New World Vistas

Air and Space Power for the 21st Century

Sensors Volume

This report is a forecast of a potential future for the Air Force. This forecast does not necessarily imply future officially sanctioned programs, planning or policy.

Executive Summary

Sensors Panel

"To Know More and To Know It Sooner"

Introduction

Sensors are essential elements of virtually every Air Force (AF) weapon and support system. The hardware and software associated with sensing functions are generally major, and sometimes predominant, contributors to the performance, reliability, supportability, and cost of such systems. Many of the technologies associated with sensors are in a state of rapid evolution and will remain so for the foreseeable future. Moreover, many sensing functions and devices that are important to the Air Force have counterparts in commercial, industrial and medical applications. This combination of ubiquity, operational impact, technology leverage, and dual use potential makes the subject of sensors especially important to the themes of *New World Vistas*.

Sensors have played an important military role in the past and will play an increasingly important role in the future as air power is called upon to respond to a wide range of conflicts and to apply force with exquisite precision, no collateral damage, and nearly instantaneous response. Sensors provide data and information that lead to increased knowledge about our own and the enemy's forces, circumstances in the battlespace, and, ideally, the enemy's plans and intentions. Knowing more and knowing it sooner than the enemy provides an advantage and motivates the goal of acquiring "near perfect" knowledge of the battlefield as well as overall global situation awareness at any time and under any weather condition. The growing emphasis on smarter and smarter weapons, the difficulty of detecting and identifying concealed targets, the growing concern about proliferation of inexpensive cruise missiles and weapons of mass destruction, the need for precise target information and the detailed information needed for counter-terrorism activities are all additional examples that motivate the desire for larger numbers of better and more affordable sensor systems.

Sensors represent a very broad and pervasive class of measurement systems. Sensors can exploit the full electromagnetic spectrum by intercepting reflected or naturally occurring electromagnetic radiation; detect various forms of mechanical energy, for example, seismic and acoustic; and physically sample and analyze a diverse set of chemical and biological components. Moreover the sensors can be active or passive, where an active sensor is one that stimulates its external environment and measures a reflection or other response, and a passive sensor is one that does not. Sensors can be operated from a variety of platforms in space, in the air, on the surface or below the surface of the earth. The sensors can be operated from stationary platforms or moving vehicles that can be inhabited or not. Indeed, many of the sensors of the future may be transported by small, mechanical, crawling or flying devices. Section 2 of this Volume is a discussion of the sensing process in general which establishes a framework for systematic treatment of this exceptionally diverse topic. Tables 1 and 2, on following pages, present a sampling of the taxonomies developed in Section 2 to give a sense of the range of sensor types and uses with which we must deal.

Table 1. Examples of Active and Passive Sensor Types Employing Various Phenomenologies

Physical Phenomenon	Active Sensor Types	Passive Sensor Types
Electromagnetic		
• DC/Low Frequency		Conductivity, Squid, Magnetometer
• RF Wavelengths	Radar, IFF	CNI, SIGINT, Radiometer, ESM, RWR
• EO/IR/UV Wavelengths	LADAR, LIDAR, X-Ray	FLIR, IRST, NVG, TV
Mechanical		
• Acoustic	Ultrasonic NDI, Active Sonar, Radio-Acoustic Sounder	Microphone, Hydrophone/Passive Sonar
• Seismic	Active Tomographic	Geophone/Seismometer
• Tilt		Tiltmeter
• Inertial		Micro-IMU, Accelerometer, Gyro
Chemical/Biological	Differential Absorption LIDAR (DIAL)	Spectrometer, chemical reaction Flow-PCR Mass Spectrometry SAW-based selective adsorption Enzyme-based electrochemical UV-fluorescence spectroscopy

