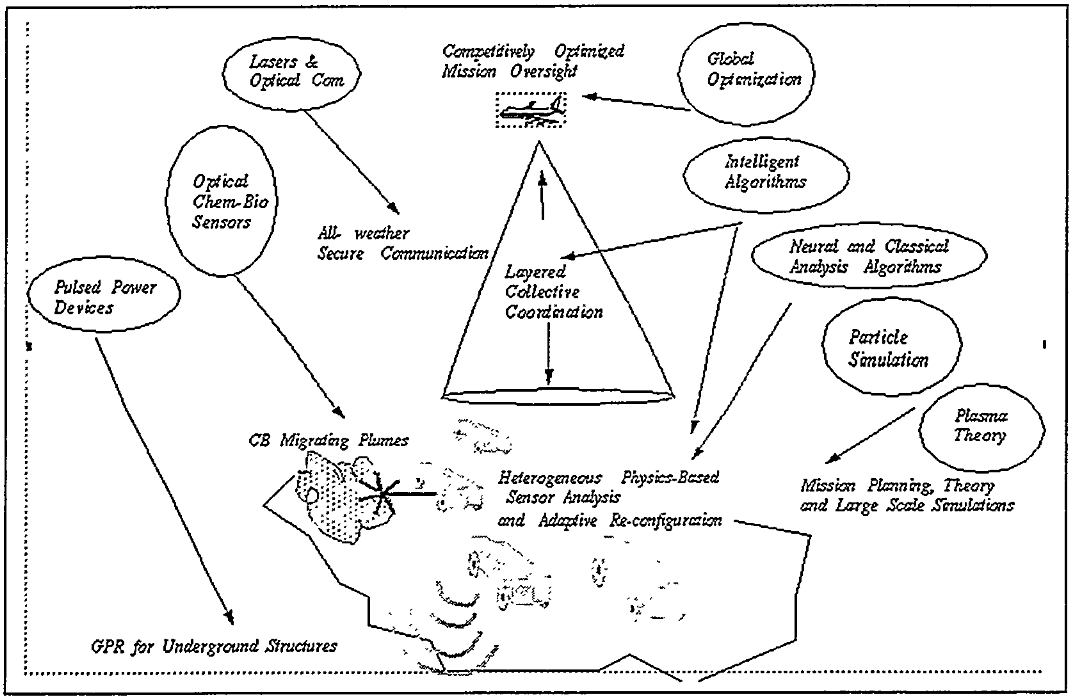
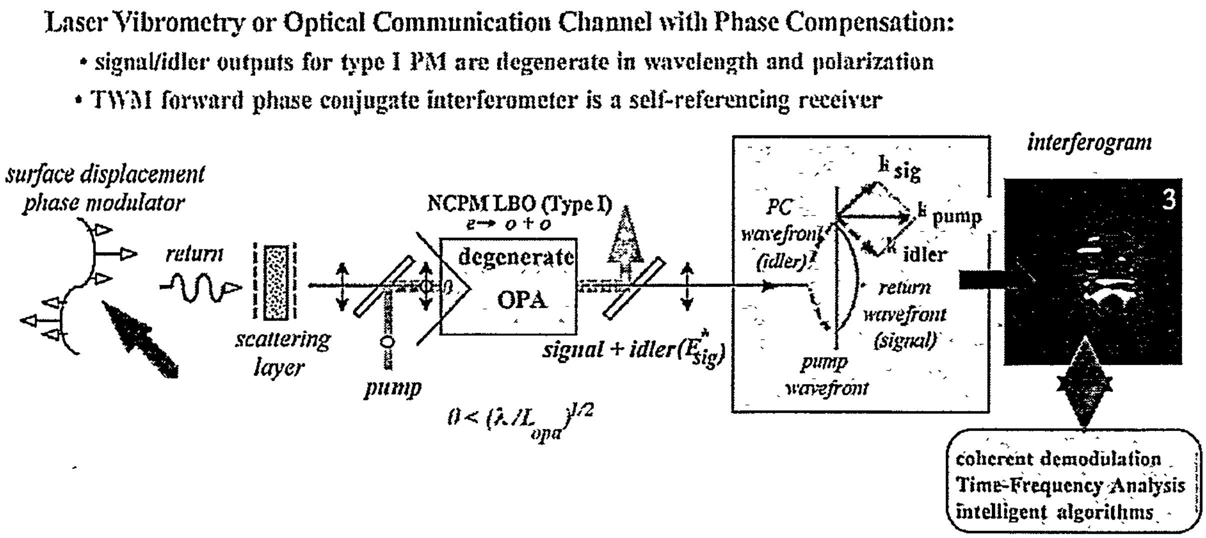


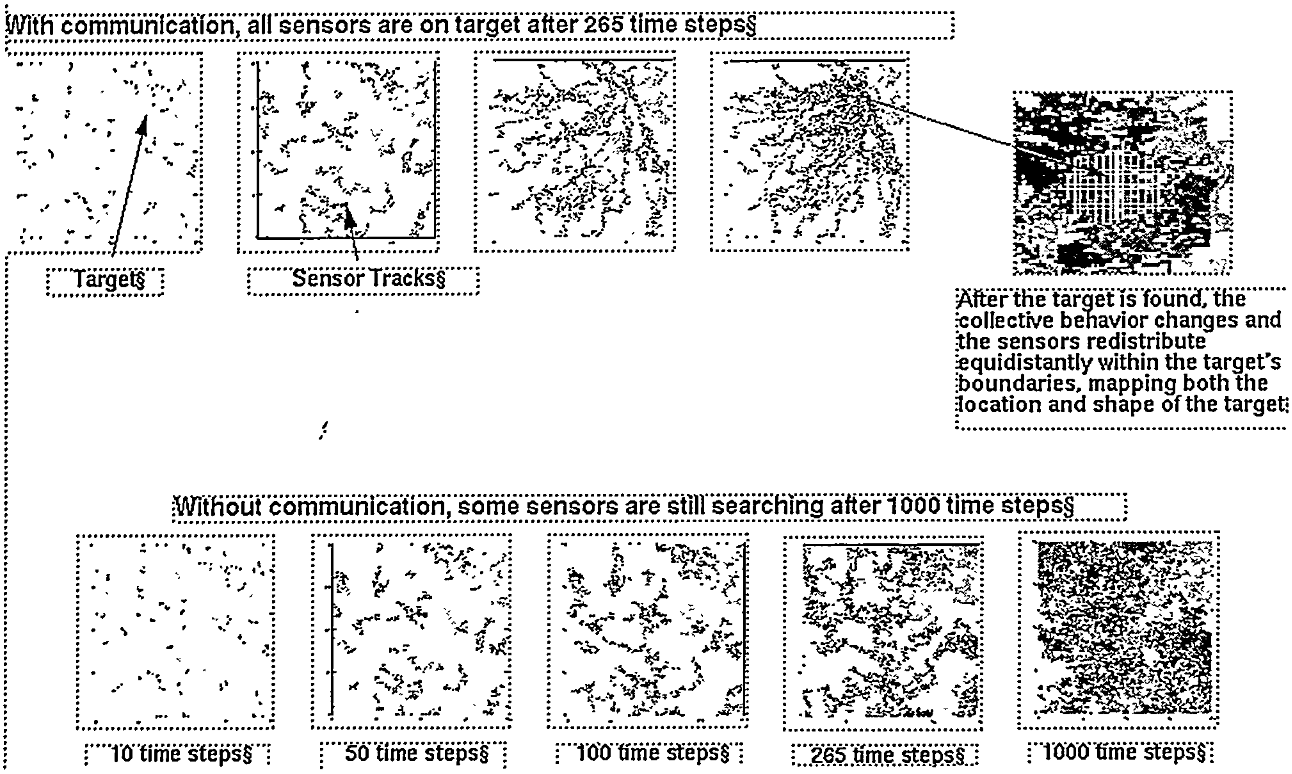
Figure 2. Key Components in Mission Execution.



Laser Vibrometry or Optical Communication Channel with Phase Compensation:

- signal/idler outputs for type I PM are degenerate in wavelength and polarization
- TWM forward phase conjugate interferometer is a self-referencing receiver

Figure 3. Laser Vibrometry.



With communication, all sensors are on target after 265 time steps§

After the target is found, the collective behavior changes and the sensors redistribute equidistantly within the target's boundaries, mapping both the location and shape of the target:

Without communication, some sensors are still searching after 1000 time steps§

Figure 4. Adaptive Sensor Distributions Implementing Agent-Robots

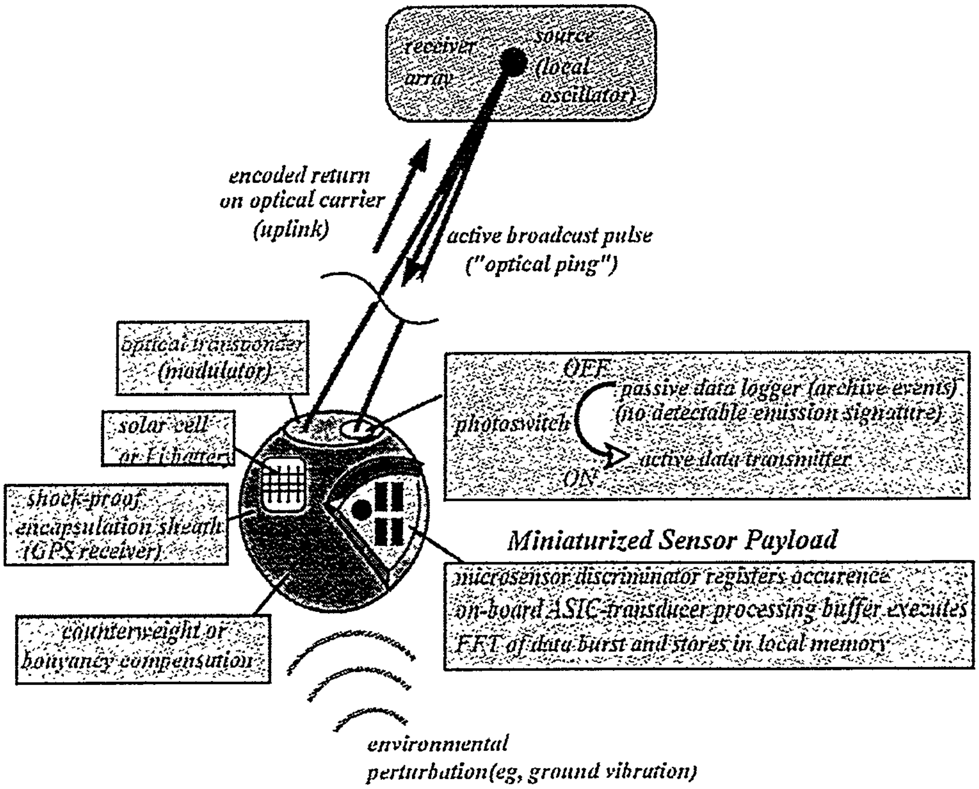
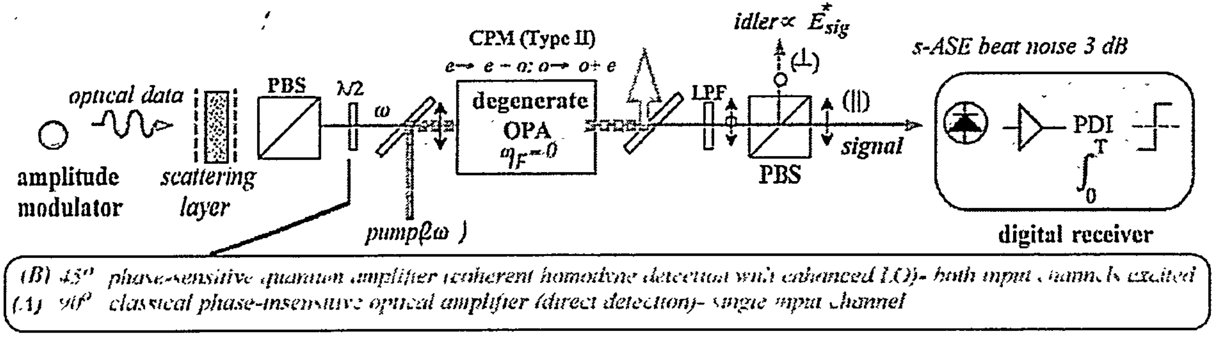


Figure 6. Optical Communications Overview.

Optical Communication Channel with Noise reduction:

- signal/idler outputs for type II PM are degenerate in wavelength, and nondegenerate with respect to polarization
- for nonideal detector (characterized by thermal noise), optical preamp can improve electrical SNR



(B) 45° phase-sensitive quantum amplifier (coherent homodyne detection with enhanced LO)- both input channels excited
(A) 90° classical phase-insensitive optical amplifier (direct detection)- single input channel

Figure 7. Hardware Implementation of an Optical Communications System.