Table 2. Examples of Sensors Used for Various Operational Tasks

Sensor Applications	Typical Sensor Types
Wide Area Surveillance	Radar (AWACS, Joint STARS, OTH, etc.), Passive EO, SIGINT
Threat Warning	Passive EO (missile launch detection/approach warning), RWR, CNI/ESM, SIGINT, Radar
Reconnaissance/Battle Damage Assessment	Imaging EO, Imaging Radar, ESM, Fire Control Sensors
Air-to-Air Detection, Tracking, & Fire Control	Radar, IRST, ESM (e.g., ARM seeker)
Air-to-Ground Targeting & Fire Control	Radar (SAR), FLIR, LADAR, ESM
Missile Guidance	Inertial, Stellar, GPS, Radar, LADAR, Passive EO, ESM, Beam Rider, Proximity Fuze
Navigation	Inertial, GPS, Imaging Radar, Stellar, CNI
NBC Detection	Specialized Detectors, DIAL, Hyperspectroscopy, LIDAR
Ground Traffic	Acoustic, Seismic, including UGS
Weather	Radiosondes, Doppler Radar, Imaging EO
Science and Technology (S&T)	Imaging EO and Radar, ESM/SIGINT
General Intelligence and Indications and Warning (I&W)	ESM/SIGINT, Imaging EO and Radar, Wire Taps, Acoustic/Seismic, UGS
Medical/Crew Health Monitoring	Multiple Biomedical Instruments
System Health Monitoring	TSMD, Built-In Fault Detection/Isolation, NDI

Observations

We are at the threshold of the fourth revolution in military "sensing" that started with the human observer and is now leading to real time remote sensing worldwide. In the first phase of reconnaissance and surveillance, the human observer provided direct input–eyes on target–to the field commander for his direct action. For this early history of warfighting, the range of direct action (such as arrows and cannon fire) was well matched to the sensory range of the human observer. As extended range artillery, rockets and the airplane increased the range of action, reconnaissance changed from balloons observing over the trenches to airplanes with film cameras. However, with the extended range of sensors, came a penalty to the field commander in terms of timeliness. To improve responsiveness, the third revolution of real time sensing systems was developed and fielded. We now find our reconnaissance capabilities based on a few high performance systems that must be shared across all field commanders. Changes in the velocity of maneuver, range and precision of theater weapons and the potential use of WMD require a revision in our sensing system strategies.

As we enter the fourth phase of military sensing, we must detect a wide spectrum of target information ranging from traditional solid targets, for example tanks, to chemical and biological effluents. The implementation of this phase is beginning with low cost UAVs distributed among supporting commanders at all echelons. This concept, taken to conclusion, leads to a wide variety of low cost micro-sensors providing warning, targeting, and battle damage assessment. The use of distributed micro-sensors is not new to the military; but historically, these sensors have been expensive and cumbersome and applicable to only the highest priority national problems. Recent developments noted above present new opportunities for the use of these sensors. They may be used for distributed surveillance and targeting as well as for enhanced sensing that is difficult with current sensors. They may also serve to increase the survivability of larger conventional surveillance and reconnaissance systems while reducing the operational costs. These and other concepts related to the fourth revolution in sensing are reflected throughout this Volume of *New World Vistas*.

Stressing Operational Tasks

We have approached the future of sensor capabilities and systems from the logical extremes of operational pull and technology push. First, we have derived seven representative operational tasks in which sensor capabilities are prominent and which stress the current state of those capabilities. Section 4 of the Volume spells out in some detail the nature of each of these representative tasks and the associated sensor capabilities needed to support the warfighter in each scenario.

The representative operational tasks are listed in Table 3, along with samples of the sensor concepts associated with each. These tasks span the operational spectrum in such a way that an inventory of fielded sensor systems that adequately satisfies these needs would be highly competent in virtually any operational scenario.

We have also identified some of the key enabling technologies associated with the operational tasks. These are summarized in Table 4. In parallel, we have extensively surveyed the overall sensor technology arena, including receiving extensive briefings and papers from leading R&D organizations. From the many dozens of interesting technology ideas thus identified,

Table 3. Representative Operational Tasks and Associated Sensor Capabilities

Stressing Operational Task	Typical Related Sensor Capability
Acquire, maintain, and disseminate a full, near-real-time situational awareness picture of the battlefield.	All-condition, high resolution imaging to detect, locate, and classify targets and activity patterns and build time histories.
Maintain continuous world-wide surveillance of nuclear, biological, and chemical (NBC) weapon manufacture, storage, and transfer.	Multispectral active sensors for detection and identification of trace chemical effluents from NBC facilities.
Locate, observe, and target assets and activities in hardened/underground facilities.	Seismic sensors capable of deriving 3-D conformations of underground structures.
Acquire, locate, track and identify air and ground targets to deliver munitions with high accuracy.	Combined imaging and moving target sensors to detect and locate moving targets in heavy clutter.
Detect, track, intercept, and destroy theater ballistic missiles and cruise missiles.	Internetted missile launch detection and tracking sensors.
Acquire, maintain, and disseminate information to plan and execute military operations other than war (MOOTW).	Special sensors for counter-terrorist and hostage rescue, for example, detection of personnel in buildings.
Acquire information for force sustainment.	Portable, nondestructive inspection instruments for flightline detection of corrosion, cracking, and delamination.

Table 4. Enabling Technologies

Operational Task	Enabling Technologies
Battlefield Situational Awareness	RF Conversion Moderate Power Tunable Lasers High Efficiency Solar Cells Mass Storage Devices Intelligent Agents High Rate, Highly Linear Analog-to-Digital Converters Fusion/Correlation Techniques Automatic Target Recognition
Surveillance of Weapons of Mass Destruction	Multispectral Laser Radar for Effluent Detection Low Cost Focal Plane Arrays Micro-Machinable Electromechanical Systems Materials Tagging Adaptive Tasking Information Fusion/Correlation Femtosecond Laser Radars Unattended Ground Sensors (Acoustic, RF, IR, Seismic)
Surveillance of Underground Facilities	RF/Seismic Sensors With Tomographic Processing Multispectral Laser Radar for Effluent Detection Unattended Ground Sensors (Acoustic, RF, IR, Seismic) HF/VHF Synthetic Aperture Radar Weapon Borne Battle Damage Assessment Sensor
Accurately Deliver Munitions	Multifunction EO/IR Modular, Multifunction RF Components 3-D Laser Radar Miniature, High Accuracy Inertial Measurement Unit Imaging IR Sensor Multispectral Laser Radar Automatic Target Recognition Weapon Borne Battle Damage Assessment Sensor
Find Theater Ballistic Missiles and Cruise Missiles	Space Based Radar High Energy Lasers Optical Fire Control System Unattended Ground Sensors (Acoustic, RF, IR, Seismic) HF/VHF Radar
Special Operations and Military Operations Other Than War	Miniature Focal Plane Array Chem Lab On a Chip Multispectral Apertures RF Sensors Multispectral Laser Radar for Effluent Detection Unattended Ground Sensors (Acoustic, RF, IR, Seismic)
Force Sustainment	BIT/FIT Sensors Corrosion Sensors Crack Detection Sensors Disbonding/Delamination Sensors

we have eleven technology areas that have high potential to leverage operational capabilities, and we describe these in Section 6 of the Sensors Volume.

Trends and Opportunities

Several trends and opportunities have emerged from this study and call for both near term concrete Air Force actions and long term diligence in developing and exploiting emerging technologies. These trends should be exploited and the opportunities should be pushed forward to gain real benefits. In the following, we summarize the over-arching trends and opportunities along with some illustrative technology examples.

1. Affordable and Enhanced Sensing Through Signal Processing

Many of the advances in sensors that have been achieved recently and will be achieved in the future are directly related to concurrent and supporting improvements in two key areas—computer technology and signal processing algorithms. The exponential growth in computational capacity (ever increasing mega instructions per second [MIPS] per pound, watt, and dollar) is well known. Also important for the advance of sensing systems, but less well publicized, are the dramatic innovations in signal and data processing algorithms, for example, efficient large-array image registration. By exploiting these two key areas, it is possible to shift some of the burden from the sensor itself to the signal/data processor to achieve more affordable and/or enhanced overall sensing systems. This opportunity is often called “trading mass for MIPS” and generally involves using processing power to compensate for inadequacies in sensing hardware.