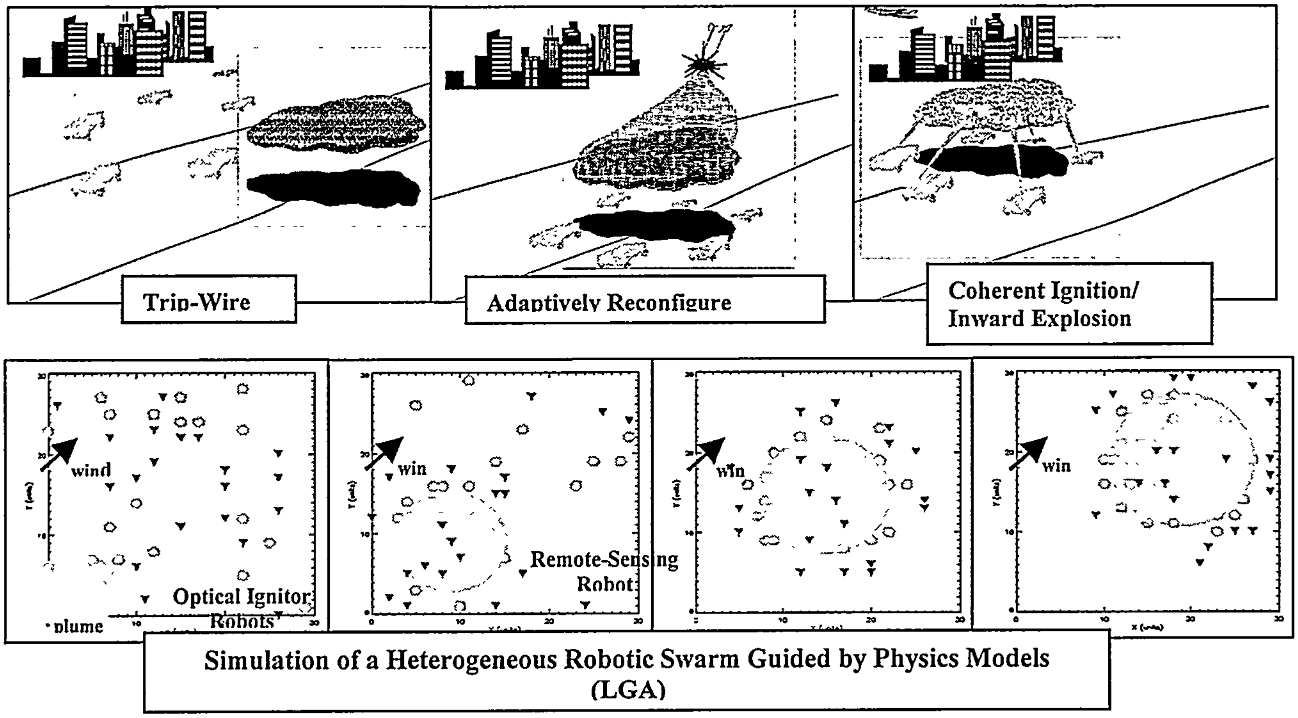


Figure 7. Remediation/Mitigation of Bio/Chemical Effluent Implementing a Heterogeneous Sensor Array