An example of an important future sensor concept that illustrates this opportunity is “relaxed-optical-tolerance imaging.” In the next several decades, the Air Force will have an increased need for fine resolution optical imaging of targets and scenes on a global basis. Using current technology, a space-based optical system with a large aperture would be very heavy to insure structural integrity and rigidity. It would also be expensive and cumbersome to fabricate and deploy. A solution to the current technology shortfall is to relax optical tolerances (thereby reducing weight) on the primary mirror and recover the loss with post detection processing. For example, the primary collector could be a non-rigid (floppy) monolithic or segmented or sparse device involving a very thin mylar surface stretched over skeleton structure. The large aberrations associated with this system would then be overcome with post-detection processing involving algorithms such as *phase-diverse speckle imaging* or *multiframe blind deconvolution*. These algorithms all involve a large number of computations that require on the order of tera-operations for a single million pixel image. The use of new algorithms and advancements in computer technology will allow the development of more affordable and improved imaging systems such as this.

Similarly, signal processing can provide the capability to exploit SAR image data from space or airborne platforms to detect and measure subtle changes in a scene between imaging passes. This technique is often called “coherent change detection” and involves using the phase differences between two SAR images taken with antennas that are displaced either spatially or temporally to retrieve information on motion, change, or surface elevation differences within the images. Differences in phase are indicative of subtle changes between imaging cycles. For example, decorrelation in the image phase indicates changes have occurred in the scene microstructure due to surface disturbances. These changes are usually not observable to a human viewing the scene nor can changes be seen in a conventional SAR image. This class of sensing techniques will have increasing utility in dealing with many operational tasks of interest to the Air Force in the future.

2. Increasing Use of Multidimensional Phenomenology

A second trend in sensor technology is the growing use of multiple physical phenomena in the sensing process. In addition to the extension to three-dimensional (3-D) spatial imagery, other dimensions can be used as well. Examples include multi, hyper, and ultraspectral (US) optical imaging concepts that use information from a large number of spectral bands. Other concepts combine information from optical and radio frequency bands, from vibration and polarimetry, from reflected spectra, from seismic and RF responses and so on. The common characteristic of these combinations is that they provide additional, often critically discriminating, information about targets of interest, allowing these objects to be detected and characterized with much improved error rates. It has been said that an enemy may hide from us in a few dimensions but not in all dimensions. We must continue to develop and use sensors that involve more and more phenomenological dimensions.

3. Continuing Improvement in Sensor Systems and Component Technologies

Sensors will continue to improve due to developments in enabling technologies as well as in system design. For example, Air Force radar systems are steadily advancing in terms of resolution, ability to penetrate foliage, moving target indication/indicator (MTI) capability, levels of electronic integration, and reliability. Similarly, electro-optical systems boast denser focal planes with broader spectral response, on-chip tunability, and uncooled operation. Inertial systems show steady improvement in drift performance, reductions in size and cost and ever tighter integration with external aids. Supporting electronic components such as A/D converters and embedded signal processors are also improving, becoming faster, smaller and more reliable. These trends will continue and will provide opportunities for improved sensor systems and fundamental changes in the way sensors are designed and used.

One example of new enabling technology described in Section 6 of the Volume is micro-electro-mechanical systems (MEMS). This technology uses material processing methods from the microelectronics industry to make useful structures, including pressure sensors, uncooled IR detectors, bio/chem detectors, accelerometers, gyroscopes, valves, and switches. The distinction is that these devices can be very small (down to lithography scales) and can be mass-manufactured with electronics already integrated, making unit costs potentially very low. Combined with communications and processing, these features enable sensing concepts comprised of many small distributed elements. Such concepts represent a major change of philosophy away from today's larger centralized systems. They also create entirely new sensing possibilities such as micro-sensors for in-situ surveillance and reconnaissance, embedded sensors for autonomous vehicle and aircraft systems, microactuators for adaptive and precision alignment of imaging systems, and microjets for turbulence control over airframes.

Current focal plane array (FPA) technology includes numerous high spatial resolution devices for the ultraviolet (UV) through the Long-Wave IR (LWIR) wavelength range. In general, visible device technology is more mature than that found in the IR. Key IR detector materials are undergoing constant refinement to improve sensitivity. Quantum efficiency (QE) gains have been secured in PtSi through refinement of the wafer preparation and platinum deposition process and the addition of Fabry-Perot microstructures to the detectors. Notable advances have been made in other materials to reduce detector 1/f noise through improved materials purity and processing techniques. Microscopic lens arrays to increase detector fill factor can also be added. More advanced approaches for FPAs that could lead to dramatic performance improvement include Quantum Well Infrared Photodectors (QWIPS) and strained layer superlattices. These advanced techniques need much development, but could lead to more uniform arrays at long wavelengths and a higher degree of radiation hardness.

Other examples of improvement in sensor systems are related to achieving a nearly continuous observation capability needed for many operational tasks. Continuous observation implies day/night and all-weather operation and suggests the use of microwave imaging sensors. In principle, this could be accomplished by a large number of SAR sensors on LEO satellites or a few in synchronous orbit. The standard type of geo-synchronous satellites have the advantage of continuously seeing a large portion of the earth, but the disadvantage from a SAR point of view is that there is no relative motion to create the synthetic aperture. Previous studies have considered putting the satellite into an inclined orbit, which gives an apparent north/south motion once per day. The drawback to this design is that a fine resolution image requires a significant fraction of a day to collect. The use of Bistatic SAR in which a microwave illuminator is placed in a synchronous orbit with lower orbiting receivers or airborne receivers is an interesting alternative (see SAB Report, “Offboard Sensors to Support Air Combat Operations,” April 1992). In this Volume, we describe a low cost space-based surveillance concept involving the use of approximately 10 to 20 LEO satellites for SAR coverage of a theater.

4. Increasing Interconnectivity and Functional Integration

While advances in specific sensor types are important means to achieve required operational capabilities, our analysis has consistently pointed to the power of integrated use of multiple sensors to cope with stressing information gathering situations such as concealed targets. We discuss this subject in the context of a “system of systems” architecture in Section 2. There are both physical and functional dimensions to this integration. On one hand, internetting of sensors through robust, high performance data links to allow coordinated functioning and to rapidly aggregate data at fusion nodes is essential to the basic idea of bringing relevant data from all sources to bear on a given problem. On the other hand, adaptive sensor control algorithms, data fusion, and other information processing functions must be integrated for the available assets to be optimally employed as a single entity.

The subject of sensor correlation and fusion is so fundamental and pervasive that we have devoted all of Section 3 to it. Recognizing that no taxonomy of fusion processes is perfect, we have adopted the four-level model articulated by the Joint Directors of Laboratories and accepted the fact that some important ideas and design principles overlap the levels of this model. Despite decades of research, the state of the art in data fusion is still largely heuristic and the number of actual fielded systems with nontrivial fusion processes is still small. Section 3 of the Volume surveys the many bases on which sensor signatures can, in principle, be combined and highlights the reality that most existing processes come down to multiple hypothesis testing using one or more statistical models chosen on the basis of the data and its known or assumed errors. We again emphasize our recommendation that this is an area where concentrated attention to the underlying mathematical tools would produce major benefits.

Sensor internetting is intimately related to the trend toward higher dimensionality in sensing described earlier. Since it will often be impractical to implement the full range of sensor types needed in a given scenario on a single platform, tight linkages and integrated control become essential to the registration of various target signatures and to adaptive control of individual sensors based on the composite or fused target picture. Internetting is also important as a means to achieve overall robustness in the sensing structure by exploiting inherent redundancies among systems to cope with loss of assets to failures or hostile action.

To make these general ideas more concrete, Table 5 summarizes the seven "illustrative concepts" described in Section 5 of the Volume. These concepts have been chosen to illustrate the ways in which advanced technology can be harnessed in specific system designs to address the improved operational capabilities identified previously. As the table suggests, both improvements in individual sensor species and the trend toward higher levels of functional integration are central to progress in performance and affordability.