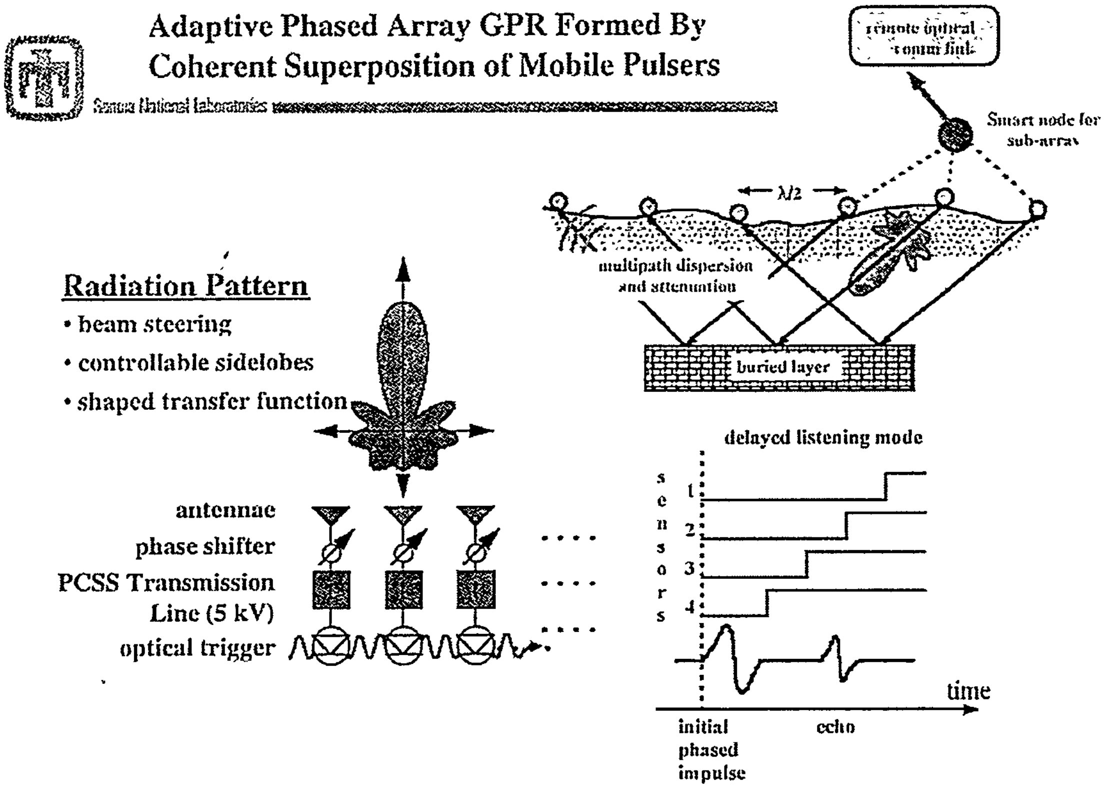


Figure 8. Ground-Penetrating Radar Diagram.

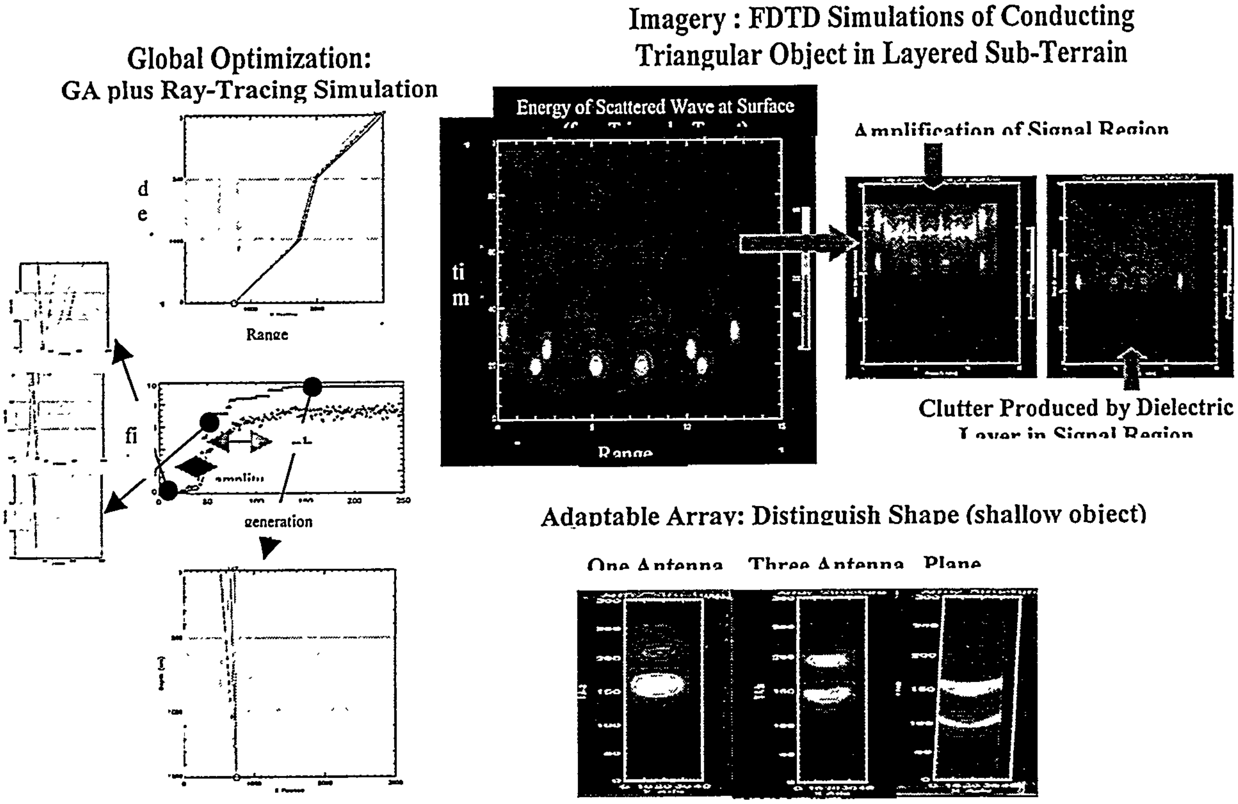


Figure 9. Ground-Penetrating Radar Simulations: GA optimized antenna positions, three antenna simulations of an underground conducting triangular target (~11 meters deep) with a horizontal dielectric layer inbetween, and shape determination of a triangular dielectric target implementing one, three, and infinitely many intennaes.