Table 5. Examples of Sensor Integration as Part of Illustrative Concepts for Future Systems

Sensor Concept	Example of Improved Sensor Performance	Example of Sensor Integration
UAV Target Reporter	Lightweight, Multimode UAV SAR	Fusion of Multiple Onboard plus Unattended Ground Sensors (UGS)
Internetted UGS	Sensitive, Highly Specific, Passive Chemical Detectors	Area Coverage from Multiple Small UGS of Various Types
Buried Target Surveillance	Microsensors for Covert Penetration of Facilities	Fusion of Seismic, RF, Acoustic and Other Sensor Signatures
Concealed Target Detection	Broadband Low Frequency SAR for Foliage Penetration	Cueing of Fine-Resolution SAR by Wide Area Sensors
Weather Forecasting	Multiwavelength Radar for 3-D Measurement of Clouds, Rain	Fusion of Active and Passive RF and EO Sensors
Multifunction EO Sensor	Optics with No Moving Parts for Low Cost	Multiple Functions Through a Common Aperture
Low Cost Space-Based Surveillance	Multiple Technologies for Light-Weight, Efficient Multimode Radar	Integration of Space and Airborne Surveillance for Affordable Long Term Coverage

5. Rapid Data Exploitation/Automatic Target Recognition

The capability to reliably and automatically recognize sensed visual, IR, and radar images or electronic signatures will provide significant operational benefits to the Air Force in mission areas requiring rapid target identification, intelligence data analysis, battle damage assessment and automatic sensor queing. The state of the art of (spatial) pattern recognition does not yet provide sufficient accuracy or reliability to perform independent and unambiguous automatic target recognition (ATR) for lethal attack in mission applications, but it does provide the ability for rapid screening and automatic sensor cueing (ASC) to support the warfighter.

Classification/recognition algorithms all operate by matching attributes of the measured (unknown) signature with *a priori* information about the potential targets that could be present in the scene. Algorithm technologies differ in terms of the type of information used to match, the way in which the *a priori* information is encoded, and the approach used for matching. The matching algorithm technologies that have been the focus of classification/recognition research fall into four broad categories:

- *Statistical Pattern Recognition*: partitions the space of possible target identities according to target signature attributes.
- *Neural Nets*: models the information flow across components in the human brain to perform the reasoning process that matches pre-stored target features against the unknown to identify it.
- *Template Matching*: codifies the topological structure of the target signatures from a priori data and matches these against the unknown signature to select the most likely identity.
- *Vision*: applies reasoning based incremental signature correspondence between the unknown and the signature properties of all feasible targets to determine the most likely identity of the unknown.

There are basically two fundamental elements required to successfully field ATR/ASC systems. The first and most obvious are the necessary algorithms and processing techniques and methodologies for performing the ATR/ASC function. Physical, quantitative models are required to provide a predictive capability not presently available. There is a need for rigorously derived new models and theories for such models to replace the limited heuristic and ad hoc algorithms, empirical and statistical relationships and human elements currently used for today's problems. The second fundamental element, equally obvious, is the enabling high speed signal or data processing hardware equipment on which the above ATR/ASC algorithms would be performed. Extremely high density storage, rapid onboard access to specialized databases, and extremely high performance computing elements will all be necessary to successfully field robust ATR/ASC systems.

6. Commercial Opportunities

Opportunities to cooperate in the development and utilization of commercial sensing systems are vast. The growing interest in commercial satellite remote sensing systems and plans for collecting fine resolution panchromatic, multispectral (MS), and eventually SAR imagery provide the opportunity to purchase these data for military purposes. The capabilities of these commercial systems need not be duplicated, but rather can serve as part of the overall mix of sensor systems serving the military. Similarly, the development of intelligent, autonomous inspection systems for industrial operations involves a wide variety of sensors and associated recognition systems that are directly related to military applications. Small sensors based on MEMS and surface acoustic wave (SAW) devices are being developed to produce very small, low cost industrial instruments for chemical detection and analysis. These "chemistry lab on a chip" devices have obvious application in counter-proliferation. Another important example is the exploding consumer application of GPS that will provide ever smaller, cheaper receivers for potential military use. These and many other commercial cooperation opportunities bode well in our quest to field affordable sensor systems.

Recommendations

The Sensors Panel has concentrated on identifying the operationally important enabling technologies for which increased Air Force investment is considered important. These recommendations are contained in the report, and the reader is encouraged to review the entire report in order to grasp the total picture. These efforts will lead to the advent of new technologies and architectures that effectively support the application of air power in the coming decades. Major changes are foreseeable in command, control, communications, and intelligence (C^3I), signal and image processing, ATR and expert systems, providing the potential to acquire a timely and superior knowledge of ourselves and our enemies. Leveraging a tremendously accelerating base of commercial technologies in the digital and computing domain will contribute significantly to these efforts.

Several areas, however, deserve special attention, and the associated recommendations follow. The Air Force should:

1. Establish a central authority to define and control the information architecture, and its sensor segment, as a system of systems

As an overarching recommendation, the Panel believes the Air Force should designate a central authority to define and control overall force structure architecture, specifically the information architecture and its sensor segment. The objective is to halt the proliferation of stovepipe, non-interoperable systems and begin a migration to a “system of systems” architecture that delivers the maximum warfighting effectiveness from the affordable suite of assets. The information architecture should define the requirements levied on individual systems such as sensors and weapons, the interfaces among all elements, and the operating modes through which these assets support dynamic battle command and control. The Air Force should continue the development of systems based on demonstrable technologies such as sensing and data acquisition sensor systems with wholly digital output supported by large-scale networking of these sensor systems supporting “system-of-systems” concepts. Network transport protocols of broad functionality supporting this concept are also needed, with a strong preference for broadly supported commercial standards.

2. Improve multifunction radio frequency apertures

The Air Force should initiate a program, including activities from 6.1 through 6.3, to significantly improve the state of the art in multifunction radio frequency (RF) apertures for radar, radiometry, threat warning and countermeasures (both non-destructive and destructive) and for communication, navigation, and identification (CNI). The basic measure of merit is the product of radiated power, bandwidth, and direct current (DC)-to- RF/RF-baseband conversion efficiency. The goal is technology for affordable RF apertures with multioctave coverage (ultimately operating in selected bands from 1 to 160 GHz), wide instantaneous bandwidth (at least 1 GHz), high radiated power (20 to 100 W) and high efficiency (50 percent across the bandwidth). R&D on RF solid state devices for both transmitter and receiver functions, as well as broadband radiators and high performance signal processing, is central to this program.

3. Improve multifunction electro-optical/infrared modules

Two themes run through our sensor considerations. They are affordability and multidimensionality. Wavelength tuning adds another dimension to our traditional spatial target detection/recognition. Focal plane arrays (with more pixels) and lasers capable of narrow-band tuning over a broad wavelength region are required for expanded multidimensionality. Inexpensive methods of pointing and stabilizing electro-optical systems are required for affordability. Sensitive focal plane arrays that are uncooled or thermo-electric cooled are also required for affordability. The Air Force should initiate a program, including activities from 6.1 through 6.3, to develop multifunction EO apertures for passive target detection, active target location and identification (ID), missile warning and infrared countermeasures (IRCM), and laser communications.

4. Develop a family of air-monitored, unattended ground sensors

UGS offer special promise for a wide range of applications, and the unique abilities of the Air Force to seed as well as read out sensors by aircraft deep in hostile territory suggest a much stronger Air Force UGS technology program. Multiple phenomena (20 or so are obvious to the Panel) and target identification sensing for ground sensors will provide a much better picture of the area under surveillance. No breakthrough in technology is needed to develop a demonstration capability for ground sensing many types of targets. Prototype sensors with advanced signal processing should be fielded to determine the proper mix of sensing elements required to classify various targets. The post-detection processing using fusion with other intelligence to extract and display critical information is the major challenge.

5. Develop a family of micro-sensors for use in airborne, spaceborne, and ground sensor systems

The Air Force should develop a family of microsensors (including MEMS technology) that can be used in airborne, spaceborne and ground sensor systems. This involves monitoring commercial advances in acoustic, seismic, inertial and pressure sensors; testing them for performance in likely military environments (space, jungle, desert); and cataloging suitable sensors for future applications. It also involves developing micro-sensors for specific military unique missions. The most important of these are chemical and biological warfare (BW) agent detectors.

6. Develop tags for air-monitoring the movement of materials and equipments

The Air Force should pursue development of dopant materials which would respond to airborne active and passive sensor systems to reveal the location of the carrier material (chem/bio agents, drugs, raw materials for munitions, etc.). Such dopants might be spectrally identifiable by stimulated or natural fluorescence. Similarly, tagging devices such as optical, infrared, or radio frequency transmitters, retro-reflectors and transponders should be developed to be evident to reconnaissance, surveillance and attack aircraft to locate and track weapons systems, munitions, vehicles, and personnel. Included should be some ability to locate these tags even in foliage and in buildings.

7. Stress sensor affordability through emphasis on revolutionary and evolutionary signal processing concepts

The AF should implement programs for the development of improved algorithms for relaxed tolerance imaging, image compression, ATR, and so forth. Human computer interactions and interface designs for next generation virtual reality displays supporting an "immersive environment" for users should be extracted or modeled from commercial developments in the sensory engineering areas. Robust and quantitative theories and algorithms for effective "system-of-systems" designs optimized for a variety of missions need to be developed.

The rapid improvement in digital technology is recent years allows opportunities to use reduced cost sensor components. We expect that this trend will continue. Digital signal path systems can cost less in both acquisition and life-cycle if sensor technologies and algorithms improve. Additionally, digital systems make possible and practical the design of major systems that will accommodate technological change over several decades (insertion as they become available), thus mitigating technology obsolescence.

8. Exploit the advantages of the multidimensionality offered by multiple sensor regimes

To increase the probability of target detection, recognition, or identification while maintaining a constant false alarm rate (CFAR), one can use a limited number of target dimensions with very high resolution (synthetic aperture radar [SAR] with electro-optical, for example) or increase the number of orthogonal dimensions with limited resolution in any dimension (MTI + SAR + UGS + electronic support measures [ESM], for example).

By expanding the dimensionality of target parameters, more difficult targets can be recognized in clutter/hides and correctly identified. The Air Force should emphasize development of multi and hyperspectral (HS) sensors, combinations of orthogonal dimension sensors such as acoustic with magnetic UGS, and robust fusion/correlation algorithms. Fundamental to the data fusion development is a 6.1 program to formulate a comprehensive mathematical basis for such algorithms.

9. Develop ATR and ASC for sensor systems

ATR and ASC offer very high payoff in improving target identification, reducing latency, greatly lowering data transfer requirements, and simplifying aircrew workload. Major emphasis on the associated technologies, based on further research into the underlying foundations for ATR/ASC, with consideration given to a bio-mimetics processing architecture is needed. Exploitation is required of unattended ground sensor data, moving target indication(s) and both radar and electro-optical/infrared imagery.

Although much needs to be done on next generation capabilities, just as much needs to be done to field in the short term capabilities that exist today. The Air Force should field existing technology systems, however limited, to gain an invaluable set of experiences as they relate not only to technology but to utilization. We can obviously create ideas and concepts for ATR/ASC systems easier than we can employ them. However, valuable experience derived from even limited ATR/ASC systems may conjure up whole new ways of fighting that are not obvious today.

10. Investigate innovative concepts for sensor systems that exploit improved components and integrated operations

The Sensors Panel has identified a number of illustrative sensor system concepts that exploit the advanced technology projections for the purpose of providing significantly persistent wide area surveillance with enhanced target detection and recognition. These concepts are briefly described, along with the attendant technologies, in the Report and include:

- *Target Reporter*. Long endurance unmanned air vehicle with range of air and ground sensor/tag reporting for persistent battlefield surveillance.
- *Integrated Arrays of Distributed Unattended Ground Sensors*. Large areas seeded with multiple micro-sensors implemented on small devices, monitored and processed by aircraft.
- *Underground Target Surveillance*. A system for monitoring underground facilities typically associated with NBC weaponry, leadership centers, and TBM depots.
- *All-Condition Concealed Target Detection*. Exploitation of multiple sensors for the detection of targets under foliage, in camouflage, and in hides.
- *Weather Surveillance and Prediction*. Multiple sensors integrated to provide broad area and local military-unique weather.
- *Modular, Integrated, Multifunction Phased Array Based Electro-Optical System*. Affordable and robust, multiaperture defensive and attack processing.
- *Low Cost Space-Based Surveillance*. A mix of high resolution radar and imaging electro-optical sensors on small, launch-on-demand satellites.

The picture which emerges from these concepts is that of a feasible, affordable approach to greatly enhanced information gathering in the battlespace through a combination of advances in individual sensor technologies and, especially, processing for cooperative sensor operations.

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